Living With The Lakes: Challenges and Opportunities

Annex A
Past and Future
Water Level
Fluctuations

LIVING WITH THE LAKES:

CHALLENGES

AND

OPPORTUNITIES

ANNEX A

PAST AND FUTURE
WATER LEVEL FLUCTUATIONS

PREPARED BY FUNCTIONAL GROUP 1
FOR THE PROJECT MANAGEMENT TEAM

International Joint Commission
Water Levels Reference Study

MAY, 1989

EXECUTIVE SUMMARY

The Great Lakes Basin is a valuable natural resource shared by Canada and the United States. Its water levels have fluctuated for thousands of years, reflecting the climatic conditions in the basin. There are those times when nature, in its vagarious moods, subjects the lakes to extreme fluctuations, rendering hardships to many, civilization in particular. This has never been truer than in the last several decades, during which time the governments of Canada and the United States have forwarded several references to the International Joint Commission (IJC) to investigate the fickle nature of the lakes. The current study, to examine and report upon methods of alleviating the adverse consequences of fluctuating water levels in the Great Lakes-St. Lawrence River Basin, was initiated in August 1986. Annex A is part of this study and is an attempt to promote better understanding of the Great Lakes, including a discussion of the past and what the future might hold.

The Great Lakes Basin, almost 300,000 square miles in area, supports a lake system containing over 5,400 cubic miles of water and has a shoreline length of 11,000 miles. The quantity of water in the lakes at any time is dependent on various hydrologic factors such as precipitation, run-off, evaporation, ice, weeds, winds, temperatures and the natural uplift of the earth's crust. To some degree, artificial factors such as lake regulation, channel modifications, ice booms, land-use modifications, diversions and consumptive use also have an influence on lake levels.

To answer one nagging question as to what the future may hold for the lakes, especially if their levels are appreciably different from the past, and another question as what further lake regulation can do, this study examines a wide range of issues; including estimates of levels and outflows for both wet and dry conditions that could result from climatic changes, and the effects of projected consumptive water use, interbasin diversion, land-use modifications and further regulation (such as on Lake Erie.

FOREWORD

Water levels of the Great Lakes have fluctuated for thousands of years, in response to a number of natural factors. More recently, the influence of society's development in the watershed has also had an effect on the natural water level regime. Great Lakes water level fluctuations have been observed, recorded and studied exhaustively over the past several decades. Information on how and why levels have varied in the past century is well documented. As expected, the future regime of Great Lakes water levels is less well understood, being a function of the hydrometeorologic process to which the past is a guide, but not a forecast. Adding to the uncertainty about future water levels is the increasing influence of society in the form of water-use and consumption, land-use modifications, effects on the atmosphere and climate and other activities that change or could change the hydrologic cycle of the system. These factors and others will likely contribute to defining the future levels of the Great Lakes. This in turn will affect physical and biological processes in the Lakes ecosystem.

But what of the future? What uncertainties does the future hold with regard to lake level fluctuations? How will the "natural" features of the lakes and their dependent lifeforms continue to evolve? How will the interaction that society has with the lakes change; or, to put it another way, how do we expect to change the way we interact with and benefit by the lakes?

In addition to describing current hydrologic conditions, this annex contains a projected and somewhat speculative view of what the future holds for the Great Lakes. Planning for present conditions is fruitless. Planning for the future, uncertain as it may be, is vital if we are to improve on the past.

PHASE 1 REPORT OUTLINE
IJC FLUCTUATING WATER LEVELS STUDY

MAIN REPORT

ANNEX A - PAST AND FUTURE WATER LEVEL FLUCTUATIONS

ANNEX B - ENVIRONMENTAL FEATURES, PROCESSES AND IMPACTS: AN ECOSYSTEM PERSPECTIVE ON THE GREAT LAKES - ST. LAWRENCE RIVER SYSTEM

ANNEX C - INTERESTS, POLICIES AND DECISION MAKING: PROSPECTS FOR MANAGING THE WATER LEVELS ISSUE IN THE GREAT LAKES - ST. LAWRENCE RIVER BASIN

ANNEX D - THE GREAT LAKES ECOSYSTEM PERSPECTIVE: IMPLICATIONS FOR WATER LEVELS MANAGEMENT

ANNEX E - POTENTIAL ACTIONS TO DEAL WITH THE ADVERSE CONSEQUENCES OF FLUCTUATING WATER LEVELS

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IJC REFERENCE STUDY
ON
FLUCTUATING WATER LEVELS IN THE
GREAT LAKES-ST. LAWRENCE RIVER BASIN

ANNEX A
PAST AND FUTURE WATER LEVEL FLUCTUATIONS

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SECTION 1

HISTORICAL WATER LEVEL REGIME

OVERVIEW OF LEVEL FLUCTUATION FACTORS

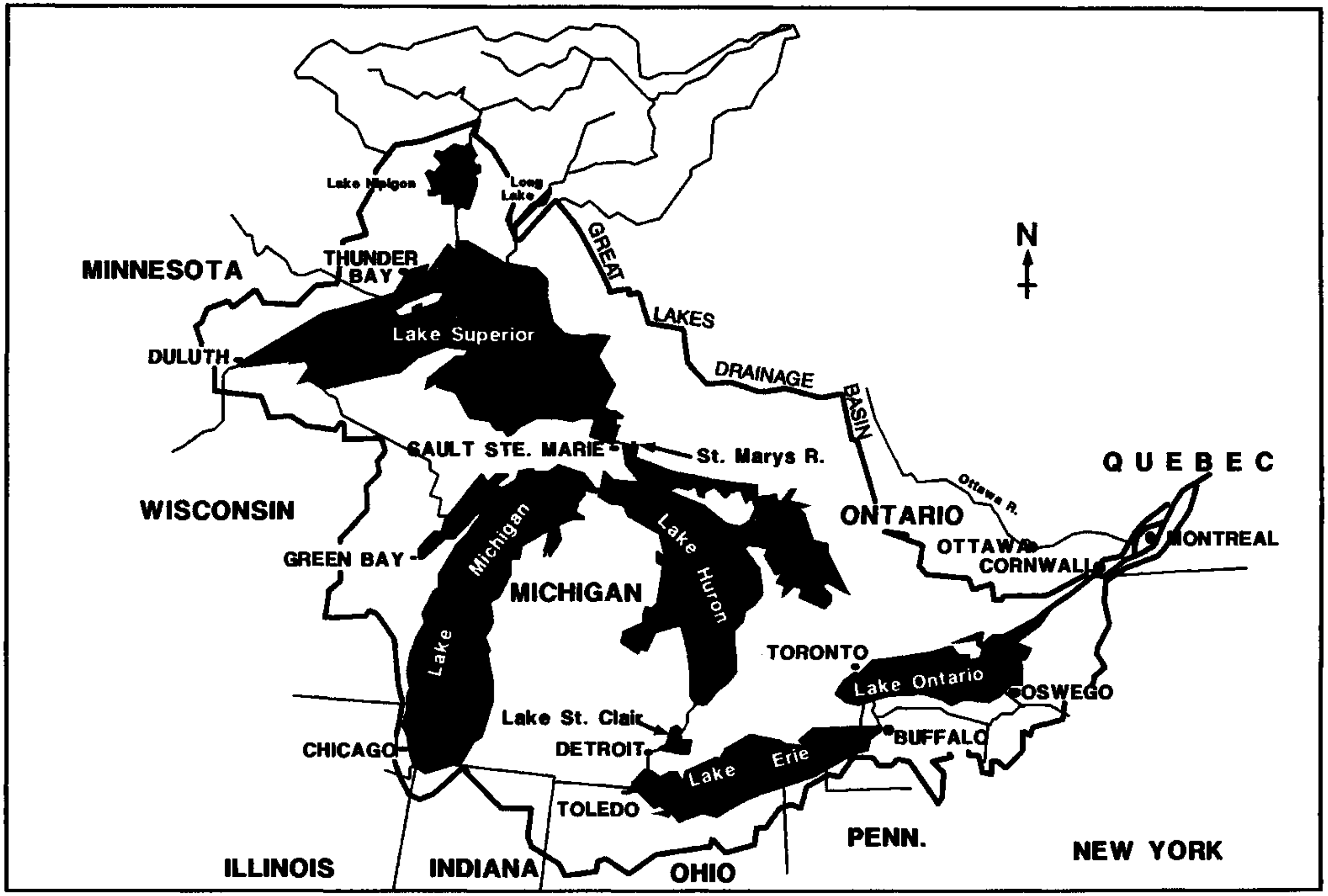
The Great Lakes' water levels fluctuate according to many natural and artificial factors. The principal natural factors include precipitation, evaporation and transpiration, runoff, groundwater, inflows and outflows and ice and aquatic growth (weed) retardation. Other natural factors include short-term meteorologic disturbances, crustal movement and minor diurnal tides. Artificial factors include lake outflow regulation, dredging and other interconnecting channel modifications, land use modifications, diversions and withdrawals and consumptive uses. The hydrologic cycle and other water resources processes, are monitored by a number of agencies in the Great Lakes Basin. Some processes can be observed directly; for example, precipitation and streamflow. Others can be derived based on observed hydrometeorologic factors; examples being evaporation and weed and ice retardation.

Civilization's activities have, to a certain extent, modified some of the natural factors affecting lake level fluctuations. The increase in urbanization in areas around the Great Lakes has altered the runoff characteristics. Industrial activities may be changing precipitation patterns. Agricultural activities have impacts on runoff and evapotranspiration. These changes in the hydrometeorologic processes are, however, very difficult to quantify as separate factors.

FEATURES OF THE GREAT LAKES - ST. LAWRENCE RIVER BASIN

The Great Lakes Basin is about 297,000 square miles in area (Figure A-1-1), extending from about 50 miles west of the western tip of Lake Superior to the outlet of Lake Ontario, and from Lake Nipigon in the Province of Ontario south to near the central portion of the State of Ohio. About 123,000 square miles are in Canada and the remaining 174,000 square miles are in the United States and include the entire State of Michigan and portions of Minnesota, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania and New York. A noteworthy feature of this basin is that the five Great Lakes with their connecting channels and Lake St. Clair have a total water surface area of about 95,000 square miles. This is about one-third of the total Great Lakes drainage area. When at their average levels, the Great Lakes hold about 5,460 cubic miles of water and have a total shoreline length, including islands, of about 11,000 miles. The St. Lawrence River, from Lake Ontario to Quebec City, adds an additional 130,000 square miles of drainage area, most of which is located in the Province of Quebec and the State of New York.

Maximum water depths range from 23 feet, excluding the navigation channel, in Lake St. Clair to over 1,300 feet in Lake Superior. The navigation course from the western end of Lake Superior to the Atlantic Ocean is about 2200 miles.



GREAT LAKES-ST. LAWRENCE RIVER BASIN **FIGURE A-1-1**

The Great Lakes comprise a series of natural storage reservoirs which discharge into the St. Lawrence River (Figure A-1-2). They are positioned in a step-wise manner, with Lake Superior being the highest and Lake Ontario the lowest, and are interconnected by a series of rivers and straits. Lake Superior discharges through the St. Marys River into Lake Huron, which is connected to Lake Michigan through the Straits of Mackinac. The hydraulically unified Lakes Michigan and Huron discharge into Lake Erie through the St. Clair River - Lake St. Clair - Detroit River system. Lake Erie's outflow is discharged through the Niagara River into Lake Ontario, and Lake Ontario in turn, flows into the Gulf of St. Lawrence, then the Atlantic Ocean, via the St. Lawrence River. The St. Lawrence River, between Lake Ontario and Cornwall, Ontario (Massena, New York), has a drainage area of 3,000 square miles, including 235 square miles of water surface area. The Great Lakes, due to a very large storage and relatively restricted channel outflow capacity, have been endowed with natural regulatory features, which have been impacted by society, as discussed in Section 3, "ARTIFICIAL EFFECTS". They are considered to be one of the best naturally regulated watersheds in the world.

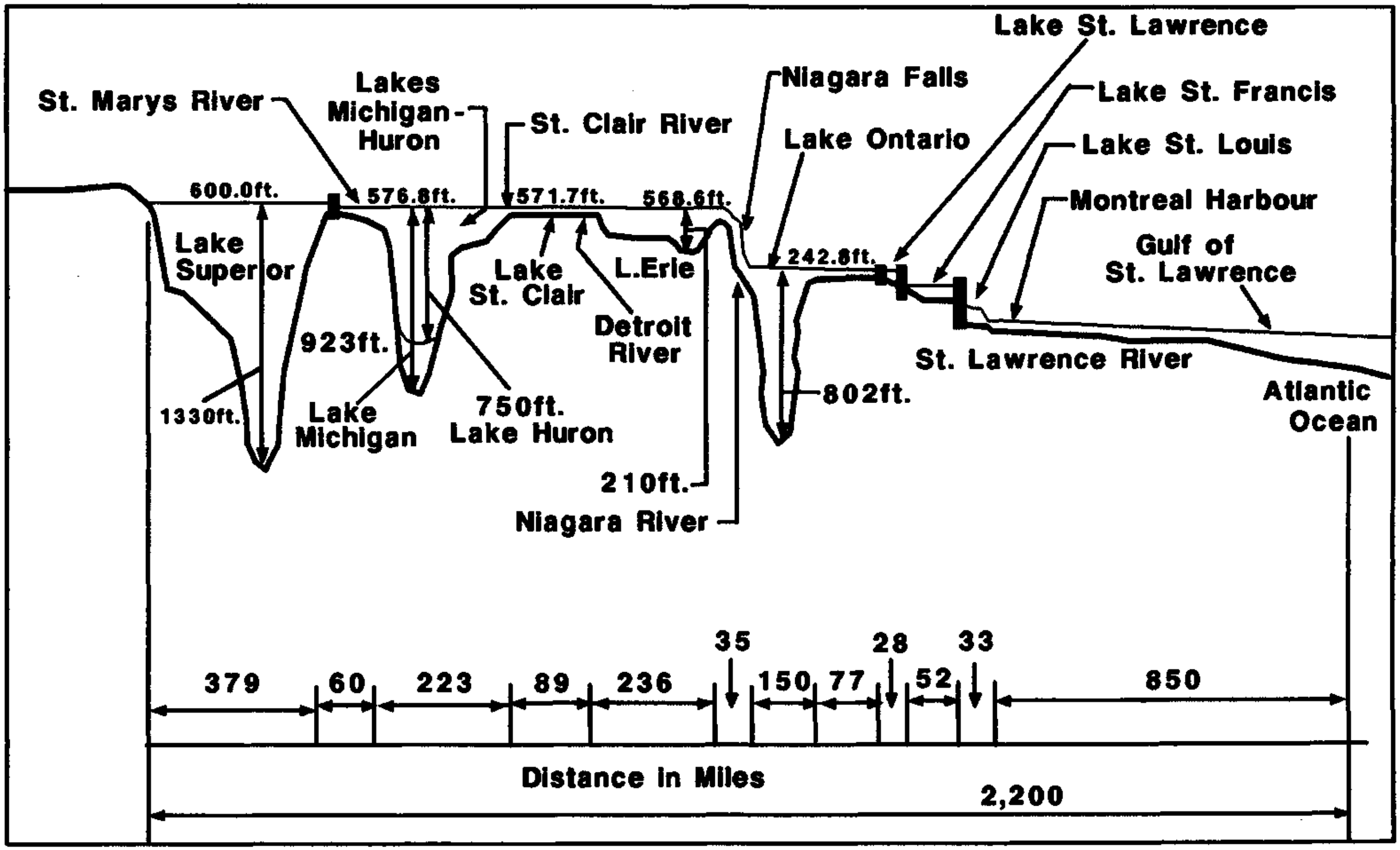
OBSERVED WATER LEVELS AND OUTFLOWS

The entire Great Lakes system, with its land surface, lakes and streams, is a well-balanced hydrologic unit. History has shown that the water levels fluctuate within a limited range, in response to changing hydrometeorologic conditions, both on a seasonal and annual basis.

There are three distinctive types of fluctuations on the Great Lakes: short-term, seasonal and long-term. Short-term fluctuations last from a few hours to a day or two and result from winds, storms and/or barometric pressure changes. The most dramatic fluctuations in the system have occurred on Lake Erie. Differences in water levels, from one end of the lake to the other, of as much as 16 feet, have been recorded. These fluctuations are discussed further in Section 2, "Wind Effects".

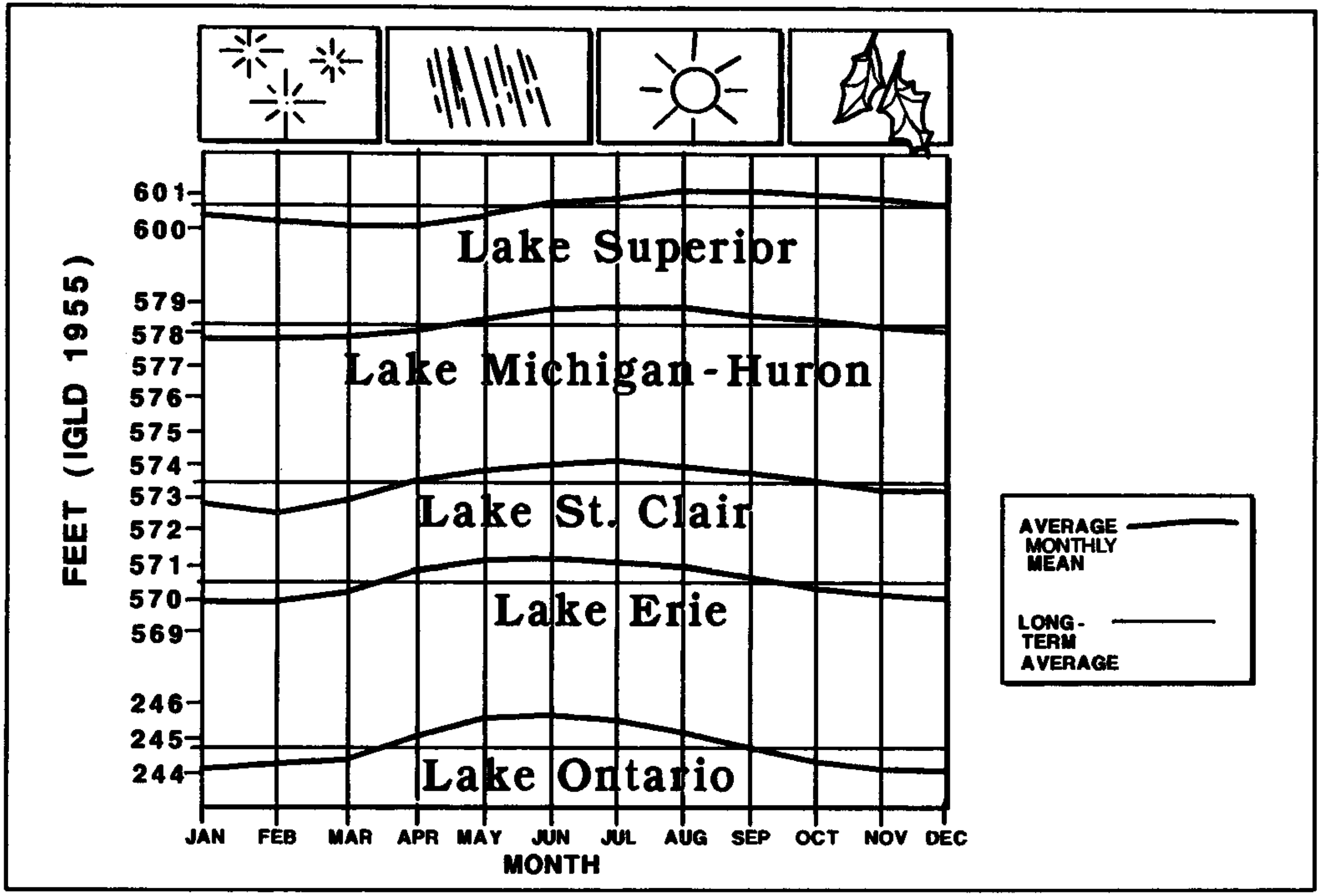
Seasonal fluctuations generally follow the hydrologic cycle, with levels reaching their peak in the late spring to mid-summer and their lowest levels occurring in the winter. These seasonal trends are shown in Figure A-1-3. The average difference between the highest and lowest monthly mean levels in any given year ranges from about 1.0 foot on Lake Superior to about 1.6 feet on Lake Ontario.

