INLAND WATERS BRANCH

DEPARTMENT OF THE ENVIRONMENT

General Hydrology of the Great Lakes and Reliability of Component Phases

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INTRODUCTION

Knowledge of the hydrology of the Great Lakes and the reliability of its component phases is basic to the management of the lakes as a water resource. Although the lakes are a unique system in terms of their area and relation to each other, they have only received intermittent attention from hydrologists during the last fifty years. As a result, today there is no complete documentation of the various components of their hydrology.

It would be presumptuous to attempt a detailed description in one paper of the hydrology of an area which occupies about one-third of a million square miles of central North America. What can be done, however, is to provide some impressions of the relationships of water to land and atmosphere of the basin. This is done through a discussion of the relationships of component phases of the hydrology of the land and lake areas. These components are also examined in terms of their relative magnitude, seasonal change, variability and reliability. This discussion will provide background for understanding the function of the hydrologic system of the lakes and their land basins and its relation to the changes in volume of the water in the lakes. The major portion of this fresh-water mass will not enter into the discussion since we will only be concerned with changes in the top few feet of the lakes. These changes in lake levels indicate the water volumes which are of concern to water resource managers who are interested in water quantities.

THE GREAT LAKES BASIN

The Great Lakes basin consists of four principal lakes (Superior, Michigan-Huron, Erie and Ontario) and the peripheral lands of the tributary areas around the shores. These vary in width from less than 10 miles to more than 100 miles. For hydrologic purposes, Lake Michigan-Huron is considered to be one lake since there is no change in level at the Straits of Mackinac. The connecting channels of the lakes are the St. Marys River between Lake Superior and Lake Michigan-Huron, the St. Clair River, Lake St. Clair and Detroit River system between Lake Michigan-Huron and Lake Erie, the Niagara River between Lake Erie and Lake Ontario and the St. Lawrence River between Lake Ontario and the Atlantic Ocean. Two of these rivers (St. Marys and St. Lawrence) and their upstream lakes (Superior and Ontario) are controlled by international agreement under the International Joint Commission. The outlet rivers of Lakes Michigan-Huron and Erie are subject to natural control although man has changed these controls by dredging and ice control.

Surrounding the basin of the Great Lakes are the Appalachian mountains on the south, the Adirondacks on the east, the Precambrian Shield on the north and the Mississippi Valley in the west. The surface of the basin shows the effects of the glacial movements of the Ice Age. In the northern portions of the basin is the Precambrian Shield consisting of rock knobs which have been denuded of their soil and ground down by glacial action, resulting in rough wooded country. In the southern areas, the country is generally rolling upland which slopes to the flatter lowlands around the lakes. Some of these lower areas have coverings of sand and silt which were deposited over the glacial tills during the high lake levels of the post-glacial period.

The climate of the Great Lakes region is dominated by the easterly movement of air masses. The region lies in the path of the prevailing westerly winds and is affected by major storms moving out of the south. The easterly movement of air results in moderated air temperatures and extremely high snowfalls in the lee of the lakes. The mean annual temperature over the basin varies from 31°F, with an average length of frost-free period of 75 days north of Lake Superior, to 48°F and an average length of frost-free period of 180 days at the western end of Lake Erie in the south.

Table 1 shows some of the physical data used in describing the basin. The important physical characteristics of the basin are the ratio of water to land, column (2) vs (3), and the large storage capacity available in the lakes, column (4). The magnitude of the water quantity changes is shown in the total of column (4), where one foot depth over all the lakes is equivalent to the mean flow of the St. Lawrence River for about four months. The average elevation above mean sea level, in column (5) of the Table, indicates that there is about 22 feet of fall between Lake Superior and Lake Michigan-Huron, about 8 feet between Lake Michigan-Huron and Lake Erie, about 326 feet from Lake Erie to Lake Ontario and about 245 feet difference in elevation from Lake Ontario to the Atlantic Ocean. This demonstrates the importance of these large reservoirs to the development of hydro-electric power since the major portion of this head is utilized. In column (6) the range of stage during the period from 1860 to 1954 is shown. These figures, when combined with column (4), show the large amount of storage available in the lakes between extremes of stage. The last two columns of the Table show the relative contribution of each lake to the outflow and the average annual depth of runoff from each basin. These characteristics of the Great Lakes basin make the Great Lakes a unique hydrologic system.

GREAT LAKES SYSTEM HYDROLOGY

The storage in the Great Lakes can be directly related to the inflow and outflow by the general hydrologic equation. The equation expresses the fundamental relationship which applies to most hydrologic problems, that is, for the continuity of a hydrologic system, the difference between the inflow and the outflow or input and output must be placed in or taken out of storage. For the land basins of the Great Lakes the equation can be written:

$$P_L - E_L - R_L = \Delta S_L \qquad (1)$$

where P_L is the precipitation on the land surface
E_L is the evaporation from the land and plant surfaces
R_L is the runoff to the lake from the land area
ΔS_L is the change in storage as snow on the ground, surface water storage, soil moisture and groundwater.