Long-term fluctuations in lake levels occur over a period of several years to a decade or more, but have no predictable pattern or cycle; they result from a prolonged aberration in precipitation and climatologic patterns, which can result in either extreme high or low levels. Figure A-1-4 shows the most recent segment (1950-1988) of the recorded hydrograph of annual fluctuations of the Great Lakes. During the period 1900-1988, the water level variations on the Great Lakes have ranged from about 4 feet on Lake Superior to about 6-1/4 feet on Lakes Michigan-Huron and Erie and about 6-1/2 feet on Lake Ontario. These ranges have been modified to about 3-1/2 feet on Lake Superior and 6 feet on Lake Ontario due to regulation of their outflows into the St. Marys and St. Lawrence River, respectively.



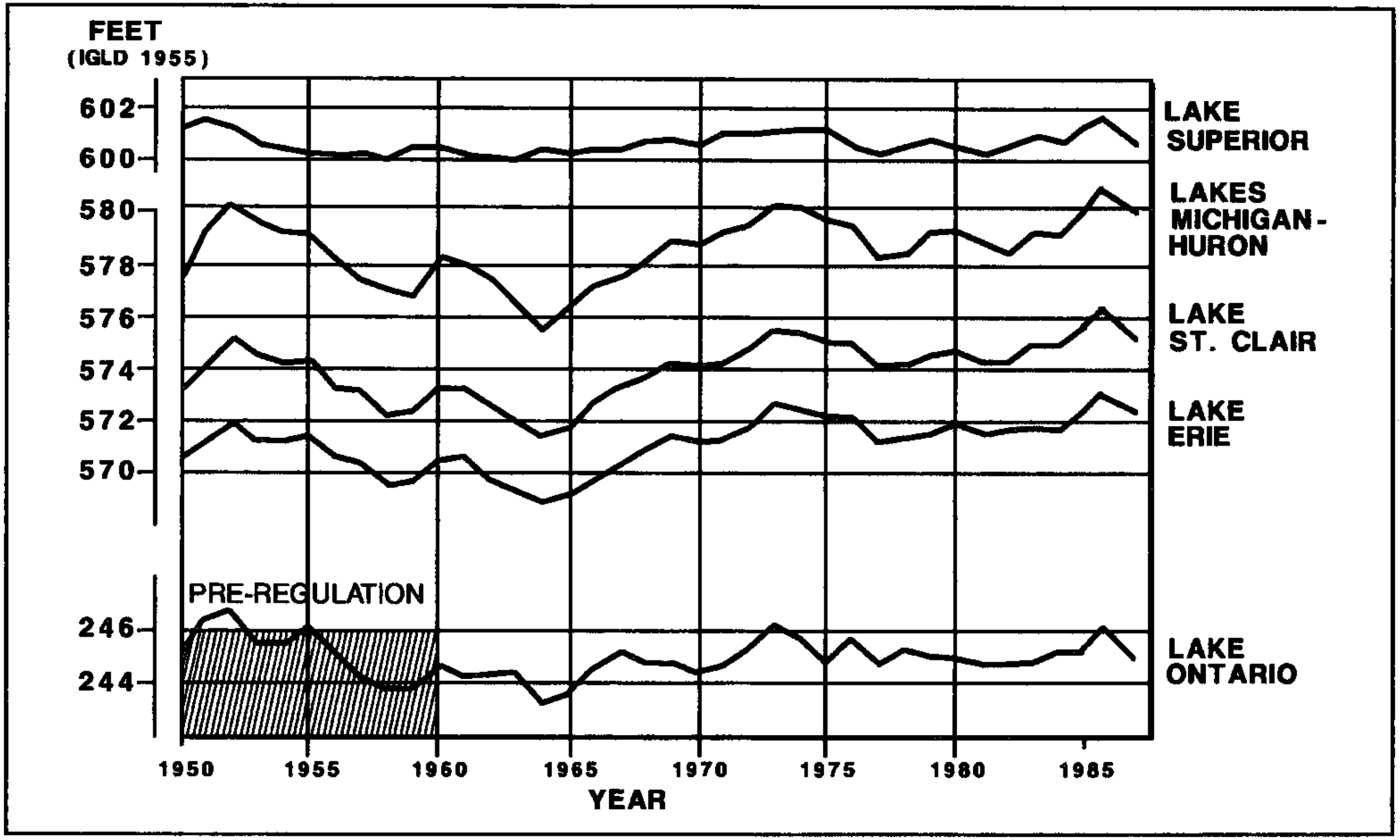
PROFILE OF THE GREAT LAKES - ST. LAWRENCE RIVER SYSTEM

FIGURE A-1-2



SEASONAL FLUCTUATIONS
GREAT LAKES WATER LEVELS
(1900-1988)

FIGURE A-1-3



ANNUAL AVERAGE GREAT LAKES WATER LEVELS (1950-1988)

FIGURE A-1-4

Information on the Great Lakes water levels is available for the past two centuries and continuous records have been kept since 1860. The Great Lakes data prior to 1900 does not permit computation of water supplies for individual lakes, and specifically, Lakes Michigan-Huron, St. Clair and Erie. Therefore, the Basis-of-Comparison data sequence is limited to the 1900 to present period. The 1800s data do, however, provide a measure of water level variability consistent with experiences of the 20th century. These data observations support the findings and assessments of future expected water level variations stated in Sections 4 and 5 of this Annex.

The terminal outflow from the Great Lakes Basin is primarily through the St. Lawrence River. The average St. Lawrence River flow, recorded near Cornwall, Ontario and Massena, New York, during the period 1900-1987, is 243,000 cubic feet per second (cfs). It has varied from a minimum monthly flow of 154,000 cfs recorded in February 1936 (before regulation) to a maximum monthly flow (after regulation) of 350,000 cfs, which has occurred in June and July 1973 and again in July 1976. During the most recent high water period, 1986, the maximum monthly flow was 338,000 cfs, occurring in November of that year. The maximum flow for a two-week period was 360,000 cfs in January 1987. This is a range of plus 44 percent to minus 37 percent from the long-term average. When compared with other major rivers throughout the world, this represents an extremely stable regime. The maximum St. Lawrence River flow is about 2.3 times its minimum, whereas the Mississippi River at St. Louis, Missouri, has a maximum flow approximately 30 times its minimum. This stability in outflow variation is directly related to the immense storage capacity of each Great Lake relative to its naturally constricted outflow channel. Nowhere throughout the entire Great Lakes system, is this modulating effect more apparent than in the St. Lawrence River.

BASIS-OF-COMPARISON

The recorded Great Lakes levels and outflows data reflect the effects of changes in the regime of the lakes and connecting channels which have occurred over the study period (1900-1986). The principal changes to the system were artificial and consist of modifications in diversion rates into and out of the Great Lakes Basin, alterations in the configuration of the connecting channels and the construction of control works at the outlets of Lake Superior and Lake Ontario.

To be able to evaluate the various lake regulation, diversion and structural plans being investigated in this study, it is necessary to develop a standard against which each scenario is compared. This standard is called the Basis-of-Comparison. The recorded (1900-1986) net basin supplies are routed through each of the Great Lakes using a set of control parameters which best describe the Great Lakes regime as it exists today. The levels and flows occurring under these uniform conditions will also be employed as a basis for assessing the impacts of the various plans.

The Basis-of-Comparison represents a set of water levels and outflows (Table A-1-1) that the Great Lakes-St. Lawrence System would have experienced, for the period 1900-1986, had present-day conditions been in effect consistently

Table A-1-1
Hydrologic Summary of Great Lakes Levels and Flows under Basis-of-Comparison Conditions (1900-1986)

Ranges of Levels in feet and Outflow in thousands of cfs

	Levels	Outflows
Lake Superior		
mean	600.4	79
maximum	601.9	120
minimum	598.6	55
range	3.3	65
Lakes Michigan-Huron		
mean	578.4	187
maximum	581.6	241
minimum	575.4	114
range	6.2	127
Lake Erie		
mean	570.7	211
maximum	573.5	276
minimum	567.9	156
range	5.6	120
Lake Ontario (w/strict application of Plan 1958-D)		
mean	244.9	246
maximum	249.8	310
minimum	241.6	188
range	8.2	122
Lake Ontario (w/application of Plan 1958-D and discretionary actions)		
mean	244.7	247
maximum	247.6	350
minimum	241.8	176
range	5.8	174

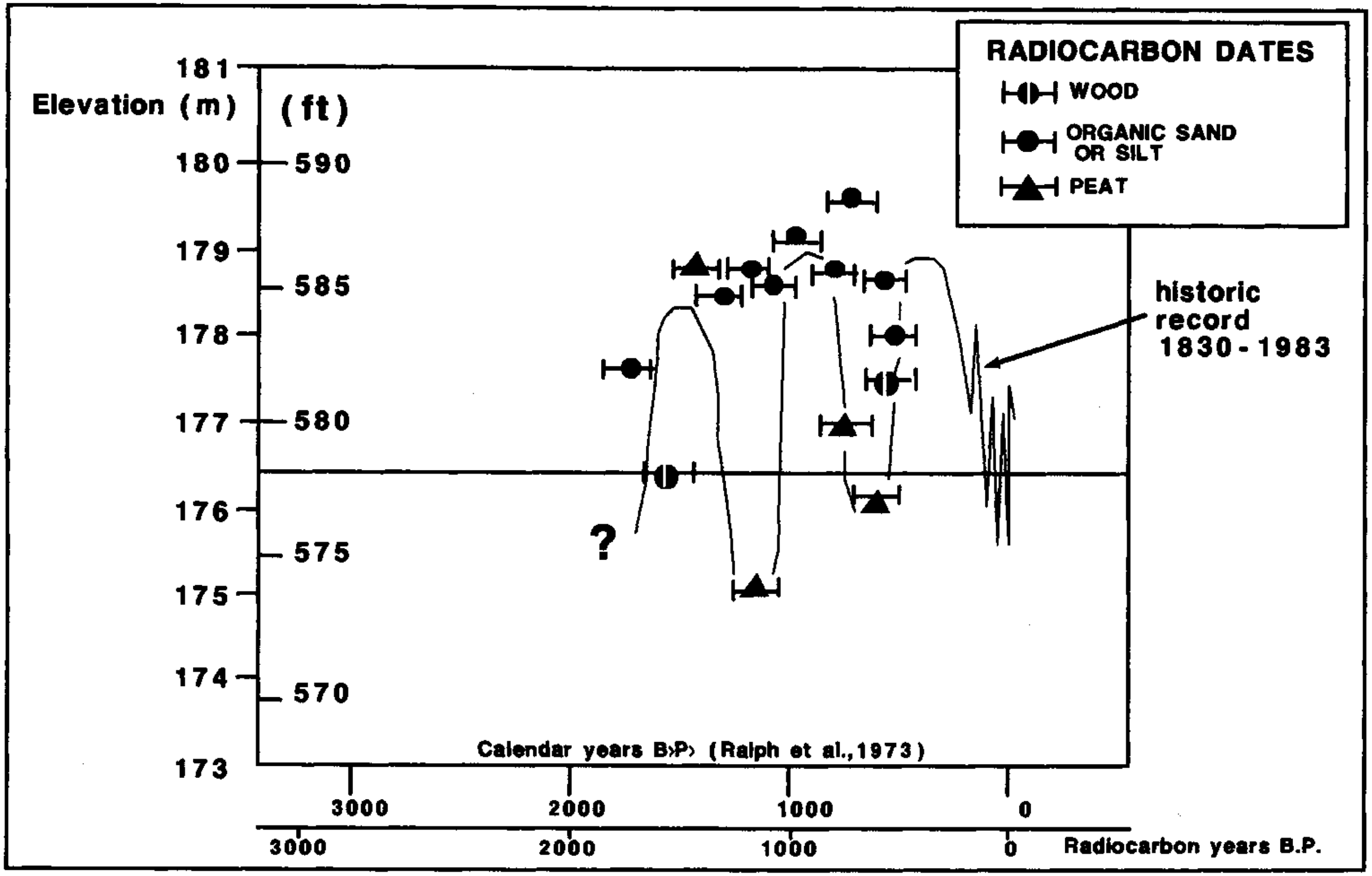
The conditions employed for developing the Basis-of-Comparison are as follows:

1. Constant diversions of, Long Lac and Ogoki of 5,600 cfs into Lake Superior; Chicago of 3,200 cfs out of Lake Michigan; Welland Canal of 9,200 cfs out of Lake Erie, into Lake Ontario; and, New York State Barge Canal of 700 cfs out of the Niagara River, into Lake Ontario.
2. Lake Superior regulated in accordance with Plan 1977.
3. 1962-68 outlet conditions for Lakes Michigan-Huron.
4. Present (1987) outlet conditions for Lake Erie (Niagara River).
5. Lake Ontario regulated with strict application of Plan 1958-D and with discretionary deviations as applied.
6. Recorded Ottawa River flows and other local inflows into the St. Lawrence River.

throughout the 87 years. The water levels and outflows resulting from the various lake management scenarios are then compared with the Basis-of-Comparison. The differences between these two are the hydrologic effects of that particular scenario.

HYDROGEOLOGIC INFERENCE OF ANCIENT WATER LEVELS

Geologists and archaeologists have researched the Great Lakes Basin in an effort to uncover historically related water level fluctuations. Figure A-1-5 shows about 2,000 years of possible Lake Michigan water levels, as reconstructed through geologic and archaeologic data by Curtis Larsen under the sponsorship of the Illinois Geological Survey. Some major lake level fluctuations appear to have occurred. Of particular interest is the inference that prior to the last century or so, the range of levels was much higher than today. Another point to note is the relatively small amount of reliable data (that which has been documented in the last 129 years) as compared with benchmark elevations estimated as much as 2,000 years ago. This might lead one to believe that future lake levels could be expected to exhibit a considerably larger range of fluctuations than those experienced between the extreme years of 1964 and 1986. In fact, Dr. Larsen suggests that the lakes could rise 3 to 5 feet higher than the highs recorded in the mid-80's, during the next several centuries. To experience such a water level rise, the Great Lakes Basin would have to receive about 150 to 180 percent of the current average annual precipitation over several years, while at the same time, the lake outflows would have to remain unrestricted by any movement of the earth's surface (crustal movement). For comparison purposes, during the wettest year in this century (1985), precipitation was only 126 percent of average. Thus, it is recognized that for a significant lake level rise to happen, a major climatic change must occur. Most scientists and engineers agree that the recent high water period was probably only one of many incidents of high level conditions that have occurred in the past and will likely be repeated in the future, in spite of the onset of any major permanent climatic changes. The same philosophy can also be associated with past and future occurrences of low levels within the Great Lakes system.



FLUCTUATIONS IN LATE HOLOCENE LEVELS IN SOUTHERN LAKE MICHIGAN

FIGURE A-1-5

SECTION 2

PHYSICAL PROCESSES AFFECTING WATER LEVELS

PRECIPITATION

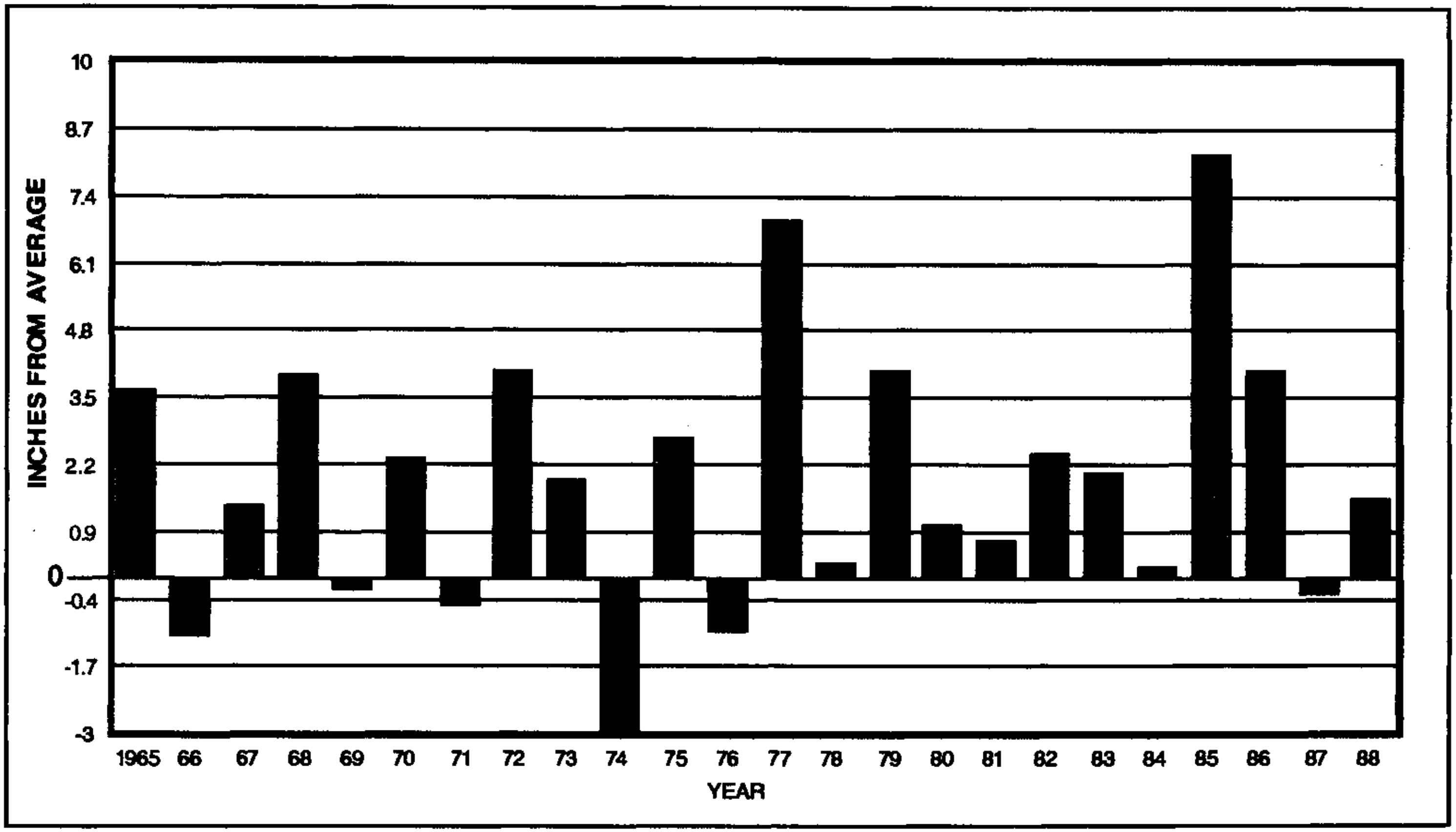
Precipitation over the Basin's water and land surfaces is the primary source of water to the Great Lakes. Precipitation over the water surface contributes directly to the water supply of the Great Lakes and its tributaries. Precipitation over land is an indirect and time-dependent contribution, some of which seeps into the ground and some of which is lost to evapotranspiration, with the remainder running off into the lakes. The average annual precipitation over the entire Great Lakes Basin is 32 inches (varying from 30 inches for Lake Superior to 35 inches for Lake Ontario). Overlake precipitation averages slightly higher than the precipitation over land. Precipitation data are coordinated between U.S. and Canadian agencies and the records are maintained by both countries. Figure A-2-1 shows the annual precipitation ranges for the period 1965-88 and Figure A-2-2 shows the fluctuations for each month of the period 1984-88.

There is relatively little variation in precipitation between seasons. Winter precipitation is generally less than in the summer months, except in the snowbelt areas downwind of the lakes, where it can be 20 to 30 percent higher in winter. It is these annual and seasonal variations in precipitation, when combined with evaporation, that are the primary factors in determining supplies to the lakes.

Figure A-2-3 shows the combined precipitation over Lakes Michigan, Huron, St. Clair and Erie since 1900. From about 1900 through 1940, there was a light precipitation regime on the Great Lakes, with the majority of the years falling below the average. From about 1940 to date, the region has generally experienced an above average precipitation regime. Of particular interest is the high precipitation in the early 1950's, the low precipitation in the early 1960's and the consistently very high precipitation from the late 1960's to 1986. A comparison of the recorded water levels coincident with precipitation shows a close correlation between precipitation and the low lake levels of the 1930's and early 1960's, and similarly, with the high lake levels of the early 1950's and 1970's. The period 1940 to 1979 averaged about 6 percent higher precipitation than from 1900 to 1939.

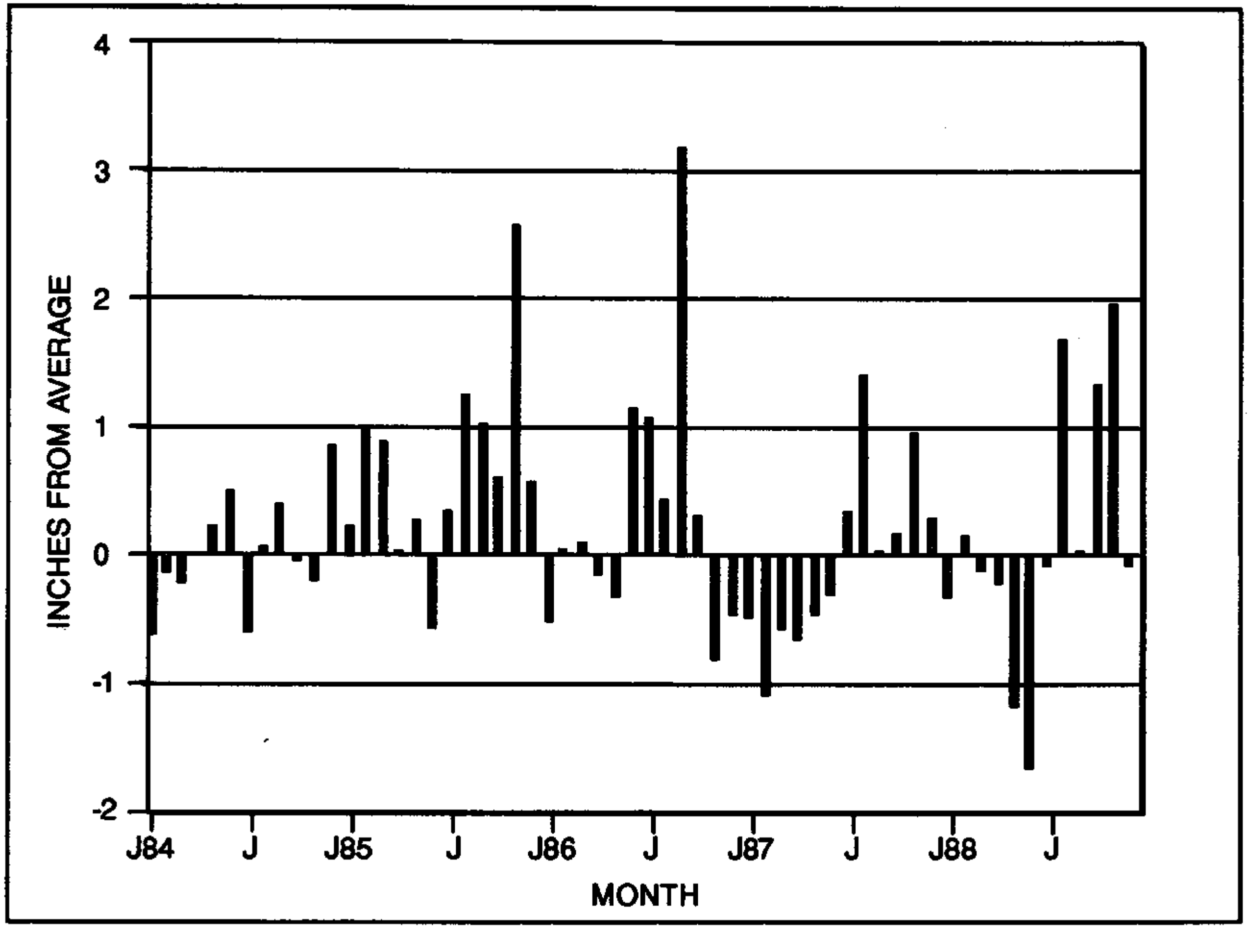
In the early to mid-1930's much of the North American continent was extremely dry and the resultant "dust bowl" was disastrous to farmers. Because precipitation was well below average in the Great Lakes drainage basin, the lakes also set record low levels. Similar conditions existed in the early 1960's over much of the northeastern United States and eastern Canada. Many city water supplies were exhausted, crops were poor and the lakes were again very low.

From the last 129 years of record, the period 1985-1986 is characterized as having a high water regime on all the lakes. The heaviest precipitation over

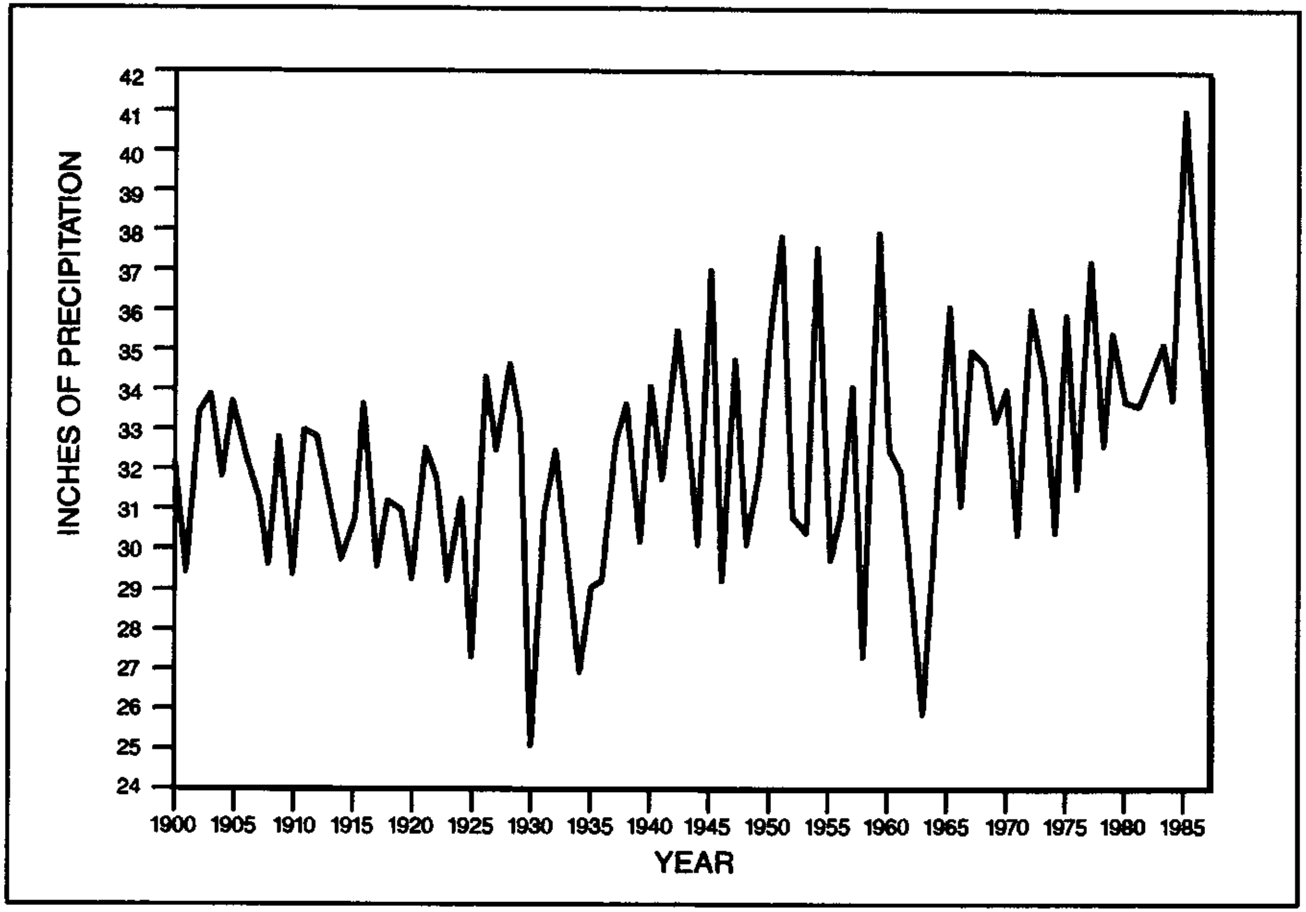


GREAT LAKES BASIN ANNUAL PRECIPITATION (1965 - 1988)

FIGURE A-2-1



GREAT LAKES BASIN MONTHLY PRECIPITATION (1984-1988) FIGURE A-2-2



COMBINED PRECIPITATION
LAKES MICHIGAN-HURON, ST. CLAIR AND ERIE
(1900-1987)

FIGURE A-2-3

the Great Lakes Basin since 1900 occurred in 1985 (about 40 inches as compared to an average of 32 inches). Although precipitation in 1986 was also above average, it was the cumulative effect of the previous 18 years of generally above-average precipitation that set the stage for the record high levels on the Great Lakes in 1985-86. This excessive build-up of water in the basin and the subsequent slow reaction of the lakes to the onset of reduced precipitation in 1986 and 1987, resulted in a continued high water regime on some of the lakes until mid-1987. Eventually, the near-drought conditions in the springs of 1987 and 1988 caused the lakes to decline dramatically.

Variations in lake levels directly reflect changes in water storage. In 1964, when the Great Lakes were at record or near-record low levels, the total volume of storage was reduced by about 30 cubic miles from the average. In the high year of 1985, the storage was increased by about 30 cubic miles. This overall range of 60 cubic miles of water represents only about one percent of the volume of all the lakes, when compared at their average levels.

In 1985, basin-wide precipitation was over 8 inches above average. The resulting excess water received by the lakes was equivalent in volume to about 38 cubic miles. This volume of water is equivalent to an increased inflow to the basin of about 175,000 cfs for one year. Since the various outlet channels of the Great Lakes cannot accommodate such large flow increases, the bulk of the water went into storage, thus raising the Great Lakes' levels. Consequently, 1985 water levels were up sharply, setting new monthly records on all lakes except Lake Ontario. A post-1900 monthly mean high of 602.24 feet was set at the Marquette gage in October and November (Table A-2-1). The trend towards establishing new highs continued in 1986, breaking records just set the previous year. Lakes Michigan-Huron and St. Clair set new records for every month that year. Lake Erie set new records each month, except January and April. Lake Superior established new records for the first eight months in 1986. The upward trend continued into 1987, and saw new records set on Lakes Michigan-Huron and Erie during January. Since that time, Lake Superior has dropped about 1.5 feet, while Lakes Michigan-Huron, St. Clair and Erie have dropped about 2.5 feet and Lake Ontario about 2 feet.

RUNOFF

Precipitation which falls on the land surface is carried through several phases of the hydrologic cycle. Some phases delay the eventual arrival of the water into the Great Lakes, while others result in precipitation being lost. During freezing weather, precipitation accumulates on the surface as ice and snow, which is held in storage until warmer weather causes snowmelt. If there is more water available at the ground surface from snowmelt or rainfall than can drain into the soil, the water will move as runoff to become surface water storage in streams, lakes or swamps. Some water moves through the ground surface replenishing soil moisture (which vegetation uses as a source of water supply). When the soil moisture is recharged, the remainder of the precipitation becomes groundwater storage. Groundwater storage, combined with the outflow from the surface storage in lakes and swamps, provides the dry weather flow for streams. The rainfall during the fall and spring months, and

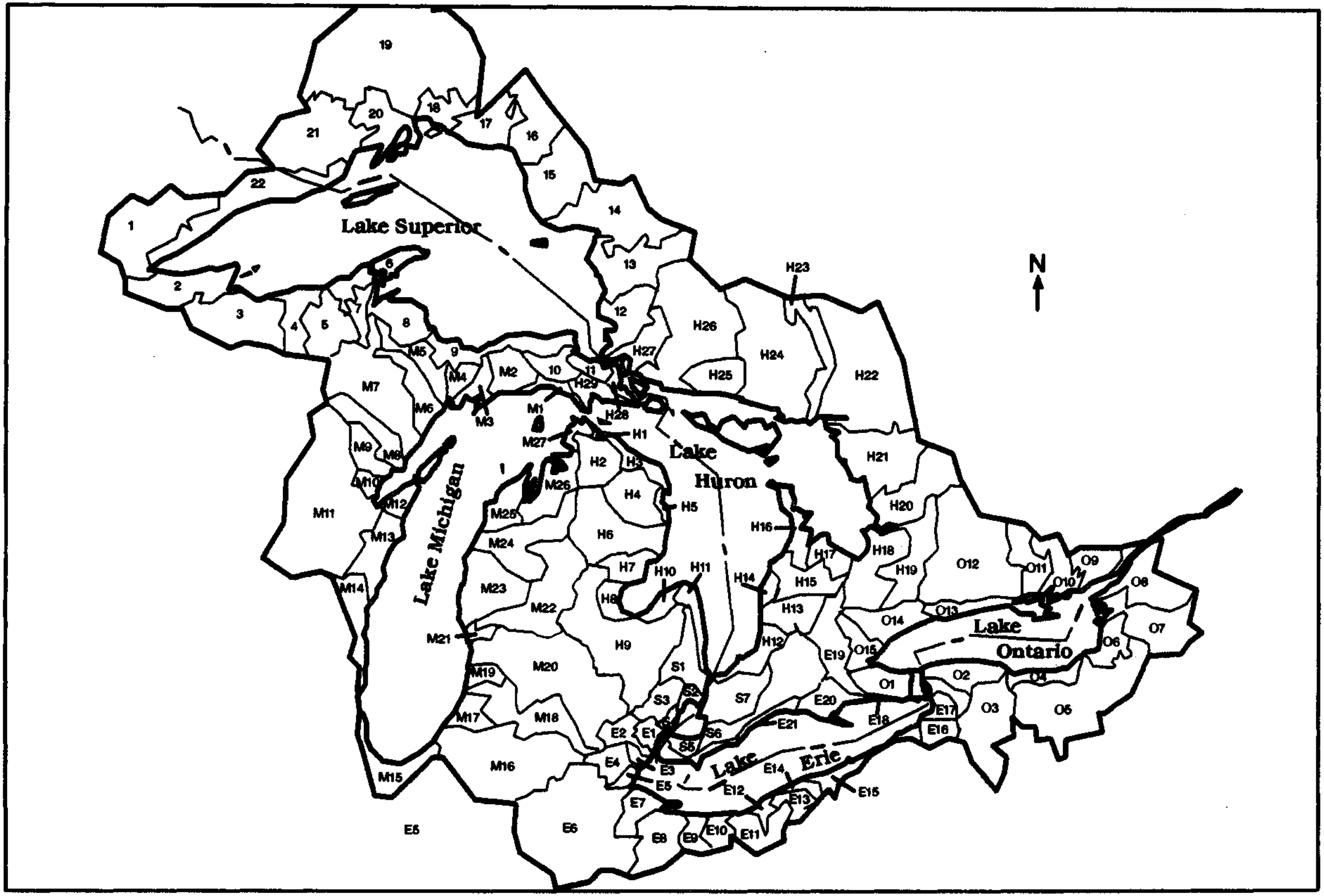
Table A-2-1
Great Lakes Record High Monthly Mean Water Levels (feet, IGLD 1955)
1860-1987

Period	Superior at Marquette	Michigan-Huron at Harbor Beach	St. Clair at St. Clair Shores	Erie at Cleveland	Ontario at Oswego
1860-99	602.06* August 1876	581.94 June 1886	----	572.57 June 1876	247.74 May 1870
1900-84	602.02 August 1950	581.04 July 1974	576.23 June 1973	573.51 June 1973	248.06 June 1952
1985-87	602.24 October, November 1985	581.62 October 1986	576.69 October 1986	573.70 June 1986	none
Previous record (1860-1984) exceeded by	0.18	----	0.46	0.19	----

Data source: NOAA, Great Lakes Water Levels, 1860-1985.
*The IJC Task Force Study deduced that this elevation may be about 602.31 feet.

snow accumulation during the winter, provide the major portion of the water contributed from the land areas to the lakes.

The land areas tributary to the Great Lakes are divided into sub-basins ranging from 10 to 100 miles inland from the lake shore (See Figure A-2-4 and Table A-2-2). The runoff distribution varies by lake depending on the climate and physiographic characteristics of the individual tributary basins of each lake, such as the precipitation pattern over the seasons, soil moisture, land use and evapotranspiration. The average annual runoff for the individual lakes (Lakes Superior, Michigan, Huron, St. Clair, Erie and Ontario) are 55,000, 42,900, 58,900, 4,500, 24,700 and 38,900 cfs, respectively. This translates into a range of 0.8 cfs to 1.4 cfs per square mile of land.