For the lake areas of the Great Lakes the hydrologic equation can be written similar to (1):

$$I + P - E + R_L - O = \Delta S \qquad (2)$$

where I is the inflow from the lake above (Lake Superior excepted)
P is the precipitation on the lake surface
E is the evaporation from the lake surface
R_L is the runoff from the land area [see equation (1)]
O is the outflow in the outlet river
ΔS is the change in storage in the lake as measured by change in level.

For purposes of this discussion the units used are feet on the lake and the time unit is one month. These units are used to portray the relationships of the component phases of the hydrology to the lake levels - the most noticeable variable characteristic of the lakes. The time unit of one month is used because of the slow change which takes place, on the average, in the water storages on the lakes.

TABLE 1

Physical Data Pertaining to the Great Lakes

Lake	Drainage Area		Storage Capacity Per Foot of Stage of Lake (cfs for one month)	Average Elevation (above m.s.l.)	Range of Monthly Mean Stage * (ft.)	Outlet River	Mean Outflow	
	Land Area (Square Miles)	Water Surface Area (Square Miles)					(cfs)	Depth on Total Drainage Basin (inches)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Superior	49,000	31,800	337,000	600.4	4.1	St. Marys	75,000	12.6
Michigan- Huron	46,600 49,400	22,400 23,000	481,000	578.8	6.2	St. Clair Lake St. Clair Detroit	189,000	11.6
Erie	29,400	9,900	105,000	570.4	5.4	Niagara	205,000	10.6
Ontario	27,100	7,500	80,000	244.6	6.6	St. Lawrence	241,000	11.1
TOTALS	201,500	94,600	1,003,000					

* Period of record 1860-1954.

(from Morton and Rosenberg[1]).

The land and lake equations describe the hydrology of the system. From the land equation (1), the principal contribution of the land area to the lakes is by land runoff (R_L). Land runoff results from precipitation (P_L) after evaporation (E_L) from land and plant surfaces. Precipitation falls on the land surface and may move over the surface to streams and/or surface water storages. However, a portion of the precipitation excess moves through the soil recharging soil moisture storage (which the plants use as a water supply) and/or groundwater storage or to surface water storage. Groundwater storage is the source of springs and, with surface water storage in small lakes and swamps, provides the dry weather flow in streams. For purposes of this discussion, it is assumed that the sum of the direct groundwater components from the land to the lake and vice versa is small when compared to the other hydrologic elements, and that the groundwater divide of the basin is essentially the same as the topographic divide.

In the winter during freezing weather, the excess precipitation accumulates on the land surface as snow. The moisture stored as snow accumulates until warmer weather causes snowmelt and the resulting spring freshet with accompanying recharge of soil moisture, groundwater and surface storages. The contribution of land runoff from snowmelt in the spring comprises the major volume of water added to the lakes from the land.

The hydrology of a lake is described by the lake equation (2). For Lake Superior, which receives no inflow from an upstream lake, the first term "I" (inflow from upstream lake) is omitted from the equation. The runoff from the land surface plus the inflow from the lake above and the precipitation on the lake surface comprise the total supply to the downstream lakes. Some of this supply is lost to evaporation from the lake surface. The amount by which this net total supply or inflow is greater or less than the outflow results in a rise in level (an increase in storage) in the case of excess supply or a decline in levels (a decrease in storage) in the case of deficient supply. The land equation (1) and lake equation (2) are related through the common term land runoff (R_L).

An important aspect of the hydrology of the lakes is their storage characteristic (change in level) since this results in near constant outflows from each of the lakes. This characteristic of the lakes is attributed to their large surface area. Due to their large areas, a small rise or fall in level represents, on these surfaces, a large volume of water. In Lakes Michigan-Huron and Erie, which are not regulated, the outflows are dependent on the level of the lake. As a result, a small incremental change in level (a large volume in the lake) represents a small change in the outflow from the lake. This relationship gives unregulated lakes their ability to provide relatively constant month-to-month outflows with limited variability and great reliability. The regulated lakes of Superior and Ontario are operated to rules which approximate the natural storage-outflow relationship. However, the regulated outflows are manipulated generally within the limits of previously unregulated flows to provide lake levels and outflows which are better suited in time to man's needs for water for domestic and industrial use, navigation, power and shore property.

COMPONENT PHASES OF THE HYDROLOGY OF THE GREAT LAKES

The component phases of the hydrology of the Great Lakes are the terms of equations (1) and (2). To demonstrate the general function of the system, the component phases of its hydrology and their relationship to the land and lake equation are discussed. In order to describe the month-by-month variation of the component phases of the hydrology of the Great Lakes and consequently their reliability, two statistics are used. These are the mean or average and the standard deviation. If a variable is normally distributed about the mean or average, about 68 percent of the population will be within one standard deviation on either side of the mean. These statistics will then provide some concept of the dispersion of the components about the monthly mean and are a measure of their reliability.

The data presented here represent the 16 years from October 1950 to September 1966 inclusive. This is a relatively short period compared to the level data for the lakes which dates back to 1860. However, this period is used because estimates of all the components of the hydrology of the lakes could be made for most of the period.

The data for this paper have been obtained from several sources, adjusted for man-made diversions into and out of the system, and assumptions have been made to obtain estimates of the component phases which are applicable to all the lakes.

Precipitation (P_L, P) - Precipitation is the source of water for the system and is the principal input. Figure 1 shows the annual run by months of the precipitation on lake basins in feet on the lake. Lake Superior shows a seasonal fluctuation of from one-quarter to one-third of a foot of precipitation on its surface in the summer and fall months to about one-sixth of a foot during the winter months. From Lake Superior down to Lake Ontario, this seasonal fluctuation is less apparent with the surface of Lake Ontario receiving, on the average, almost a constant one-quarter of a foot in all months. The month with the greatest variability in monthly precipitation, as shown by the standard deviation, is September on the upper lakes (Superior and Michigan-Huron) and October on the lower lakes. The precipitation falling in December through March is generally snow and results in the accumulation of a snowpack on the land basins of the upper lakes with short period accumulations on the Lake Erie basin. Persistent periods of several months of high or low precipitation during successive years result in precipitation excesses or deficiencies which are accumulated in the storages on the lakes.

The mean monthly values shown in this paper were obtained from those published by the Lake Survey District, Corps of Engineers, United States Army. They have been developed from data supplied by the Meteorological Service of Canada and the Environmental Data Service, United States Department of Commerce. The data are made representative of the land basins of the Great Lakes using standard area weighting techniques. Very few measurements of precipitation are made over the lake surfaces. Initial evidence[6] indicates a seasonal variation over the lake surfaces; however, the differences are within the range of error of the measurement of precipitation. For purposes of this discussion, the land precipitation values were assumed to apply to the lake surfaces also.

Evaporation (E_L, E) - Evaporation, the process by which water is lost to the atmosphere, is a most important output from the land and water surfaces of the Great Lakes basin. Figure 2 shows the annual run by months of the evaporation from each of the Great Lakes. Evaporation from a large lake depends on the characteristics of the air masses passing over the lake, the available energy, ice cover and the heat storage capacity of the lake. Negative values (usually occurring in the spring) indicate condensation