SUB-BASINS OF THE GREAT LAKES BASIN **FIGURE A-2-4**

TABLE A-2-2

GREAT LAKES SUB-BASIN IDENTIFICATION

Lake Superior		Lake Michigan		Lake Huron		Lake St. Clair		Lake Erie		Lake Ontario	
1	St. Louis	M1	Epoufette	H1	Mill Creek	S1	Black	E1	Rouge	O1	Tonawanda
2	Bayfield	M2	Manistique	H2	Cheboygan	S2	Anchor Bay	E2	Huron	O2	Erie
3	Bad-Montreal	M3	Sturgeon	H3	Ocqueoc	S3	Clinton	E3	Stony Creek	O3	Genesee
4	Presque Isle	M4	Whitefish	H4	Thunder Bay	S4	Grosse Pointe	E4	Raisin	O4	Sodus-Irondequoit
5	Ontonagon	M5	Escanaba	H5	Holcomb Creek	S5	Belle	E5	Ottawa	O5	Oswego-Seneca
6	Keweenaw	M6	Ford	H6	Au Sable	S6	Thames	E6	Maumee- Auglaize	O6	Sandy Creek
7	Sturgeon	M7	Menominee	H7	Au Gres	S7	Sydenham	E7	Portage	O7	Black
8	Yellow Dog	M8	Peshtigo	H8	Kawkawlin			E8	Sandusky	O8	St. Lawrence
9	Two Hearted	M9	Oconto	H9	Saginaw			E9	Huron	O9	Cataraqui
10	Taquamenon	M10	Pensaukee	H10	Pigeon			E10	Black-Rocky	O10	Salmon
11	Pendills	M11	Winnebago	H11	Rock Falls			E11	Cuyahoga	O11	Black-Moira
12	Batchawana-Goulais	M12	Door	H12	Au Sable-Bayfield			E12	Chagrin	O12	Mississagua-Indian
13	Montreal	M13	Manitowoc	H13	Maitland			E13	Grand	O13	Ganaraska-Consecon
14	Michipicoten-Magpie	M14	Milwaukee	H14	Teeswater-Mill Creeks			E14	Ashtabula	O14	Humber
15	White-Pukashkwa	M15	Calumet	H15	Saugeen			E15	Walnut Creek	O15	Credit Creek
16	Pic-Black	M16	St. Joseph	H16	Bruce			E16	Cattaraugus Creek		
17	Steel-Aguasabon	M17	Black	H17	Owen Sound			E17	Buffalo- Gazenovia Creeks		
18	Gravel	M18	Kalamazoo	H18	Nottawasaga			E18	Niagara		
19	Lake Nipigon	M19	Macatawa	H19	Simcoe			E19	Grand- Conestogo		
20	Black Sturgeon	M20	Grand	H20	Muskoka			E20	Otter-Big Creeks		
21	Kaministiquia	M21	Mona Lake	H21	Magnatawan			E21	Roundeau		
22	Baptism-Pigeon	M22	Muskegon	H22	French						
		M23	Pere Marquette	H23	Wahapitei						
		M24	Manistee	H24	Spanish						
		M25	Leelanau	H25	Little White						
		M26	Charlevoix	H26	Mississagi						
		M27	Paradise	H27	Garden						

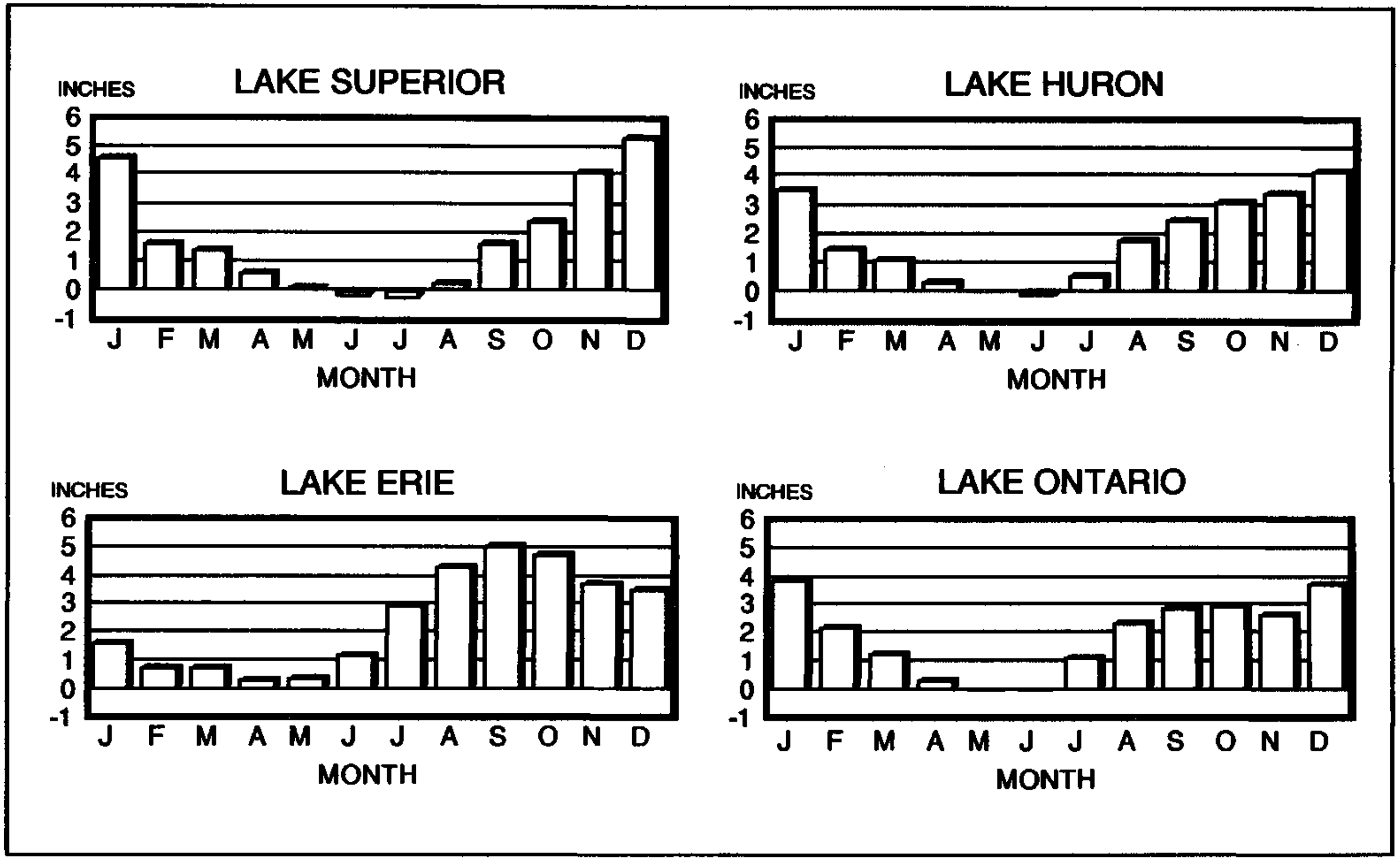
EVAPORATION

There is no direct means of measuring over-lake evaporation. Several estimates using energy balance, water balance or empirical mass transfer relationships have been obtained for each lake. It has been estimated that evaporation is of a similar magnitude to runoff from the land, except on Lake Superior where evaporation is considerably less. The computed values of annual evaporation are as follows: Lake Superior, 21 inches; Lakes Michigan-Huron, 26 inches; Lake Erie, 29 inches; and Lake Ontario, 23 inches. Figure A-2-5 shows the monthly evaporation patterns for the individual lakes. Figure A-2-6 shows schematically, the weighted distribution of the various hydrologic factors on the Great Lakes.

Consider as an example, the effect of one inch of rainfall over the entire Lake Superior Basin (land and water surface), on the St. Marys River flow, due to evaporation. On the average, approximately 62 percent of the 74 billion cubic feet of precipitation on the lake would be lost to evaporation from the lake's surface, leaving about 28 billion cubic feet to flow down the St. Marys River. A one inch rainfall on the Lake Superior land area is equivalent to about 114 billion cubic feet of water, of which 51 percent (on the average) is lost to evapotranspiration, absorption by the soil, and so forth. This leaves about 56 billion cubic feet to reach the lake as runoff and (assuming none of this portion of the water is evaporated from the lake's surface) to eventually flow down the St. Marys River. Thus, for a one-inch rainfall over the entire Lake Superior Basin (land and water), about 84 billion cubic feet of water would eventually pass down the St. Marys River and into Lake Huron.

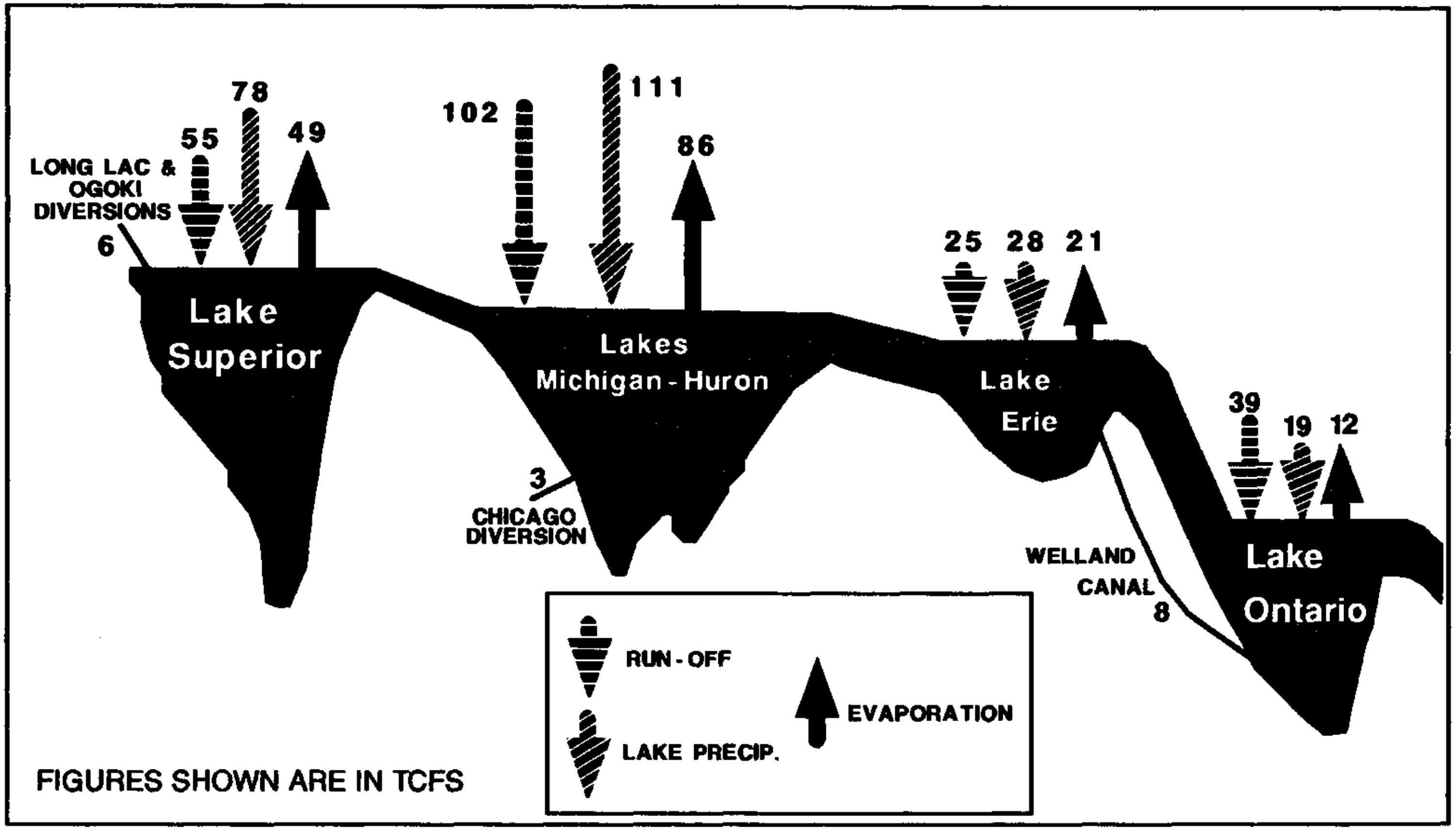
ICE AND WEED EFFECTS

An ice cover can convert an open river into a channel similar to a pipe or culvert with resultant increases in head loss and reductions in flow. When velocities are greater than 2.5 feet per second, as they are in many parts of the connecting channels of the Great Lakes, a stable ice cover usually cannot be maintained. As a result, ice floes which pass through high velocity areas tend to turn up on end or submerge under the leading edge of the downstream ice cover. When this happens an ice jam or hanging dam forms. The result is a constriction in the river channel and the outflow may become seriously reduced. This can occur in the outlets of both regulated and unregulated lakes. One technique used in the St. Lawrence River to minimize the chances of ice jamming and the formation of a hanging dam, is to reduce the flow (when possible) at the onset of ice formation so that the velocities are lowered in the critical sections of the river. This allows a consolidated smooth ice cover to form. However, a control or regulating structure, such as a hydropower plant, must be available in the river in order to implement this procedure. The historic average reductions in carrying capacities, in percent, due to ice in the outlet rivers during the period January through March are as follows: St. Marys, 4; St. Clair, 10; Detroit, 2; Niagara, 2; and St. Lawrence, 3. Ice retardation generally results in higher lake levels than under ice-free conditions (0.4 foot rise for Lakes Michigan-Huron). Although ice retardation on the St. Clair River causes a lowering of the



AVERAGE MONTHLY EVAPORATION
(1965-1987)

FIGURE A-2-5



HYDROLOGIC FACTORS AND DIVERSION RATES ON EACH OF THE GREAT LAKES (1965-1985)

FIGURE A-2-6

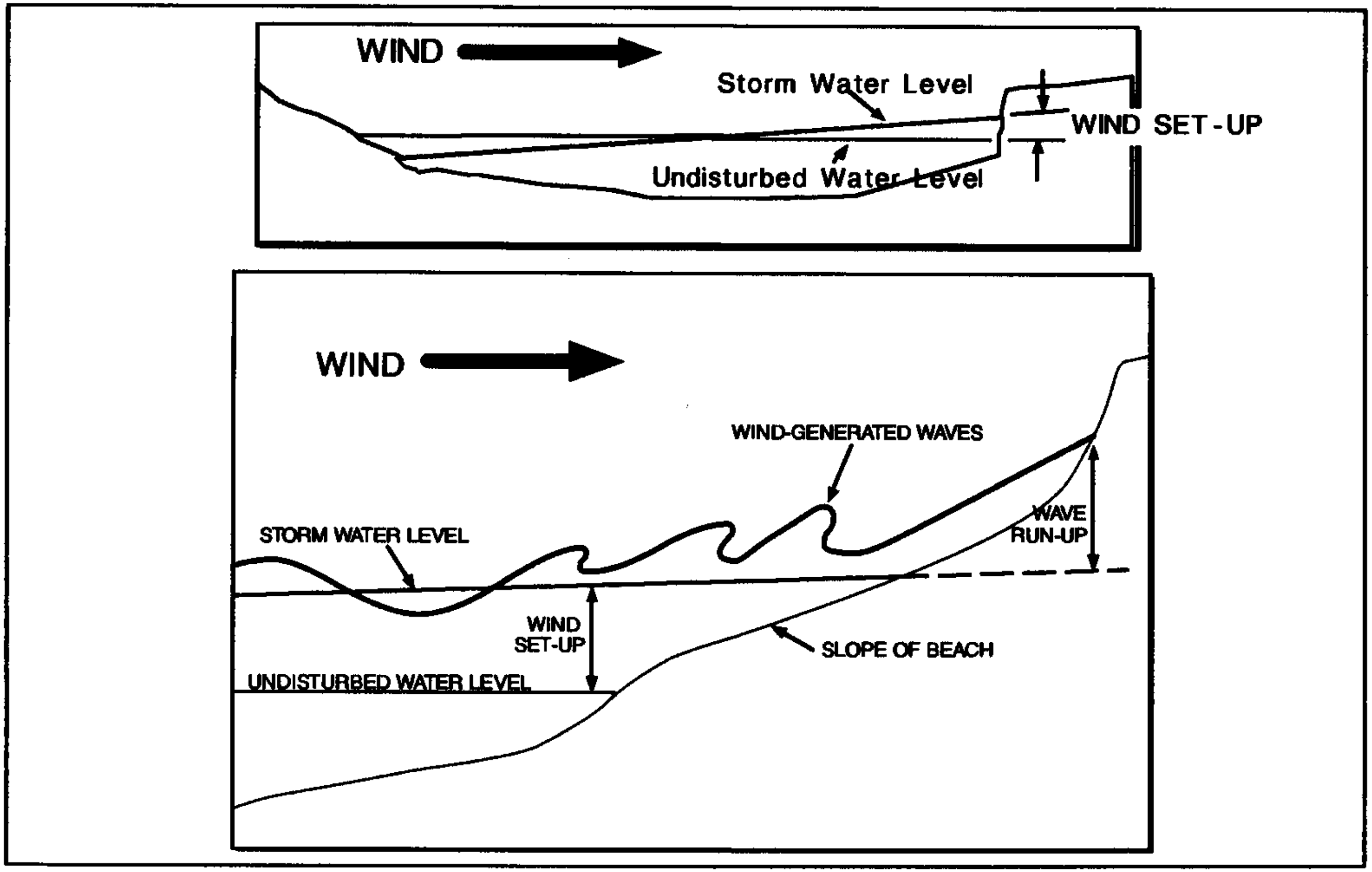
levels of Lakes St. Clair and Erie, these effects are usually dissipated before the following ice season. Ice retardation on the Niagara River has been significantly reduced, since the winter of 1964-65, due to the annual installation of the Lake Erie-Niagara River ice boom.

During the open-water season, the nutrient content of surface waters causes an increase in vegetative growth in the waters of the connecting channels. In certain areas, heavy bottom growth increases hydraulic roughness, which in turn reduces outflow capacity. This condition is most evident in the Niagara River, which has large areas of relatively shallow water. This effect can amount to as much as a 10,000 cfs/month flow reduction during the period June to September. In the other connecting channels, lesser weed retardations occur.

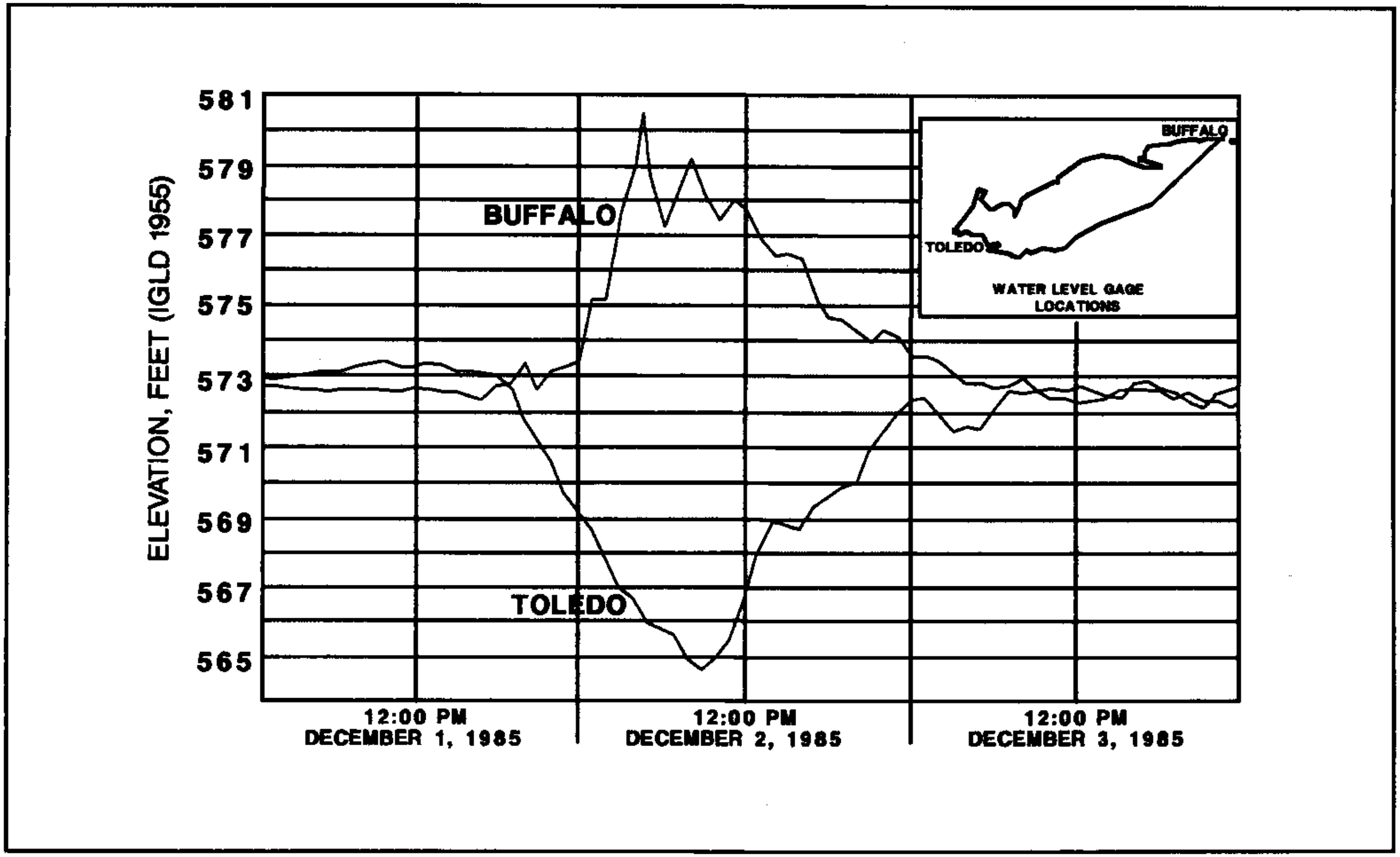
WIND EFFECTS

Short-term storm-induced fluctuations in lake levels can be very destructive and affect all of the Great Lakes. They can result in rises of water levels reaching several feet (Figure A-2-7). When added to long-term and seasonal high water effects, they can produce disastrous flooding and increased shoreline erosion. They are caused by strong winds blowing over the lake surfaces, often accompanied by differences in atmospheric pressure. The result of these forces is a rise in the water surface at the leeward side of the lake, with a corresponding drop in level on the opposite shore. Winds can drive surface water in one direction at a faster rate than subsurface currents can return it to the upwind shore. When this occurs, the lake "piles up" at one end. This effect is most pronounced where subsurface currents are restricted by shallow off-shore bathymetry and where convergent shores tend to concentrate the water in a restricted space. Each of the lakes is elongated in one direction and, as a result, has somewhat confined areas at its ends. Several large bays, such as Green Bay, Georgian Bay, Saginaw Bay, and Whitefish Bay are examples where confinement occurs. Numerous smaller shoreline features and shoal areas are also affected to some degree. When high winds blow in the direction of Erie's long axis, the resulting short-term fluctuations in level are the most severe of any produced in the lakes (Figure A-2-8). Differences in levels between Toledo on the west end and Buffalo on the east end have reached as much as 16 feet. The recent storm of December 2, 1985 caused a 7-foot rise at Buffalo and an 8-foot drop at Toledo. This was estimated to have been about a once-in-12-year storm. The effect of the 7-foot rise in the water surface on the downwind shore, added to a high stage from long-term and seasonal fluctuations, coupled with wind-driven waves and ensuing seiche action, caused considerable damage to the shoreline.