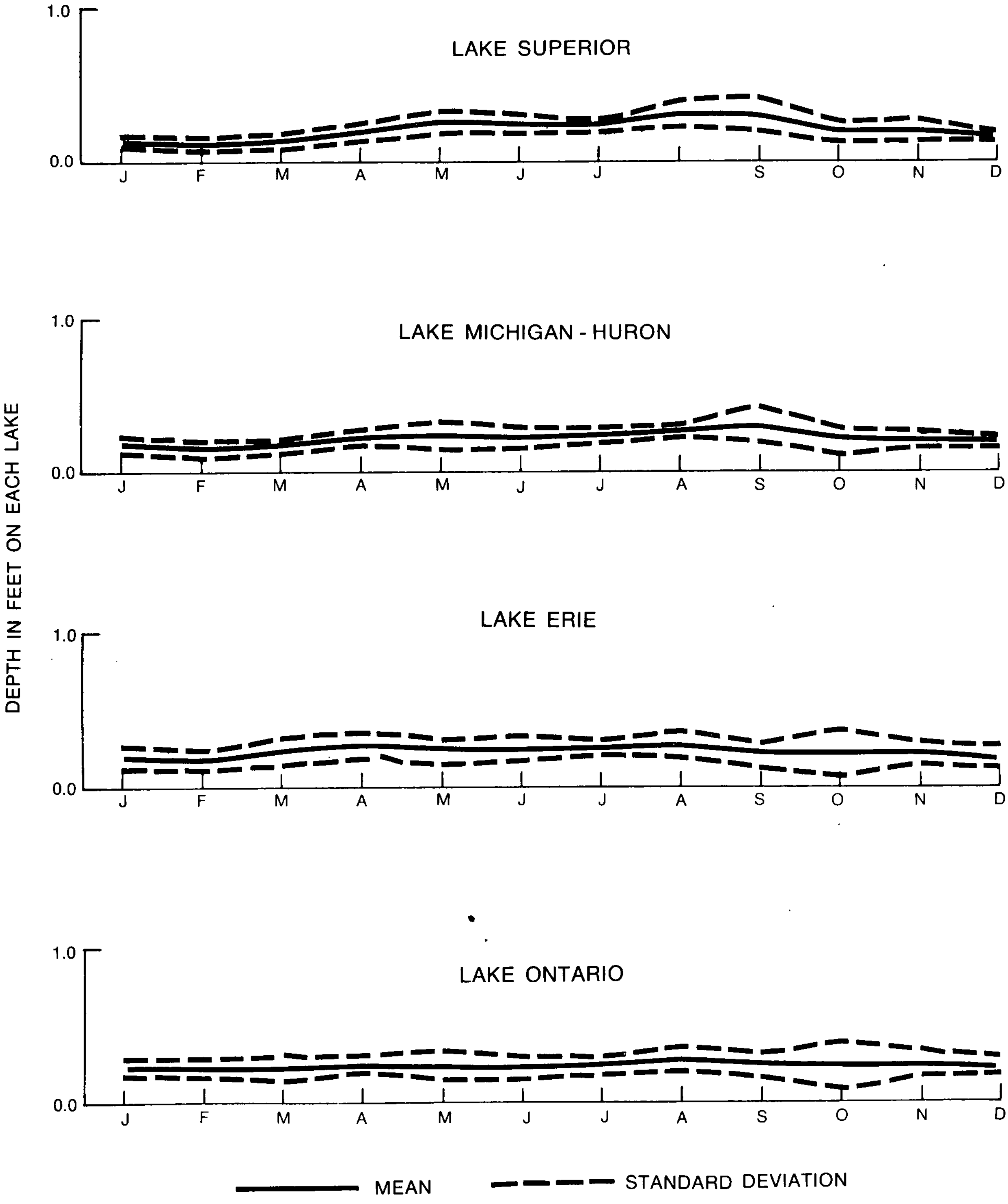

FIGURE 1 PRECIPITATION

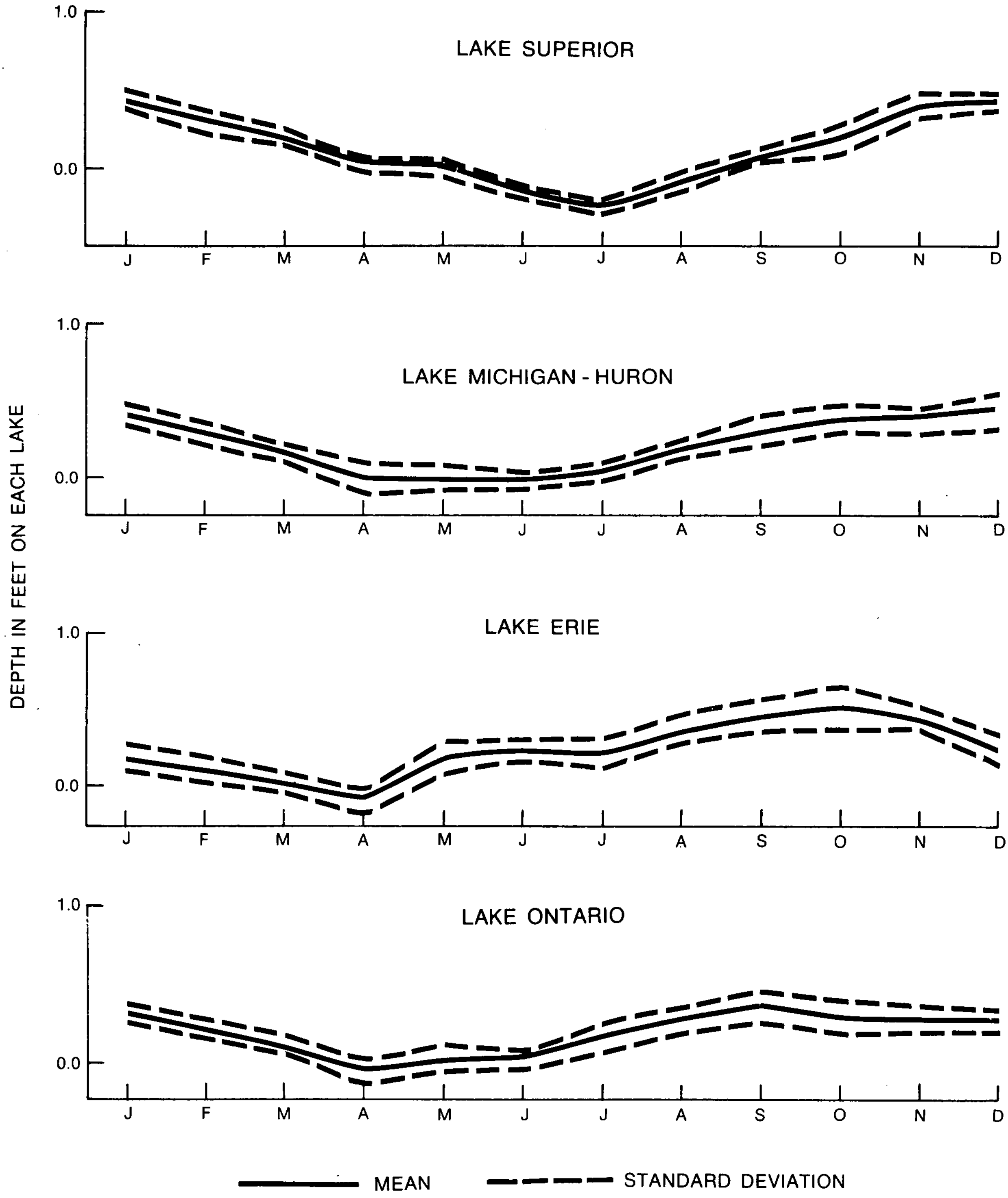

FIGURE 2 EVAPORATION

resulting from warm moist air over a cold lake. Lake Superior, with its great heat storage and negligible ice cover, is subject to dry cold air masses in winter resulting in high evaporation in the winter and low evaporation or condensation in the early summer. Lakes Michigan-Huron and Ontario follow a similar pattern. Lake Erie which has a regular winter ice cover has its highest evaporation loss in the fall and lowest in early spring. It demonstrates the effect of a shallow lake with low heat storage and an ice cover. Persistent periods of low evaporation and high precipitation cause rising lake levels while periods of low precipitation and high evaporation result in lowering of lake levels. All lakes demonstrate similar variations in monthly evaporation as indicated by the monthly standard deviations. Evaporation estimates used are those published by Richards and Irbe[2]. Estimates of this component are available since 1959 for Superior and the Huron portion of Michigan-Huron. For purposes of this paper, it was assumed that the depth of evaporation for Lake Michigan was similar to that for Lake Huron.

Land Runoff (R_L) - This phase of the hydrology of the Great Lakes system is an output from the land areas and an input to the lakes.

Each of the land basins shows similar average runoff characteristics (Figure 3). All have a spring stream-rise due to snowmelt followed by a long recession. In the case of the upper lakes, on the average, the month with the highest runoff occurs in April on Michigan-Huron and May on Superior. Of the lower lakes, Erie receives the peak runoff in March and Ontario in April. Both of these lake basins demonstrate a tendency to higher runoff during the fall and winter months because precipitation of more rainfall and less snowfall, during a period of low evaporation, results in an excess of precipitation causing runoff. The characteristic stream-rise, due to snowmelt, occurs early (March) in the south and later (May) in the north. The variability of runoff to the upper lakes is similar in all months with slightly greater variation in the spring during snowmelt. On the lower lakes the variation is greatest during snowmelt which can occur in any month of the winter.

Runoff to the lakes was estimated using data provided by the Water Survey of Canada[3] and the United States Geological Survey[4] for the most downstream gauging station of the basins flowing into the lakes. About two-thirds of the land basin of the Great Lakes is gauged. Estimates for the remaining ungauged areas were made using data from nearby gauged basins which have similar climatologic and topographic characteristics.

Change in Storage ΔS - The change in storage (Figure 4) on the lakes reflects the differences between the inflows (inflow from the lake above, precipitation and land runoff) and the outflows (evaporation and outflow). When inflow exceeds outflow, changes in storage are positive and indicated by an increase in lake level. When inflow is less than outflow, changes in storage are negative and indicated by a decline in lake level. Since the precipitation and outflow are about constant on the average, the changes in storage follow the pattern of the land runoff which is reinforced by the precipitation - evaporation difference on the lake surface. As the evaporation decreases in the winter, a lake starts its annual rise. These changes in storage are directly reflected in changes in lake level and resulting outflow. Variation in the storage about the monthly mean is similar for most months. Greater variation occurs in the fall as a result of precipitation variability. This factor, the storage, although only the top few feet on each lake, is the most important single volumetric characteristic of the lakes which man can use and is using in the regulation of Lakes Superior and Ontario.