While Lake Erie is the premier example of short-term fluctuations, the other lakes can and do exhibit similar, although lesser, fluctuations. On Lake Superior at Duluth these storm rises reach 1.3 feet in an "average" year and have reached as high as 1.7 feet. On Lake Michigan at Calumet Harbor, Indiana, the storm rise can reach 1.8 feet in an "average" year and has been as high as 3.5 feet. On Lake Huron at Essexville, an average storm rise is about 2.4 feet; it has reached a maximum of about 4 feet. On Lake Ontario at Toronto, the storm rise has reached about one foot, while at the eastern end of the lake at Kingston the storm rise has reached as high as 2.1 feet.



WIND EFFECTS ON LAKE LEVELS FIGURE A-2-7



WIND TIDE AND SEICHE EFFECT ON LAKE ERIE DURING STORM OF DECEMBER 2, 1985

FIGURE A-2-8

AIR TEMPERATURE EFFECTS

The Great Lakes Basin's climate is characterized by four distinct seasons; a variety of precipitation types and sources; small month-to-month variation in the average precipitation; marked air temperature contrasts over only 700 miles of latitudinal distance; and the influence of the lakes in modifying continental air masses. The primary climatologic factors which influence lake level fluctuations are precipitation and air temperature patterns. Temperatures and precipitation are variable within the basin with a trend to colder temperatures and less precipitation to the north. Average January temperatures range from -19°C (-2°F) in the north to -2°C (28°F) in the south, and July averages range from 18°C (64°F) to the north of Lake Superior to 23°C (73°F) south of Lake Erie.

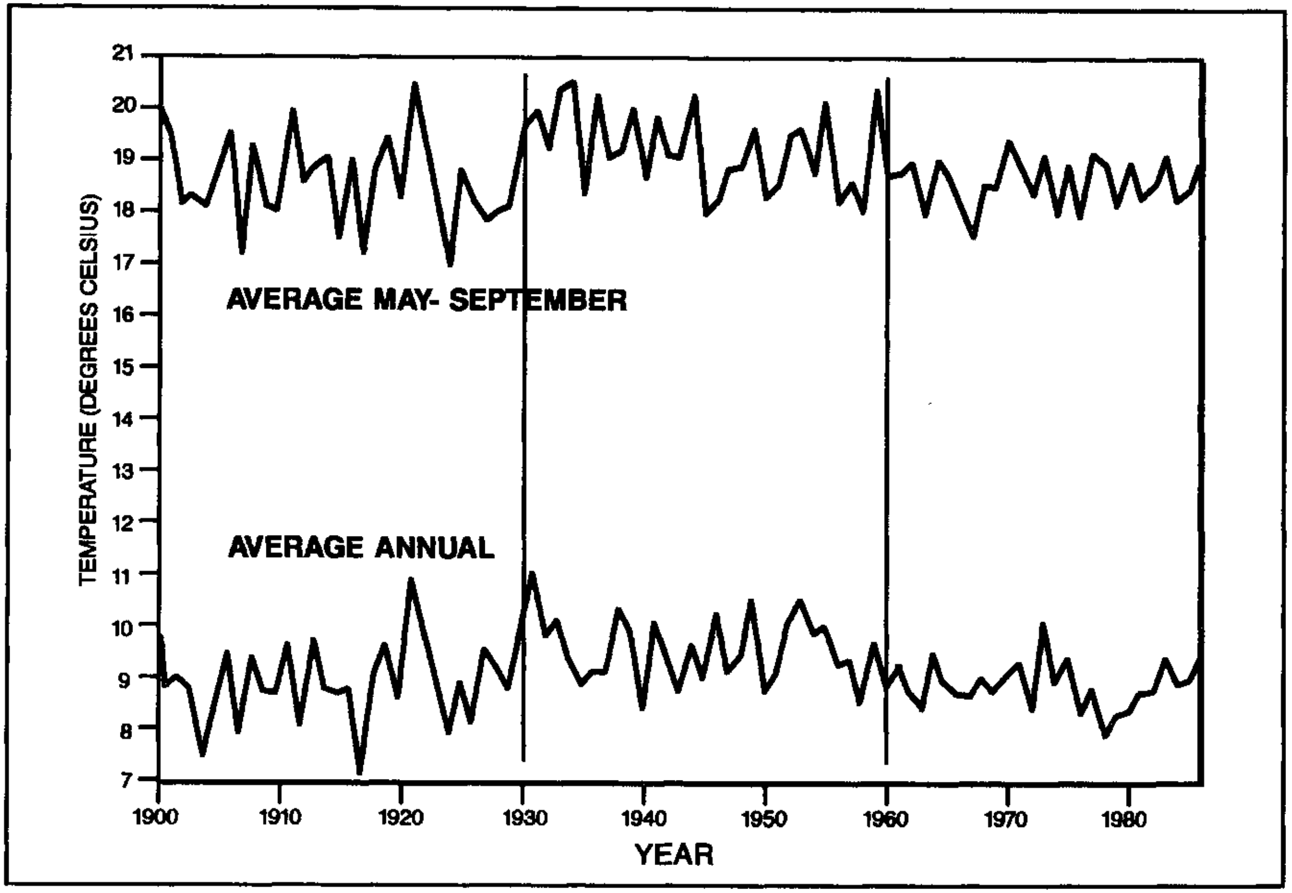
Weather observations in the Great Lakes Basin were initiated at Chicago in 1830. Continuous observations have been taken at Detroit, since 1837, and at Toronto since 1840. By 1969, the number of weather-observing stations increased to 500. An additional 430 stations report precipitation amounts only.

Figure A-2-9 shows the Lake Erie annual air temperatures in the United States portion of the basin. Three distinct temperature regimes can be seen; a low temperature regime from 1900 to 1929, a higher temperature regime from 1930 to 1959 and another additional low regime from 1960 through the present period. At higher air temperatures, vegetation tends to use more water, resulting in more transpiration, as well as higher rates of evaporation from the ground surface. This results in less runoff for the same amount of precipitation than during a low temperature period when the reverse is true. For Lake Erie, Figure A-2-9 shows that in the present regime, there has been approximately a 1°C (1.8°F) drop in the annual temperature since the 1930 to 1960 regime.

To illustrate the combined impact of climatic changes on water supply, a 6 percent precipitation increase in the Lake Erie Basin results in a runoff increase of 14 percent, and an 0.8°C (1.4°F) decrease in temperature yields an additional 5 percent runoff. The combined effect of an increase in precipitation, with a decrease in temperature results in a 19 percent increase in runoff to the lake. The high levels of the early 1970's to the mid-1980s were partly the result of an increased precipitation regime, since 1940, coupled with a lower temperature regime since 1960.

CRUSTAL MOVEMENT

Long-term changes in lake levels are also related to the geology of the basin. Geologists have discovered that an uplift of the earth's crust amounting to several hundred feet has occurred in some places in the basin since the recession of the last glaciers. The effect of this phenomenon on water level fluctuations of each of the Great Lakes has been determined for the last century by the Canada-United States Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data and documented in reports of that Committee. The effect of differential crustal movement is not uniform; generally, the rates around Lakes Superior and Ontario are greater than those

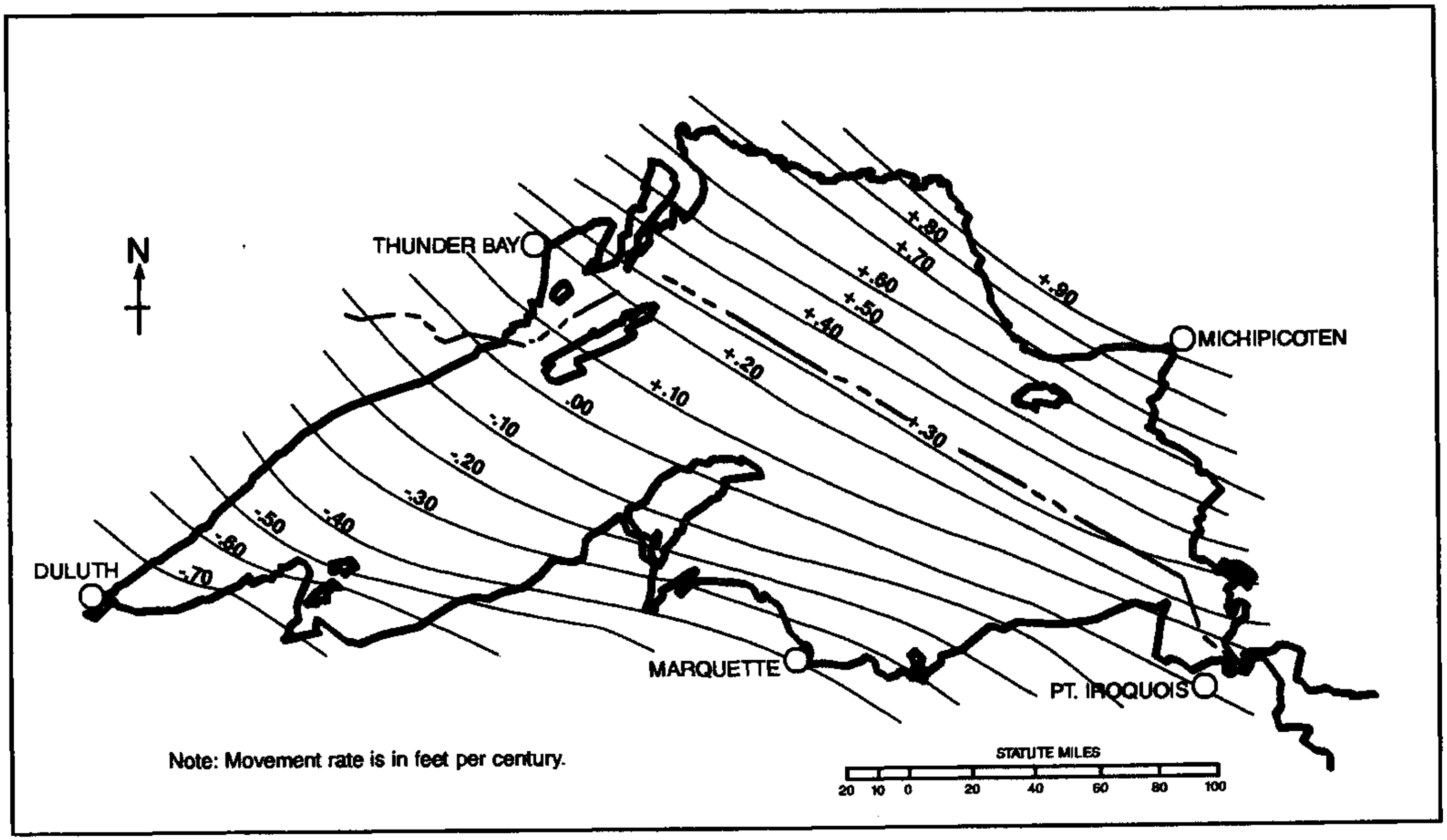


LAKE ERIE AIR TEMPERATURE (U.S.)
1900-1986

FIGURE A-2-9

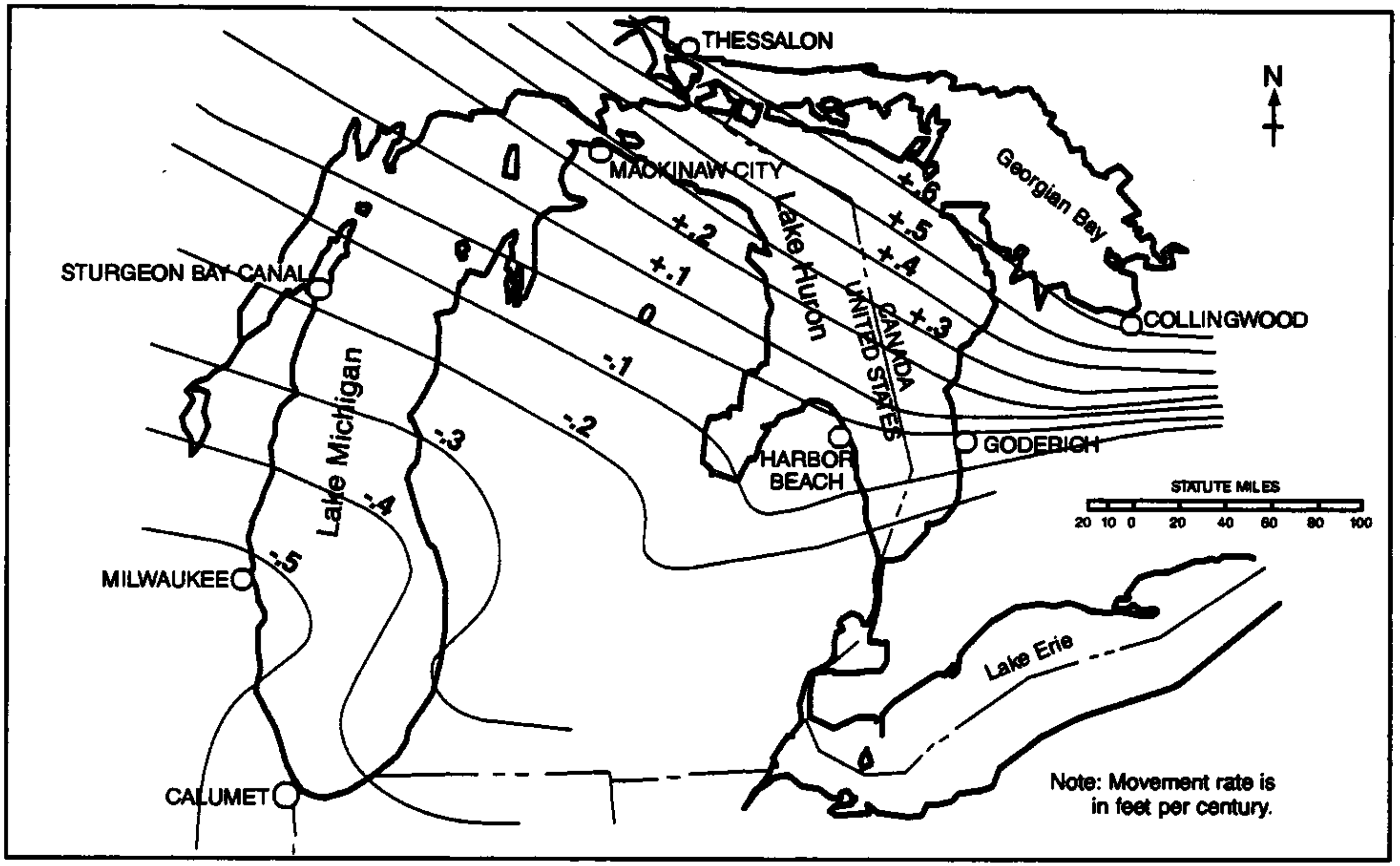
around Lakes Michigan-Huron and Erie. The effects on water levels of differential crustal movement may be better understood if the lakes are visualized as basins which are being tilted by a gradual raising of their northeastern rims. As time goes on, the water levels along shores that are situated south and west of lake outlets are rising on these shores for a given water level elevation. Similarly, water levels along the shores at localities north and east of the outlet are receding with respect to the land. This can have a significant effect on several Great Lakes major urban areas, especially in the United States. Figures A-2-10 and A-2-11 show the major effects of crustal movement on Lakes Superior and Michigan-Huron.

The implication for this study is that the effectiveness of any given measure can be enhanced or partially negated by this effect. Lake Superior can serve as an example, where Duluth is now rebounding slower than the St. Marys River area and much slower than the Michipicoten area. As such, whenever Lake Superior is subject to high levels, they appear more pronounced on the west side of the lake (Duluth) than on the east side (Pt. Iroquois). Based upon current rates of rebound, there may be about a 0.4 foot rise in water level at Duluth over the next 50 years, relative to the St. Marys area, and about a 0.9 foot rise in water level relative to Michipicoten. Measures to reduce flooding at Duluth may be hindered by about a foot relative to Michipicoten and by about half of a foot relative to the lake as a whole.



APPARENT VERTICAL MOVEMENT RATES BETWEEN OUTLET AND SELECTED SITES ON LAKE SUPERIOR

FIGURE A-2-10



APPARENT VERTICAL MOVEMENT RATES BETWEEN OUTLET AND SELECTED SITES OF LAKES MICHIGAN - HURON FIGURE A-2-11

SECTION 3

ARTIFICIAL EFFECTS

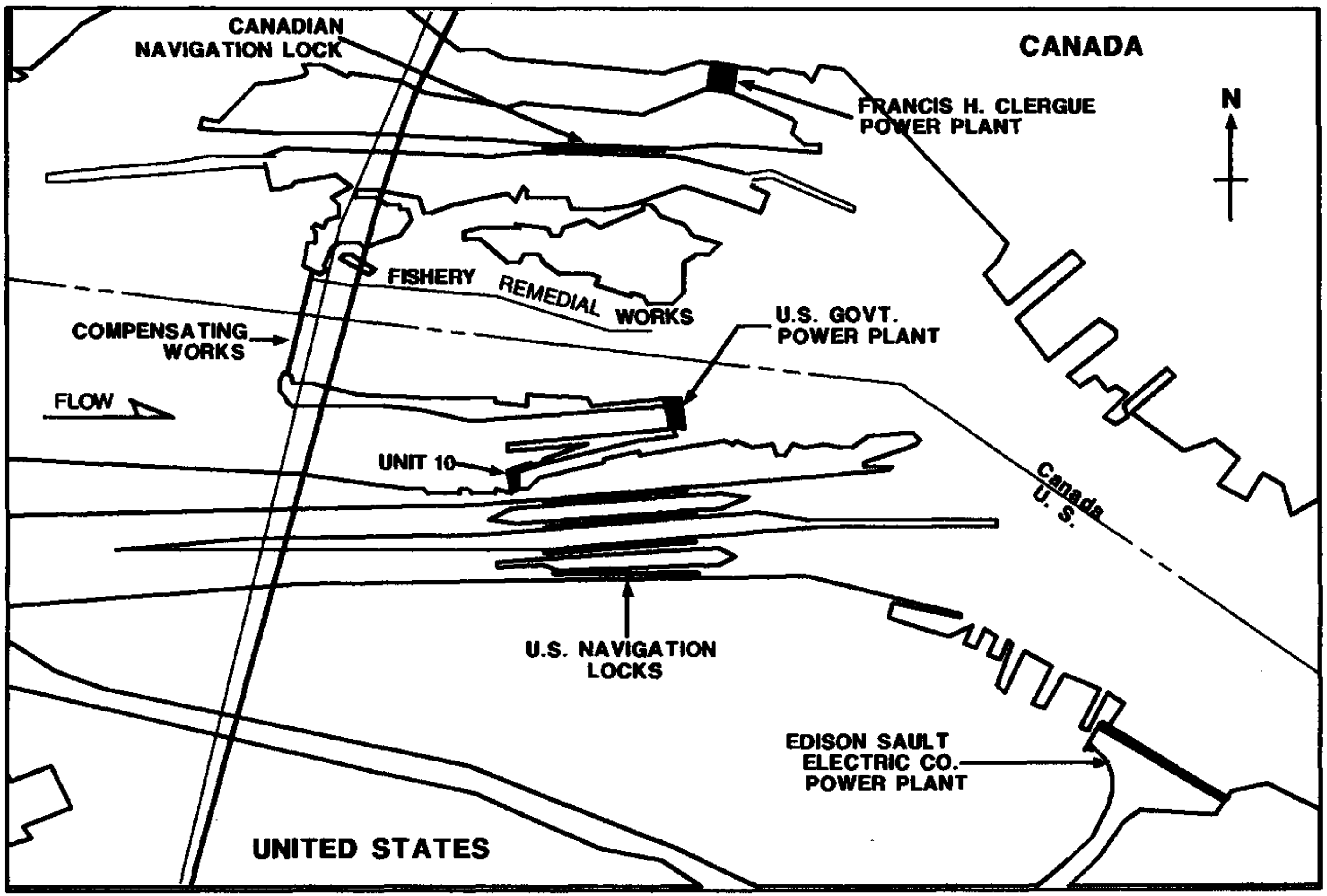
In addition to the natural factors influencing Great Lakes levels, artificial factors must also be considered. They include: regulating the outflow of Lakes Superior and Ontario; modifying the connecting channels; using ice control measures; land use modifications; regulating tributary river outflows; diverting water into and out of the lakes; and withdrawals and consumptive uses. Runoff characteristics within the basin were also modified, both qualitatively and quantitatively, due to changes in agricultural practices, urban drainage and the introduction of detention ponds.

With society's desire to better utilize the assets of the Great Lakes, changes have been made in the connecting channels to handle an expanding commercial navigation industry. Regulatory works and hydroelectric power generating stations have also been built, to meet the need for power. Bridges and shore structures have also been built, which affect the natural level-outflow relationships of the lakes. Regulatory works are located in two of the outlet channels of the Great Lakes. The works at the head of the St. Marys Rapids at Sault Ste. Marie, were built to compensate for diversions for hydroelectric power and navigation locks on both sides of the river. Of the structures in the St. Lawrence River, the international hydroelectric generating station at Massena, New York and Cornwall, Ontario, is the principal regulating structure affecting the outflows from Lake Ontario.

LAKE SUPERIOR REGULATION

In 1914, the International Joint Commission (IJC) issued Orders of Approval, permitting the diversion of St. Marys River water for power purposes and the completion of the Lake Superior Compensating Works. The 1914 Orders, together with subsequent amendments, were designed to provide a degree of protection for interests on Lake Superior, the St. Marys River, and downstream. The IJC also established the International Lake Superior Board of Control to supervise the operation of the control works, canals, headgates and bypasses and to formulate rules for their operation. Following completion of the control works (Figure A-3-1) in 1921, the Board assumed complete control of the outflows from Lake Superior.

Several regulation plans have been developed and used by the International Lake Superior Board of Control to determine the monthly outflows from Lake Superior. The regulation plan currently being used is called Plan 1977. The Plan was developed initially as Plan SO-901 during the 1973 Levels Board Study on Further Regulation of the Great Lakes. Prior plans are shown on Table A-3-1. The fundamental principle of Plan 1977 is to manage the Lake Superior outflows in such a way as to strive to keep the levels of Lakes Superior and Michigan-Huron at relatively the same position with respect to their long-term monthly averages. This concept of balancing the lake levels is accomplished while protecting Lake Superior levels from exceeding a maximum monthly mean level of 602.0 feet. To accomplish these objectives, a relationship was



LAKE SUPERIOR CONTROL STRUCTURES

FIGURE A-3-1

Table A-3-1
Lake Superior Regulation Plans

Plan 1977	1979 - Date
SO-901 (Guide)	1973 - 1979
1955 Modified Rule of 1949	1951 - 1973
Rule P-5	1941 - 1951
Sabin Rule	1916 - 1941

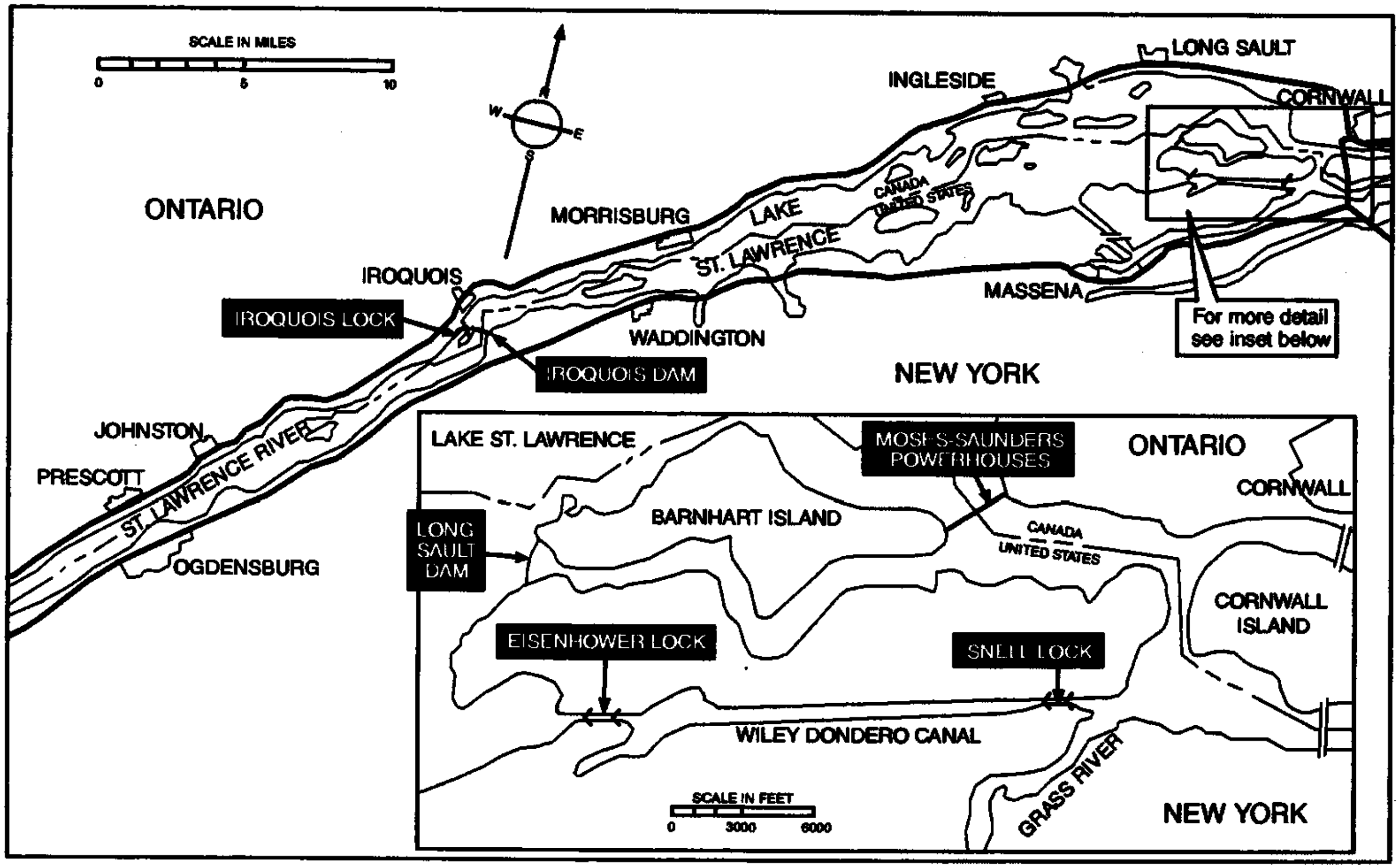
developed between the required monthly Lake Superior outflow and the beginning-of-month water levels on Lakes Superior and Michigan-Huron.

A major feature of Plan 1977 was the employment of forecasts of Lake Superior outflows based upon the probability of Lake Superior and the lower lakes receiving various ranges of water supplies. The aim of this forecast was: to provide system-wide benefits to Great Lakes interests; to minimize the number of gate movements in the Compensating Works; and to provide the most uniform flow possible in the St. Marys River.

In 1983, the International Lake Superior Board of Control (ILSBC) initiated an investigation of the regulation criteria used in Plan 1977. The purpose of this study was to evaluate any modifications which might better reflect present-day conditions (such as updating the hydrologic data base and increasing the side channel flow to reflect the redevelopment and expansion of the Canadian power plant in 1982), while also providing certain improvements for the operation of the Plan. In 1988, fundamental evaluations of possible improvements to Plan 1977 were completed and a proposed plan modification, designated Plan 1977-R, was tested against the previous regulation plan, the 1955 Modified Rule of 1949, and the current plan, Plan 1977. Since preliminary tests indicated that Plan 1977-R would raise the mean level of Lake Superior, the ILSBC asked that any further modifications for the Board be limited to smoothing month-to-month flow changes and maintaining the long-term mean. The ILSBC also indicated that any additional analyses and revisions be performed under Phase II of the Reference Study to ensure that any revised regulation plans be tailored to function with any lake management scheme which may be conceived for the Great Lakes system.

LAKE ONTARIO REGULATION

In 1952, the IJC issued Orders of Approval for the construction of the St. Lawrence Seaway and Power Project (Figure A-3-2). The International St. Lawrence River Board of Control was established to ensure compliance with the provisions of the Orders. The Board is responsible for determining the outflow from Lake Ontario in accordance with the approved regulation plan,



LAKE ONTARIO CONTROL STRUCTURES **FIGURE A-3-2**

currently known as Plan 1958-D. This plan was developed to provide benefits to perceived interests, while at the same time satisfying the criteria and other requirements contained in the Orders of Approval for the Project. The Board, using the guidelines of Plan 1958-D, determines the weekly releases from Lake Ontario and has the discretionary authority to amend flows during periods when the lake is being subjected to extreme supply conditions. The basic data required to implement Plan 1958-D are the end-of-week levels (at six gage locations) of Lake Ontario.

In 1979, the International St. Lawrence River Board of Control (St. Lawrence Board) developed three proposals for new regulation plans for Lake Ontario in an effort to better cope with the extreme supplies that were experienced during the early 1970's. These plans were tested using the recorded water supply data for 1900-1978 to determine any improvements in levels, and later, to determine the economic impacts on the various interests, using models developed for the Lake Erie Regulation Study, then in progress. It was found that none of the plans improved upon Plan 1958-D when it was being applied using prescribed discretionary outflow deviations, as specified in its Criterion (k), which provides all possible relief to riparians in periods of high supplies. This plan has been in use from 1963 to present. The results of these studies made it clear that under extreme high water supplies as received in the 1970's and barring the application of any discretionary deviations from the plan, maintenance of Lake Ontario below 246.77 feet can be achieved by modifications of the 1958-D criteria to take full advantage of existing channel capacity or by some additional channel enlargement to increase the existing discharge capacity of the St. Lawrence River.

In the ten years since completion of these studies, there has been renewed interest in improving Plan 1958-D. This has resulted from such things as the strong emergence of recreational users of Lake Ontario and the St. Lawrence River. In December 1987, the IJC informed the St. Lawrence Board that further analysis of Plan 1958-D would be performed under the Reference Study. Some analyses of refinements to Plan 1958-D have been undertaken and may be continued during Phase II of the Reference Study.

CHANNEL MODIFICATIONS

From the initial use of the Great Lakes system as a water route for native Americans and early European settlers, numerous changes were made to provide improvements in the navigation channels. Because the outflows of Lakes Superior and Ontario are currently regulated, any channel improvements that have been undertaken in the St. Marys and St. Lawrence Rivers, have no effect on their long-term outflows, but allow for an expanded range of outflows.

In addition to the control structures at Sault Ste. Marie, the International Railway Bridge was built immediately downstream of the Compensating Works at the outlet of Lake Superior. The piers of this bridge cause a small backwater effect on the control structure. Channel changes in the St. Clair and Detroit Rivers have included commercial sand and gravel mining and have lowered Lakes Michigan-Huron levels, since 1933, by about 9 inches, and since before 1900, by about 11 inches. The practice of sand and gravel mining in the connecting channels ceased in 1925.

As part of the dredging for the 27-foot navigable channel in the St. Clair and Detroit Rivers, some rock spoil was placed in shallower reaches of the rivers in an attempt to compensate for the increased outflows which would result from the deepened navigation channels. Dikes were also constructed in the lower St. Clair River and along some of the channels of the Detroit River. These were designed as compensating measures and for disposal of dredged materials. Although submerged sills were also proposed for the upper St. Clair River to compensate for increased channel capacity, they were never constructed. There are several major bridges having piers in the St. Clair and Detroit Rivers, none of which has a significant effect on outflows.

There have been a number of changes in the area of the upper Niagara River, including the construction of the Black Rock Canal and navigation channel, construction of piers for two international bridges, and various shoreline modifications along both the U.S. and Canadian shores. An investigation of these changes was included in the recent IJC Task Force Study on water levels. A study completed by Environment Canada and the U.S. Army Corps of Engineers attributed, among other things, that a 0.07 foot rise occurred in Lake Erie levels as the result of one shoreline property change alone at Fort Erie, Ontario.

Since the construction in the upper Niagara River of the Chippawa-Grass Island Pool Control Structure in 1955, the water level in the Pool immediately upstream of Niagara Falls has been maintained according to requirements established by the IJC. The operation and maintenance of the structure is monitored by the International Niagara Board of Control. The purposes of this structure are: to maintain the prescribed flow over Niagara Falls as required by the 1950 Niagara Treaty; and to facilitate efficient diversion of water for hydropower purposes. The effect of the structure on Niagara River flows is localized and has had no measurable effect on Lake Erie outflows. The flow out of Lake Erie into the Niagara River depends primarily on the level of Lake Erie.

Regulation of Lake Erie outflows through possible modifications of the Niagara River channels was investigated in two previous IJC studies. For this Reference Study, a limited analysis was initiated for a plan which could increase or decrease Niagara River flows by up to 50,000 cfs. This plan could compress Lake Erie's range of extreme levels by two to three feet; i.e., from a current range of six feet to a possible range of three to four feet. The effect of this scenario on Lakes Michigan-Huron would be less and could result in Lake Ontario being adversely affected. Refinements to this plan will continue to be investigated in Phase II of this study.

ICE CONTROL MEASURES

Ice control through the use of ice booms and ice-breaking ships can change the natural river winter regime. Ice booms are employed in the St. Marys, Niagara and St. Lawrence Rivers to stabilize ice covers and minimize head losses. Floating ice booms are used to stabilize the winter hydraulic regime and prevent its deterioration through runs of broken ice which can create ice jams and thus large head losses with reduced channel capacity. Ice breaking ships can break up an ice cover, resulting in near open-water conditions with little reduction in channel capacity. Conversely, repeated breaking and refreezing of the ice cover can cause increased flow retardation due to ice buildup in river channels. These two factors can artificially influence the hydraulics of the connecting channels of the Great Lakes. If ice control measures continue during successive winters, thereby reducing the natural ice retardation, they will have the long-term effect of increasing the winter outflows in the connecting channels and reducing lake levels. However, insufficient data are available at this time to determine the quantitative effect of all these measures.

As an example of a very successful ice control measure, the International Niagara Board of Control supervises the operation of the Lake Erie-Niagara River Ice Boom. The boom, located at the head of the Niagara River, is installed each winter by the power entities to reduce massive ice runs that could restrict power intakes, cause over-bank flooding and damage docks. Towards the end of the winter, the power entities remove the boom in accordance with procedures established by the IJC. The boom has no effect on Lake Erie outflows.

LAND USE MODIFICATIONS

Significant land use changes have taken place in the basin within the last century. Some of the major changes include deforestation and conversion to agricultural land, drainage of swamps and fields and urbanization. These have affected vegetative cover, evaporation, transpiration, infiltration and hydraulic characteristics of flows. Most of these changes have taken place gradually and the effects of individual activities are not easily differentiated or quantified.

Of all the effects of society on the basin, the most significant may have been the scope and extent of deforestation. The amount of runoff and erosion is directly influenced by the amount and type of forest cover. Deforestation has the effect of both increasing runoff and stream and overland erosion.

Another major land use change has been the drainage of swamps, wetlands and fields for agriculture and urban use. Only a fraction of the swamps and wetlands that originally existed still remain. This has eliminated much upstream storage, increased runoff and flooding in the spring and has resulted in less flow for the summer and fall. Since there are large amounts of clay soils in the basin, many areas were drained through ditches and drain tiles to allow earlier and increased agricultural production. This too has increased runoff and changed the hydraulic characteristics of surface and subsurface flow.

Both of the previously mentioned land use changes are linked to urbanization, as the population of the basin has increased. It is well-known hydrologically, that urbanization leads to increased volume of runoff at a faster rate. Urbanization has led to changes in water quality as well as quantity.

A statistical analysis was performed to determine if land use modifications have affected runoff into the Great Lakes. Regression equations of average annual streamflow versus average annual precipitation were developed for each of 42 tributary watersheds throughout the Great Lakes Basin. These watersheds are not significantly affected by regulation, and nearly all have more than 40 years of streamflow and precipitation data. The residuals of the 42 regression equations were then analyzed to identify any trends. It was assumed that any significant trend in the residuals over the period of record would be due to land use change. Fifteen of the watersheds showed increasing residuals over their periods of record, suggesting that land use changes were causing higher runoff. Four of the watersheds showed decreasing residuals, suggesting that land use changes were causing a reduction in runoff. The remaining 23 watersheds showed no trend. These results indicate that land use modifications have had some impact on total water supplies to the Great Lakes. In the fifteen watersheds that showed an increasing trend, the result indicated an average increase in runoff due to land use changes of about 30 percent. Further analyses would be required in order to quantify this impact with greater degree of accuracy.