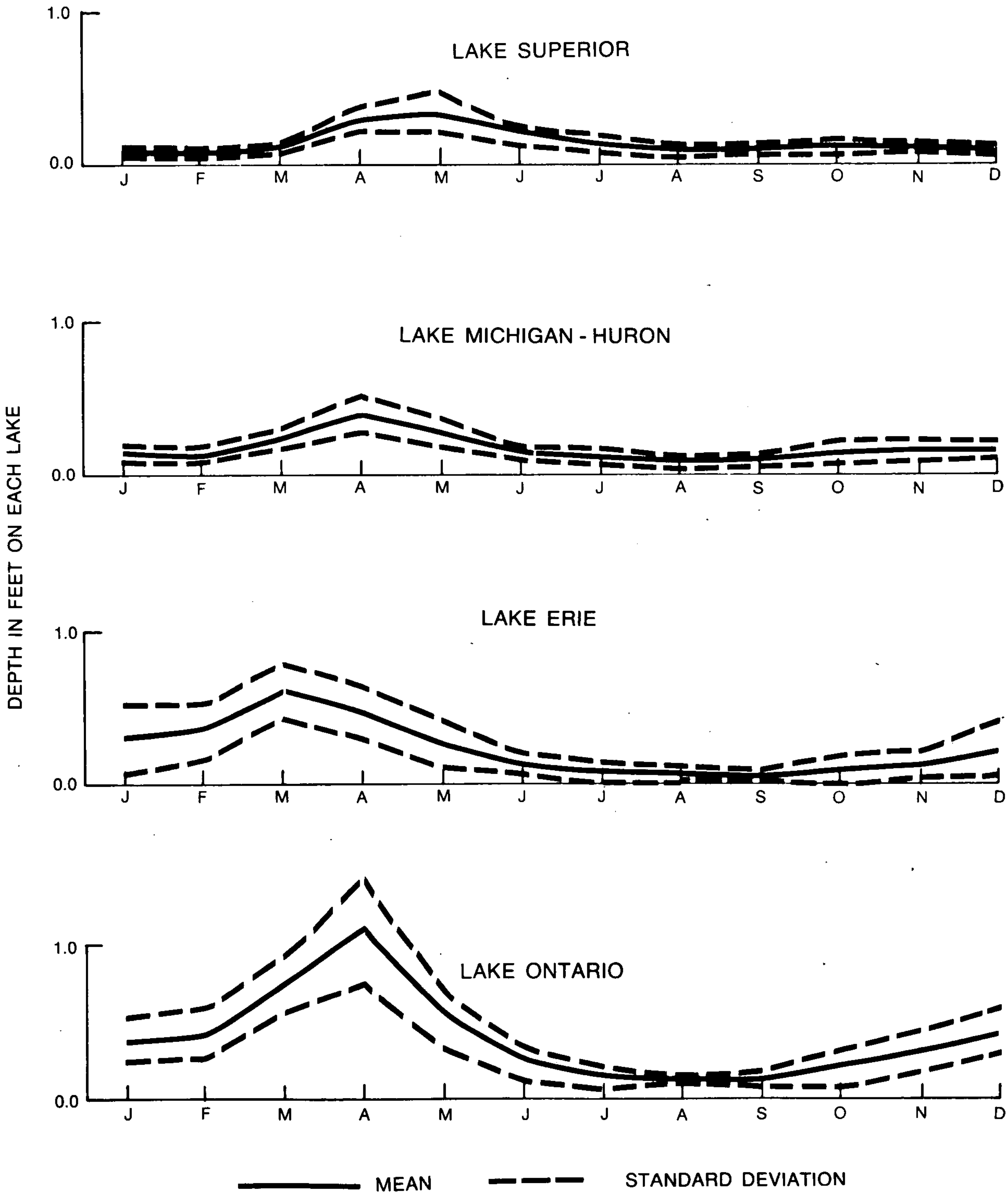

FIGURE 3 LAND RUNOFF

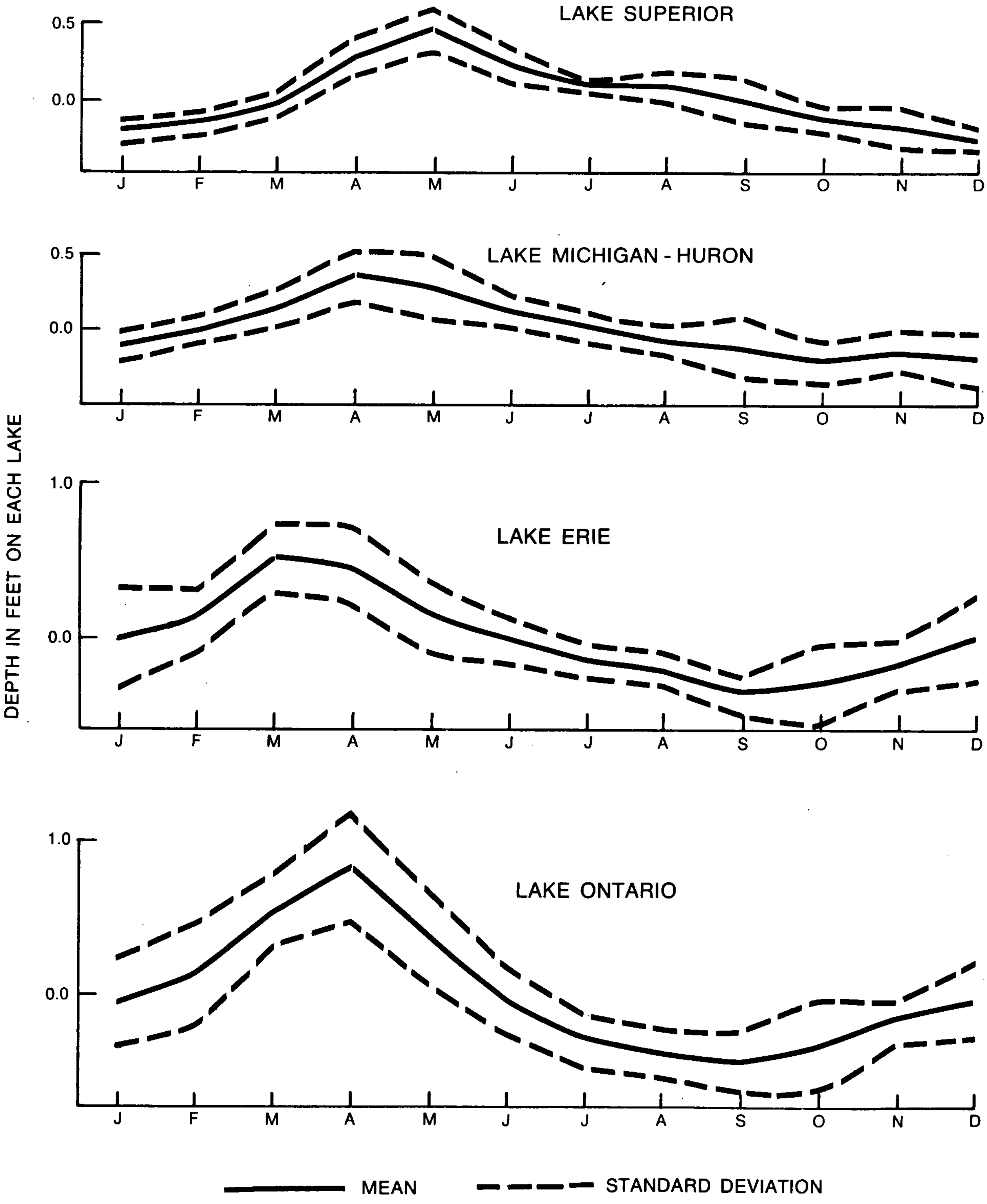

FIGURE 4 CHANGE IN STORAGE

Changes in storage, in this paper, are indicated by changes in mean lake level. These are determined from data collected by the Lake Survey and the Water Survey of Canada. Ideally, the storage should be evaluated by an instantaneous calm level. However, the water levels of the lakes are seldom calm and are frequently disturbed by wind and pressure changes in the air masses passing over them. Therefore, considerable error can be included in the inference of a current state of storage from a single instantaneous level. As a result, storage is evaluated from a level which is averaged over several hours to minimize these short term meteorological effects of wind and pressure.

Outflow (O) - The outflows from the lakes (Figure 5) reflect the summation of the component phases of the hydrology of the land and lake surface as shown in equation (2). The land contributes the major portion of the supply to the lakes (see Table 2). The outflow from the upstream lake becomes the inflow to a downstream lake. The variability which is seen in the other hydrologic components is greatly reduced by this storage or reservoir effect of the lakes. It is particularly true of the upper lakes with their very large surface areas. A similar effect is shown on the outflows from the lower lakes. However, the low outflows shown for the lower lakes in February result from ice jams in the outlet channels. The ice in the St. Clair River restricts the outlet and reduces the outflow. This increases the storage on Lake Michigan-Huron and raises its level. This storage on a naturally regulated lake like Lake Michigan-Huron may affect storage and levels for over two years in the future. Any attempt at removal of the ice in the connecting channels could result in future lower lake levels.