REGULATION OF TRIBUTARY FLOWS

The flows of most of the tributaries to the Great Lakes have been regulated at some time during the period of record. During and following settlement of the Great Lakes Basin, particularly in the late 1800s and early 1900s, most streams with adequate slope had grist and saw mills, which used the streamflow as a source of energy. Even though this amounted to a limited storage of water, these mills nevertheless, regulated the streams to a minor extent. As further settlement took place and the development of large sources of hydroelectric power increased, these small mills fell into disuse. Storage development has continued on some tributary streams for hydroelectric power and for flood control. Most hydroelectric development has taken place where sufficient hydraulic head could be developed.

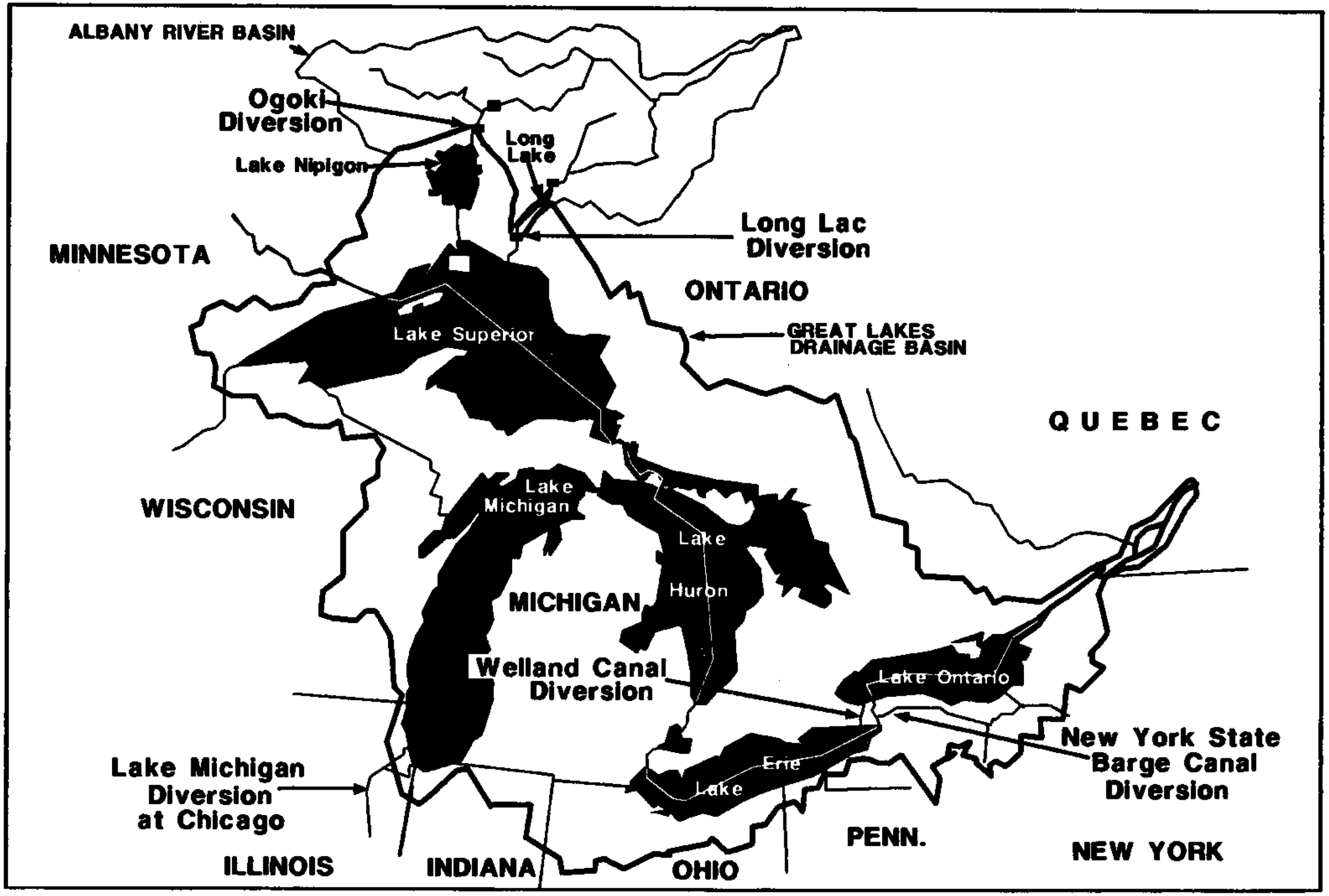
Flood control storage has been developed in the upstream areas of streams draining the more densely populated portions of the basin. All of these storage areas, developed over a period of years, tend to reduce the monthly variability of streamflow by maintaining water in the spring for release later in the year. In the case of hydroelectric power generation, some water is held in reserve until the high demand for electricity occurs. An evaluation of the effect of such regulation on the natural supplies to the Great Lakes was made as part of the International Great Lakes Levels Board Study, December 1973. It was concluded then that the effect of the tributary storages, when considered in terms of the other hydrologic processes, is negligible.

DIVERSIONS

There are five major diversions in the Great Lakes system. The Long Lac and Ogoki Diversions increase the water supply to the Great Lakes; the Lake Michigan Diversion at Chicago decreases the supply; the Welland Canal is an interbasin diversion; and, the New York State Barge Canal bypasses the natural outlet river, but returns the water to the lower basin (Figure A-3-3).

Beginning in 1939, some water destined for the Hudson Bay Drainage Basin was diverted from its tributary basin, the Albany River Basin, to Lake Superior by the Long Lac Project. In 1943, the Ogoki Project also began making diversions. Both are in accordance with an exchange of notes between the Governments of the United States and Canada, and are primarily for the purpose of developing hydroelectric power and log-driving. In their earlier years the total diversion into the Great Lakes through the Long Lac and Ogoki Projects was at an average rate of about 5,000 cfs. In recent years these diversions have averaged about 5,600 cfs and have had the effect of raising Lake Superior by 0.3 foot, Lakes Michigan-Huron by 0.4 foot, Lake Erie by 0.2 foot and Lake Ontario by 0.2 foot.

Diversion of water from Lake Michigan at Chicago began in 1848 with the construction of the Illinois and Michigan Canal. This was enlarged in 1900 when the Sanitary and Ship Canal was completed by the Metropolitan Sanitary District (MSD). This particular diversion has always been a controversial issue with both the Great Lakes states and Canada. In 1922, the State of Wisconsin successfully sought an injunction to bar the State of Illinois from diverting Lake Michigan water. However, in 1925 the U.S. Supreme Court overturned the injunction and the diversion was allowed to continue, at an average rate of 8,500 cfs, in addition to domestic pumping. A 1930 decree required a reduction of diversion flow from Lake Michigan. As a result of this decree, the total diversion after 1938 was in the order of 3,100 cfs. In 1967, a Supreme Court decree raised the total maximum allowable diversion (including domestic pumpage) to an average of 3,200 cfs. A 1980 amendment left the total maximum allowable diversion at 3,200 cfs, but modified the method of accounting for this amount. This allowed the State of Illinois to allocate more water for domestic purposes on a long-term basis, while maintaining the maximum average diversion rate of 3,200 cfs. The accumulated effect of this diversion has lowered Lakes Michigan-Huron by 0.2 foot and Lake Erie by 0.1 foot.



GREAT LAKES DIVERSIONS

FIGURE A-3-3

The Welland Canal is an artificial navigational waterway connecting Lakes Erie and Ontario. The original canal was built in 1828 and diverted about 85 cfs. The canal was improved in 1881 and water usage increased to 400 cfs. Between 1887 and 1898, hydroelectric generating capacity was added and water usage increased to about 1000 cfs. Additional hydropower units increased the diversion to about 2000 cfs in 1913. Construction of the present Welland Canal began in 1913 and, upon completion in 1932, used about 2500 cfs for navigation and power generation. Since then, this diversion has undergone many modifications, including construction of the DeCew hydropower plant, with the added capacity to utilize the prescribed water from the Long Lac and Ogoki Diversions. In its present form, the maximum flow in the Welland Canal, on an annual basis, is about 9,200 cfs, with the diversion averaging 8,500 cfs over the period 1980-1988. The impact of this interlake diversion has been to lower the level of Lakes Michigan-Huron by about 0.1 foot and Lake Erie by about 0.4 foot.

The New York State Barge Canal diverts water for navigation from the Niagara River at Tonawanda, New York. All of the water diverted, which averages about 700 cfs annually, is eventually returned to Lake Ontario. Since its entry location is downstream of the natural hydraulic control section in the upper Niagara River, between Buffalo and Fort Erie, this diversion has no effect on the levels of the Great Lakes.

WITHDRAWALS AND CONSUMPTIVE USES

The term "consumptive use", used herein, refers to that portion of the water withdrawn and not returned to the Great Lakes. Consumptive use includes water utilized by crops, incorporated into manufactured products, used in industrial processes, consumed by man or livestock, or otherwise expended. It also includes forced evaporation due to water usage by power plants. The water so consumed in any of the separate lake basins constitutes a reduction in the net basin supply to that lake and, subsequently, to each of the downstream lakes. Consumptive use of water was estimated in a previous IJC study as belonging to seven withdrawal categories: thermal power generation, manufacturing, municipal, irrigation, rural-domestic, rural-stock and mining. The rates of withdrawal and consumptive use of water within the Great Lakes watershed are not constant from year to year because of changes occurring in population; the manufacturing, industrial and power sectors; and other socioeconomic factors. The latest (1985) estimates for consumptive use for the U.S. and Canadian portions of the basin are 3,400 cfs and 900 cfs, respectively. The projected U.S. consumptive use for the year 2000 could be in the range of 5100 to 7700 cfs while that for Canada could be about 1,400 cfs. The projections for the year 2000 for combined U.S. and Canadian consumptive use in the watershed range from 6,500 to 9,200 cfs.

SUMMARY OF ARTIFICIAL EFFECTS ON GREAT LAKES WATER LEVELS

Artificial factors, as introduced over the years by society, have exerted impacts on lake levels that vary in degree and with time. The following analysis was performed in order to identify the total cumulative effect on lake levels of the measurable societal effects that have been introduced during the past one hundred years or more.

Net basin supplies for the 1900 to 1986 period were routed through the Great Lakes, using a mathematical model of the Great Lakes system under "present regime", or Basis-of-Comparison conditions. The Basis-of-Comparison is discussed further in Section 4, under the same title.

The second step was to model the reverse of this scenario; that is, the levels and flows that would have resulted from the same supply sequence without the influence of artificial factors. Adjustments were made in the mathematical model to then produce an 87 year sequence of levels and flows representative of conditions that would have occurred under the so-called "pre-project" or "natural" conditions.

Table A-3-2 presents a hydrologic summary of the levels and outflows under the Basis-of-Comparison and "pre-project" sequences. This illustrates a comparison of the relative impact of artificial factors on Great Lakes levels and flows. In order to identify the individual effects of diversions, or lake outlet and lake regulation factors on lake levels, similar exercises were performed with results as summarized on Table A-3-3. Details of conditions considered in producing these various data comparisons are contained in the footnotes to Tables A-3-2 and A-3-3.

The comparison of data from these modeling exercises are consistent with prior International Joint Commission and federal government investigations and publications on the issue. These data indicate, for example, that maximum and mean levels on Lakes Michigan-Huron have been reduced by about 1.1 feet and on Lake Erie have been increased by about 0.1 foot due to the combined effect of diversions, channel outlet modifications and lake level regulation.

Table A-3-2
Summary of Levels and Outflows under
Historical, Basis-of-Comparison and Pre-Project Conditions

	Historical[1] 1900-1986		Basis-of-Comparison[2] 1900-1986		Pre-Project[3] 1900-1986		Difference B-of-C vs. Pre-Project[4]	
	Levels[5]	Flows[6]	Levels	Flows	Levels	Flows	Levels	Flows
Lake Superior								
Mean	600.6	76	600.4	79	600.1	73	+0.3	+6
Max	602.2	127	601.9	120	601.8	106	+0.1	+14
Min	598.3	41	598.6	55	598.0	35	+0.6	+15
Range	3.9	86	3.3	65	3.8	71	-0.5	-6
Lakes Mich-Huron								
Mean	578.3	183	578.4	187	579.5	185	-1.1	+2
Max	581.6	238	581.6	241	582.7	240	-1.1	+1
Min	575.3	106	575.4	114	576.3	108	-0.9	+6
Range	6.3	132	6.2	127	6.4	132	-0.2	-5
Lake Erie								
Mean	570.5	207	570.7	211	570.6	208	+0.1	+3
Max	573.7	276	573.5	276	573.4	274	+0.1	+2
Min	567.6	118	567.9	156	567.8	146	+0.1	+10
Range	6.1	158	5.6	120	5.6	128	+0.0	-8
Lake Ontario (w/deviations)								
Mean	244.7	243	244.7	247	244.9	244	-0.2	+3
Max	248.1	350	247.6	350	249.0	333	-1.4	+17
Min	241.5	166	241.8	176	241.4	166	+0.4	+10
Range	6.6	184	5.8	174	7.6	167	-1.8	+7

[1]Historical water levels as recorded at gauge networks (Environment Canada).
[2]See Section 1, "Basis-of-Comparison".
[3]Computed "pre-project" or "natural" levels and outflows assuming no lake regulation, no diversions and no lake outlet and connecting channel modifications. Refer to FG-1 working paper for assumptions regarding pre-project conditions. No adjustments made for consumptive uses, land use changes or regulation of tributary flows.
[4]Basis-of-Comparison level (flow) minus pre-project level (flow).
[5]Water Levels in Feet (IGLD,1955) rounded to the nearest tenth of a foot.
[6]Outflows (Flows) are in Thousands of Cubic Feet per Second (TCFS).

Table A-3-3
Estimated Impacts[1] (in feet) on Pre-Project Mean Lake Levels due to Artificial Factors

Lake	Pre-Project[2] 1900-1986 Mean Level	Current[3] M-H Outlet	Current[4] Erie Outlet	Diversions[5] Long Lac Ogoki	Diversions[5] Chicago	Diversions[5] Welland Canal	Plan[6] 1977	Plan[7] 1958-D	All[8] Factors
Superior[9]	600.1	0	0	+0.3	0	0	See	0	+0.3
Mich-Huron	579.5	-1.3	+0.1	+0.4	-0.2	-0.1	Note	0	-1.1
Erie	570.6	0	+0.4	+0.2	-0.1	-0.4	#6	0	+0.1
Ontario	244.9	0	0	+0.2	-0.1	0	Below	-0.3	-0.2

[1]Impacts calculated by introducing an individual change while <u>maintaining all other factors as under pre-project conditions.</u> Calculated impacts rounded to the nearest tenth of a foot.
For example: Introducing a constant Welland Canal diversion of 9,200 cfs to the system while maintaining pre-project conditions elsewhere would lower Lake Erie by 0.40 foot.

[2]Determined by routing historical supplies under assumed pre-project conditions.

[3]Includes the effects of pre-1926 commercial dredging for sand and gravel and navigation channel dredging subsequent to 1855.

[4]Includes the effects of the Fort Erie and Squaw Island landfills, all bridge piers and the Bird Island Pier/Black Rock Canal facility.

[5]Long Lac-Ogoki diversion into Lake Superior at a constant rate of 5,600 cfs.
Chicago diversion out of Lakes Michigan-Huron at a constant rate of 3,200 cfs.
Welland Canal diversion out of Lake Erie into Lake Ontario at a constant rate of 9,200 cfs.

[6]Lake Superior Plan 1977 was designed to accommodate current system conditions including Long Lac-Ogoki, Chicago and Welland Canal diversions and Lakes Superior and Michigan-Huron outlet conditions. Computation of levels and outflows under Plan 1977 while assuming pre-project conditions elsewhere would not produce meaningful results. Target long-term levels specified by Plan 1977 are 600.4 and 578.4 feet (IGLD,1955) for Lakes Superior and Michigan-Huron respectively.

[7]Lake Ontario regulation under Plan 1958-D with historic discretionary actions. Lake Ontario regulation has no impact on the upper lakes.

[8]Figures shown are determined by comparing levels under Basis-of-Comparison versus pre-project conditions.

[9]Lake Superior under pre-project conditions is not affected by downstream factors.

SECTION 4

FUTURE POSSIBILITIES AND UNCERTAINTIES FOR WATER LEVEL FLUCTUATIONS

The past is only a guide to the future and is not a script that will be repeated with certainty. Nowhere is this more true than dealing with the sciences of hydrology and meteorology. We are constantly informed of "new" records for the coldest day, the driest month, the hottest week, the largest rainfall and the greatest windspeed, to name a few. This is due in part because mankind has come to expect that records are usually short-lived and if we wait long enough, events beyond the limits of those experienced in the past will occur. This does not mean that recorded information of past events is meaningless, as they identify a great deal about our climate and its variability and serve as a means on which to base projections of future meteorologic conditions. Great Lakes' scientists recognize that the extremes of the past can be exceeded or not exceeded for various reasons. Many predictive tools such as trend analysis, climatic modeling, other statistical analyses and "black box" models may have the same credibility when it comes to forecasting what the future may hold. In this section, the potential for future Great Lakes water level fluctuations, based on natural and artificial changes in water supply to the lakes, as well as their outlet conditions, will be explored.

HISTORICAL RECORD

It is generally accepted that the Great Lakes did not exist in pre-glacial times, but are the cumulative result of several phases of glaciation that began around 14,800 radio-carbon years before the present. Final de-glaciation took place about 9,500 years ago. The lakes reached a configuration much as they are today, about 4,000 to 5,000 years ago. The modern historical period (as far as keeping recorded information) began sometime in the late 18th and 19th centuries.

The 89-year period from 1900 to 1988 contains basin-wide drought years, such as those recorded in the mid-1930's and early 1960's. It also contains high water supply years, such as those represented by 1928-29, 1951-52, 1973-74 and 1985-86. If one were to accept that these recorded historical water supply events and the resultant ranges of water level fluctuations are representative of the future, we could proceed to plan our activities accordingly with some certainty. Sporadic records of water levels and weather conditions of the 18th and 19th centuries tell us of the occurrence of experiences outside the 20th century limits. Moreover, archaeological and geological evidence more distant in time provides evidence of historic water level conditions that may have been even more extreme in dimension. Then what did we learn from the 1900 to 1988 historical period water level information that may help us to understand what lies in the future?

The 20th century historical record tells us much about climatic and water supply variability to the lakes and how the Great Lakes levels behave in response to changing water supply conditions. These well-documented findings include:

1. Lake levels do and will continue to fluctuate in three modes, due to climatic variability. These modes are short-term storm setups, annual or seasonal water level variations and longer term water level variations ranging from 3 to 6 feet, depending upon the lake and the accumulated water supply variations over several to many years.

   a. Wind, storm and associated rapid barometric changes can cause short-term setup or water level rises, measured over several hours, of up to 8 feet at the east and west extremes of Lake Erie, of about 2 feet on Lake Ontario; and up to 2, 3.5 and 4 feet, respectively, at extreme ends of Lakes Superior, Michigan and Huron.

   b. Annual or seasonal level variations, in the order of 1 to 1-1/2 feet on all the lakes, can be expected to continue, with the timing of the seasonal minimums in winter and maximums in summer likely to remain about the same.

   c. Though happening less frequently, more dramatic changes in lake levels, ranging between the minimums and maximums of 3 to 6 feet, depending upon the lake, can occur over several years. An excellent example of this phenomena has taken place in the last 25 years, during which we have seen most of the lakes descend to, at or near their minimum in 1964, and rise to, at or near their maximum in 1973 and again in 1986. In 1987-88, the trend again reversed, and the water levels have declined rapidly throughout the Great Lakes Basin.