All lakes, with the exception of Lake Michigan-Huron, have diversions for power and navigation purposes around the control sections or from the river channels. The flows are computed by a summation of all outflows through the various structures. The Lake Michigan-Huron outflows through the St. Clair River are computed by the use of hydraulic relationships based on the levels of the upstream and downstream lakes.

Errors - Errors in the determination of monthly precipitation and evaporation are probably in the 10 to 20 percent range. Errors in estimated land runoff are probably about 10 percent. Monthly inflow and outflow errors are probably less than 10 percent where well calibrated measuring sections are maintained on the Niagara River and the St. Lawrence River. Because of the uncertainty in the current effect of the wind and pressure on water level, the estimated end-of-month level for any lake could be in error more than 25 percent of the outflow, depending on the size of the lake.

Precipitation, runoff and evaporation cannot be measured at every point but are area-averaged values estimated by independent means. Therefore, it can be assumed that the errors are likely to be random and cancelling over long periods leading to reasonable estimates of the hydrologic components.

THE LAND-LAKE HYDROLOGIC RELATIONSHIP

To provide some concept of the land-lake relationship and its importance to the Great Lakes system, Table 2 shows the distribution of the supply or inflow to each lake as a percentage of its outflow. The reason that the outflow is not totally accounted for is due to error in the estimation of the components of equation (2).

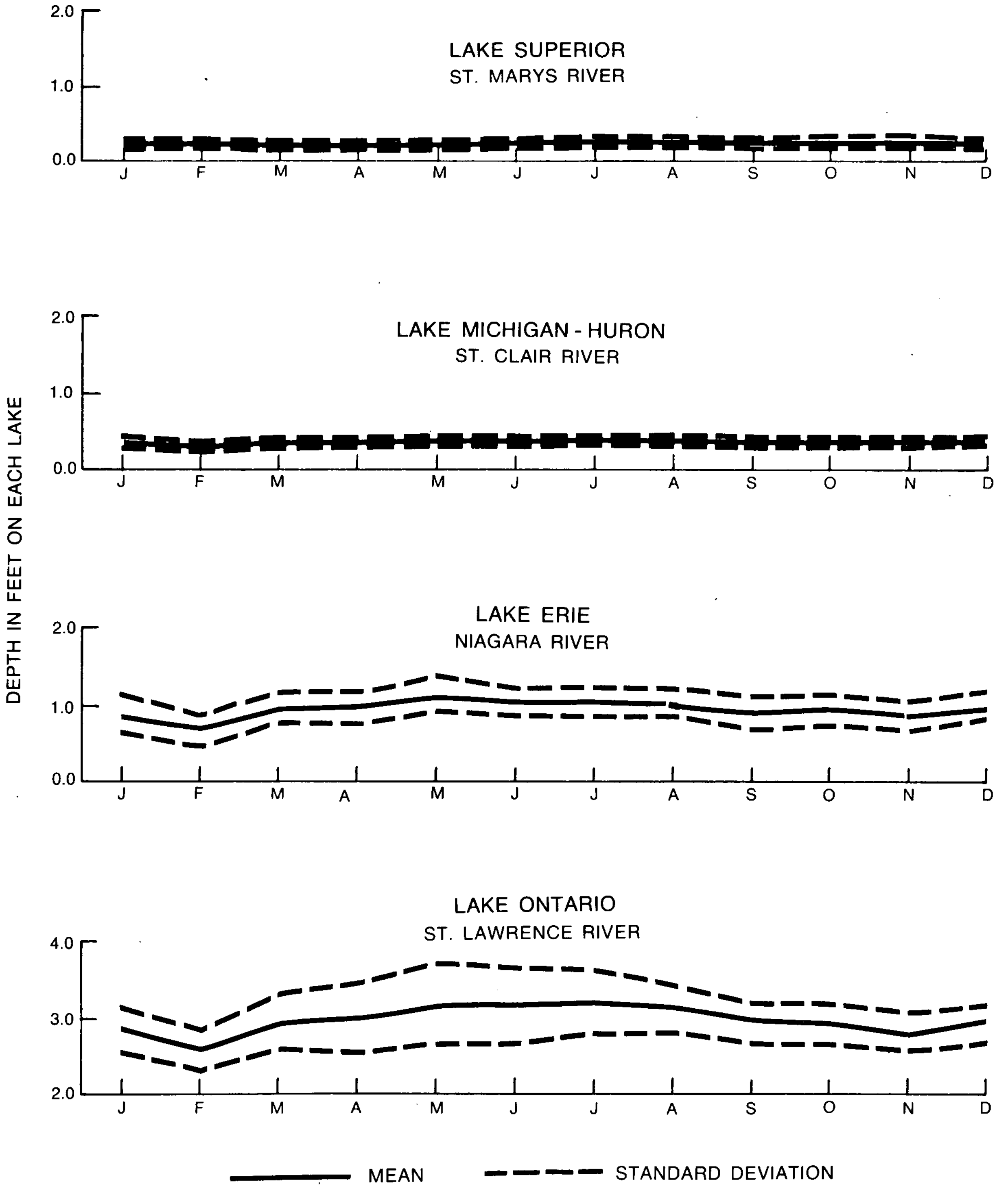

FIGURE 5 OUTFLOW

TABLE 2

Distribution of Average Water Supply to Lake in Percent of Average Outflow

	Lake Superior	Lake Michigan-Huron	Lake Erie	Lake Ontario
Inflow from upstream lake (I)	0	46	86	86
Precipitation on lake surface (P)	88	59	12	8
Evaporation from lake surface (E)	-55	-57	-13	- 7
Net (P-E)	+33	+ 2	- 1	+ 1
Runoff from land basin	62	49	12	13
Percent of total outflow accounted for	95	97	97	100

From the above table, the relative importance of the land and lake in contributing to the lake outflow can be seen. Lower evaporation rates on Lake Superior result in the lake contributing about 33 percent of the outflow while the land area contributes about 62 percent of the outflow. This shows the importance of the large lake area of Lake Superior to the water supply of the lake. On the lakes downstream, the lake is much less important in contributing to the outflow, and the precipitation on and evaporation from the lake surfaces are about in balance. On Lake Michigan-Huron, the inflow from the lake above and land runoff are of about equal importance in providing water for the outflow. On the two lower lakes, Erie and Ontario, the inflow from the upstream lake contributes about 86 percent of the outflow and the remainder is runoff from the local land basin. Table 2 shows that the major contributors to the outflows of the Great Lakes system are the land basins of the upper lakes, whereas the lower lakes contribute relatively small amounts to their outflows.

SUMMARY

This review of the hydrology of the Great Lakes has provided a brief description and some impressions of the hydrologic processes which affect the levels and flows of the Great Lakes system and some of the factors which govern the reliability and variability of the component phases of land-lake hydrology. In particular, the importance of the large lake surfaces and the water storage available in the lakes has been shown. Although the components of the hydrology of the lakes were discussed in terms of their seasonal variability and general range, the land and lakes which make up the Great Lakes basin are a dynamic system which changes in all units of time. The generality of these changes have been shown here. Even though knowledge of the relationships expressed by the hydrologic equation is increasing, there is a great scope for investigation of these relationships on large areas such as the Great Lakes. Hopefully, the terrestrial water balance program on Lake Ontario for the International Field Year for the Great Lakes will demonstrate the benefits to be gained by in-depth studies of the water balances of the lakes. This will encourage the collection and analyses of more complete data for the other lakes. Such knowledge will permit the development of the models necessary for the management of the Great Lakes as one of the most important water resources of both Canada and the United States.

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