2. The historical 20th century has also produced a data set of "natural" water supplies to the basin, which can be routed through the system of lakes and rivers to compare under any defined set of natural or modified lake outlet configurations, diversions or other existing or potential, artificial "regulatory" devices. (See "Basis-of-Comparison" discussion in Section 1).

3. Due to their considerable size and storage volume and limited outflow capacities, the water levels of the Great Lakes usually react slowly to changes in water supply conditions and are characterized by considerable persistence, or a year-to-year interdependence of lake levels. This serial correlation of annual lake levels requires modification of the traditional probability analyses of lake level data, in order to validate its use in future economic analyses. Unless there are large changes in channel outflow capacities, this natural regulation feature of the lakes will not change, and will remain both a plus and a minus feature. It is positive in that it dampens abrupt changes in levels and

flows due to sudden and short term changes in water supplies to the lakes, and is negative in that it may take a relatively long time to alleviate extremes in water levels.

4. The longer term minimum and maximum water level occurrences are irregular and unpredictable, but for reasons mentioned above, exhibit persistence. Separation between high and low lake levels may occur greater than five years and often many more.

5. Future water level variations on the order of those experienced historically in the 20th century may be expected to reoccur with roughly the same frequency of occurrence. Future water level variations greater than those experienced between 1900-86, and similar to those being investigated in the last several thousand years, may very well occur. However, no probability of occurrence can be as yet identified with these events.

EXTREME WET AND DRY CONDITIONS

In order to achieve a measure of how the Great Lakes watershed would react to future extreme wet or dry water supply conditions, an analysis was undertaken of the historic extreme wet and dry periods that had actually been experienced in the watershed. From this analysis, it was possible to identify the extreme water level fluctuations (maximums and minimums) that had occurred on the lakes and to hypothesize that they could recur in the future.

Since precipitation is one of the key parameters which ultimately determines water supplies and lake levels, the wet and dry climate scenarios were developed based upon recorded precipitation and other associated meteorologic data. The basic precipitation data used in the study are monthly overbasin precipitation (weighted overland and overwater) values aggregated on a lake year period (August through July). Two scenarios were developed representing the most extreme wet and the most extreme dry 12-year periods of precipitation experienced across the entire Great Lakes Basin between 1854-1987. This process led to the selection of lake years, August 1974 - July 1986 (hereafter referred to as 1975-1986) as the representative wettest 12-year period and lake years, August 1913 - July 1925 (hereafter referred to as 1914-1925) as the representative driest in the 1854-1987 period. Not all of the 12 years in the wettest period (1975-1986) had above average precipitation; similarly, not all of the 12 years in the driest period (1914-1925) had below average precipitation. However, taken as a whole, these were the most extreme recorded precipitation sequences.

To identify how Great Lakes levels and flows would react to even more extreme precipitation and resultant water supply sequences, these 12-year historical sequences were modified. The wettest individual years of the 1900-1987 period were substituted for the above-average precipitation years of the 1975-1986 historic wet period based on their ranked magnitude. Similarly, the driest years of 1900-1987 were substituted for the below average precipitation years of the 1914-1925 historic dry period. By this process, annual extremes were used to modify the precipitation that had been experienced during the wettest and driest 12-year periods on record. To determine the impacts of these historic extreme sequences, water supplies were computed and routed through the system. By routing these scenarios, the impacts on levels and flows under these modified extreme supplies were determined and are summarized on Table A-4-1. These results indicate that by applying the most severe wet conditions (modified wet) experienced from 1900 to 1986 to the current lake and connecting channel conditions, we could expect only marginally higher lake levels as compared to the historic wet supply sequences. On the other hand, under severe dry conditions (modified dry), the extreme low levels on Lake Superior would be about 0.3 foot below the minimum derived under the historic dry supply sequences, and range to about 1.3 feet below the minimum on Lake Erie. As indicated in Table A-4-1, both the modified wet and dry 12-year sequences of supplies resulted in failure of Lake Ontario's regulation Plan 1958-D. In other words, the regulation plan could not meet all of its operational criteria and would require the application of discretionary deviations from the Plan to function. There is a reasonable possibility of again experiencing these extreme wet and dry scenarios, since they are based on historical data - - only their sequence of occurrence was changed. Even so, they represent "snapshots" of random climatic conditions that could occur, without knowing probability or frequency of occurrence.

Table A-4-1
Comparison of Levels and Flows under 12-year
Historic and Modified Wet and Dry Supply Sequences

Summary of Levels in feet and Outflows in thousands of cfs

	Historic Wet and Dry		Modified Wet and Dry		Impacts of Modified Wet & Dry	
	Levels	Flows	Levels	Flows	Levels	Flows
Lake Superior						
maximum (wet)	602.0	119	601.9	116	-0.1	-3
minimum (dry)	598.5	55	598.2	55	-0.3	0
Lakes Michigan-Huron						
maximum (wet)	581.3	237	581.3	241	+0.1	+4
minimum (dry)	575.8	106	574.5	89	-1.3	-17
Lake Erie						
maximum (wet)	573.1	266	573.2	268	+0.1	+2
minimum (dry)	568.5	168	567.2	144	-1.3	-24
Lake Ontario						
maximum (wet)[1]	246.6	346	Plan 1958-D Failed			
minimum (dry)[2]	242.6	188	Plan 1958-D Failed			

[1]Plan 1958-D with deviations.
[2]Plan 1958-D without discretionary deviations.

POSSIBLE TREND TO WETTER CONDITIONS

Various scientists and laymen have devoted considerable time analyzing historical data to identify trends that might shed some light on possible future lake level conditions. Analysis of recorded Great Lakes levels and water supplies of the past permits identification of some trends which might provide an insight into the future.

Analysis of lakes levels, from the 1800's to the present, shows that the first forty years of the 20th century was perhaps a period of unusually low water levels on the lakes, as compared to the higher lake levels in the 1800's and earlier. This is also in contrast to the higher water levels of the second half of the 20th century.

The analyses of the entire record of 20th century Great Lakes levels and water supplies also suggests a possible continuation of the trend to higher water levels. An analysis of precipitation and net basin supplies to the lakes, by Foulds, for the high water periods of the early 1950's, early 1970's and the mid-1980's, lends credence to a possible increasing water levels trend. Examination of water supplies to the lakes, during selective five-year periods in which the highest lake levels of the 20th century occurred, shows that the supply of water to the lakes became progressively greater (due primarily to higher precipitation) as summarized in Table A-4-2.

Table A-4-2
Monthly Mean Net Basin Supplies (in 1000 cfs)
to the Great Lakes
Five-Year Means for Selected High-Level Periods

Lake	Recorded 1950-1954	Recorded 1970-1974	Recorded 1982-1986
Superior	88	86	86
Mich-Huron	131	132	143
Erie	22	25	31
Ontario	39	44	45
TOTALS	280	287	305

Great Lakes water levels vary in accordance with various components of climate, such as temperature, precipitation and evaporation, as well as under the influences of society such as lake regulation, diversions and channel changes. If one were to simply forecast future water level possibilities based on the trends of the past forty to eighty years, these predictions would show the possibility of levels beyond those reached in 1985-86. This is explained further in the following paragraph.

As shown in Table A-4-3, the modified wet supply sequence, as described in the previous section, defines water supplies that are incrementally only slightly higher than the supplies under the historic wet scenario. This "extreme wet" condition is perhaps representative of conditions that could very well be experienced on the Great Lakes in the future.

Table A-4-3
Comparison of Monthly Mean Net Basin Supplies (in 1000 cfs)
to the Great Lakes
Under the 12-year Historic and Modified Wet Supply Sequences

Lake	Historic Wet Sequence	Modified Wet Sequence
Superior	83	86
Mich-Huron	130	132
Erie	22	24
Ontario	45	49
TOTALS	280	291

LONG-TERM CLIMATIC CHANGE

In general, many scientists agree that a climatic change would influence water supplies to the Great Lakes, and hence cause a potential impact on future water levels and outflows. When this might happen, and by how much, are key questions open to conjecture.

Much has been said of the "greenhouse" effect due to increased carbon dioxide and other atmospheric changes, and how Great Lakes water levels might therefore be affected. For this study, Great Lakes water supplies and levels were modeled according to state-of-the-art climatic change technology, assuming doubling of atmospheric carbon dioxide (2xCO2). Three different global circulation models were employed which all identify a potential for higher air temperatures under the 2xCO2 scenario. This could result in higher over-land evapotranspiration and higher lake surface evaporation resulting in lower runoff to the lakes and earlier runoff peaks. The snowpack could be reduced by up to 100 percent and the snow season shortened by two to four weeks. This would result in more than a 50 percent reduction in available soil moisture. Water surface temperatures would probably peak earlier on Lake Superior as its climate would duplicate the present-day climatic conditions on the southern portion of the Great Lakes Basin. Since there would be increased amounts of heat resident in the deep lakes throughout the year, ice formation would be greatly reduced. In addition, buoyancy-driven turnovers of the water column may not occur at all on four of the six lakes. Currently, this phenomenon occurs twice a year on all lakes. Lake evaporation would generally increase, net basin supplies would be reduced and ice retardation in the interconnecting channels would also decline. The effect of reduced ice retardation to winter flow in the connecting channels may possibly be offset, to some degree by increased summer weed growth and resultant flow retardation.

In order to assess the possible future impact of climatic change on the Great Lakes levels and flow regime, water supplies based on the information from the three different Global Circulation Models (GCM) were routed through the lakes to produce three $2xCO_2$ scenarios. Some of the climatic change supply sequences yielded supplies which were so low that they caused Regulation Plan 1977 for Lake Superior and Regulation Plan 1958-D for Lake Ontario to fail; that is, the plan objectives could not be met due to a deficiency of water. To be able to continue the hydrologic modeling and evaluation exercise, the "natural" or "pre-project" outlet conditions for Lakes Superior and Ontario were assumed for all scenarios on Lake Superior and Ontario. Also, a different but comparable set of basis-of-comparison supplies, computed by the GLERL, were utilized in this analysis.

Table A-4-4 presents the range of impacts on lake levels and outflows of routing 35 years of water supplies for the three GCM scenarios through the lakes. The net effect on the Great Lakes would be a potential average reduction in lake levels on the order of about 3 feet on the central lakes (Michigan, Huron, St. Clair and Erie) with attendant outflow reductions, all other conditions being unchanged.

These results are dependent on the use of the study's three selected large-scale GCMs and are only possibilities for the future contingent upon a predicted doubling of the CO_2 in the atmosphere. Furthermore, other factors leading to and resulting from climatic change will have incremental, and sometimes offsetting, effects on water supplies to the lakes, and the time frame for realization of double CO_2 conditions. In any case, it appears probable that present and future climatic change conditions, which assume doubling of the atmospheric CO_2 content, will cause a reduction in water supplies to the lakes which in turn represents the potential for a considerable reduction in lake levels.

There are many other related and possible impacts of climatic change in the Great Lakes Basin, including increased consumptive water use for agriculture (irrigation) and municipal and industrial purposes, as well as changes in the frequency and severity of wind and rainstorms.

Table A-4-4
Potential Impacts[1] on
Great Lakes Levels (feet) and Outflows (1000 cfs) under
Doubled Atmospheric CO2 Conditions
for a 35-Year Period

	GISS MODEL		GFDL MODEL		OSU MODEL	
	feet	Tcfs	feet	Tcfs	feet	Tcfs
Lake Superior[2]						
mean	0.0	-1	-2.5	-42	-0.8	-14
maximum	-0.2	-2	-2.4	-44	-0.8	-16
minimum	-0.2	-4	-2.4	-35	-0.8	-13
range	0.0	2	0.0	-9	-0.0	-3
Lakes Michigan-Huron						
mean	-4.2	-50	-8.3	-96	-3.1	-40
maximum	-2.9	-35	-6.0	-80	-2.4	-31
minimum	-4.6	-42	-8.8	-84	-3.5	-36
range	1.7	7	2.8	4	1.1	5
Lake Erie						
mean	-3.7	-73	-6.3	-113	-2.5	-51
maximum	-2.7	-60	-4.3	-94	-1.7	-41
minimum	-4.0	-66	-7.2	-104	-3.0	-52
range	1.3	6	2.9	10	1.3	11
Lake Ontario[2]						
mean	-4.5	-91	-6.4	-126	-2.6	-56
maximum	-4.1	-89	-5.4	-117	-2.3	-50
minimum	-4.4	-81	-6.6	-112	-3.0	-53
range	0.3	-8	1.2	-5	0.7	3

[1]Impacts were derived by comparing 35-year periods of the Basis-of-Comparison conditions (but routed with GLERL-computed supplies), with each 2xCO2 scenario.

[2]Pre-regulation natural outflow conditions were assumed for these lakes.

Legend:

GISS - models of the Goddard Institute for Space Studies
GFDL - models of the Geophysical Fluid Dynamics Laboratory
OSU - models of Oregon State University

CONSUMPTIVE WATER USE PROJECTIONS

Consumptive water use, or that portion of water that is withdrawn and not returned to the Great Lakes system, was projected in 1981 to be about five times greater in 2035 than it was in 1975. In 1975, manufacturing consumption was at 51 percent, municipal consumption at 17 percent and the power industry at 10 percent, accounting for almost 78 percent of the estimated consumptive water use in the Great Lakes Basin.

The estimates contained in the 1981 report were the subject of considerable discussion and revision by the International Joint Commission, when they were compared to United States Geological Survey (USGS) projections. Consumptive use projections over sixty years, to the year 2035, were considered to be subject to many uncertainties and it was agreed that any revised estimates be projected only to the year 2000. Based on 1980 and 1985 consumptive use data developed by the USGS, and variable rates of consumptive use increases of 116 and 292 cfs/year, the current estimate for consumptive use in the Great Lakes Basin could range from 6,500 cfs to 9,200 cfs by the year 2000. The estimated current (1985) consumptive water use in the basin is about 4,300 cfs. The impact of this increase in consumptive use over the next eleven years on Great Lakes water levels would result in the removal of about 1 and 3 inches of water on Lakes Michigan-Huron and Erie respectively.

The prime uncertainty in making water-use projections is that assumptions need to be made in regard to socio-economic conditions, which can markedly change for many unforeseen reasons. These can be due to political decisions, international situations, and changes in social and environmental laws. It is believed that projecting consumptive water uses more than 20 to 25 years in advance is too uncertain to be useful.

INTERBASIN DIVERSIONS

As described in Section 3 of this annex, five interbasin diversions of significance are in operation in the Great Lakes Basin; the Long Lac and Ogoki Diversions into Lake Superior, the Lake Michigan Diversion at Chicago, the Welland Canal between Lakes Erie and Ontario and the New York State Barge Canal, from the Niagara River, discharging into Lake Ontario. The potential exists to change the flow rates of each of these diversions, excepting the New York State Barge Canal, with the objective of lowering or raising water levels on the Great Lakes. Options to manage these diversions were previously discussed in the October 1988 IJC Interim Report to Governments and are also addressed as alternative measures in another annex of this report.

If Great Lakes water levels were to approach their extremes, the potential exists to alter the rate of these diversions to help mitigate high or low lake levels. The diversion management scenario (without structural modifications) that would have the greatest effect in reducing extreme high levels consists of reducing the Long Lac and Ogoki Diversions to zero and increasing both the Chicago Diversion and the Welland Canal Diversion to 10,000 cfs each. The ultimate effect of this scenario would be to lower maximum water levels by about 1 inch on Lake Superior, almost 20 inches on Lake Ontario; and, to lower minimum water levels 1-1/2 inches on Lake Erie and 8 inches on Lake Ontario. This scenario would also reduce the average water levels by 2 inches on Lake Superior and by 5 inches on Lakes Michigan-Huron.

Conversely, the scenario having the greatest effect in raising low lake levels would direct that the Long Lac, Ogoki and Chicago Diversions remain at their present rates and reduce the Welland Canal Diversion to 2,600 cfs from the current rate of 9,200 cfs. This would raise the minimum water levels on Lake Superior by 1/2 inch and on Lake Erie by 4 inches. This scenario would also increase average water levels by 1/2 inch on Lake Superior and by about 2 inches on Lake Erie.

The Ogoki Diversion can be reduced to zero by redirecting this water to Hudson Bay via the Albany River. A lower limit for the Long Lac Diversion is about 800 cfs to avoid complete shutdown of logging activities and ensuing disruption of the local economy. However, when Great Lakes water supplies and levels are low, so too are water supply conditions in the Albany River Basin; thus, uncertainty exists as to whether the full nominal 5,600 cfs can be provided, much less, increased above that amount, during drought conditions.

The potential to increase the Lake Michigan Diversion at Chicago during times of water deficit on the Mississippi or in the U.S. midwest has been the subject of debate numerous times over past decades. The engineering repercussions of doing so are discussed elsewhere in this and other IJC reports.

A preliminary analysis of diverting 50,000 cfs into and out of Lakes Michigan-Huron was conducted. Such a plan could decrease the range of levels on Lakes Michigan-Huron, Erie and Ontario by about 1.7, 1.2 and 2.5 feet, respectively; there would be a much lesser effect on Lake Superior. A rough hydraulic analysis to estimate the size and cost of such a project to accommodate a 50,000 cfs Lake Michigan Diversion at Chicago was also conducted. The estimated cost of such an undertaking is in the order of $40 billion. This would convey the water to the Mississippi River and thence, downstream. Refining the analysis may be continued in Phase II of the study.

WEATHER AND WATER SUPPLY FORECASTING

As previously noted in the IJC's International Great Lakes Levels Board Report of 1973, the International Great Lakes Technical Information Network Board report of 1984 and in other various documents, there is a need for improved weather and water supply forecasting on the Great Lakes, for both the short and long term, in order that better water management decisions can be made.

Models to forecast the supply of water from the land surface of all the Great Lakes' Basins and to estimate lake evaporation have been developed and are in the process of being implemented. They utilize physical data (precipitation, snowpack water equivalent, air temperature, etc.) to model physical processes the water undergoes, from falling as precipitation, to eventual lake inflow (supply). The models are used to evaluate both present inflow to the lakes and to forecast future supplies. This information can then, in theory, be used to better forecast lake levels and in the existing regulation models to aid in determining current and future outflows from Lakes Superior and Ontario. Presently, these climatologic models are being tested and evaluated in a water supply study for Lakes Superior and Ontario.

There is uncertainty about when and how much these water supply forecasts will be improved. It is also uncertain if their improvement in accuracy will lead to greater risk-taking on the part of individuals and/or organizations. At present there are large uncertainties in Great Lakes climatic and water supply forecasts. Although much on-going research is needed and is underway to improve them, it is not known when and what breakthroughs will occur or how they will be used. Perhaps all one can say is that weather and water supply forecasting, if improved, will form the basis for better water management, and improved socio-economic and policy decisions by governments, agencies and individuals in the Great Lakes Basin.

FUTURE IMPACT OF LAND USE MODIFICATIONS

The population of the Great Lakes Basin is expected to steadily increase, resulting in further growth of urban centers. It has been estimated that the total urbanized area could increase at the rate of approximately 1 percent per year. This urbanization will further reduce the perviousness and water storage of tributary watersheds, resulting in both increased volume and rate of runoff. It has been estimated that annual runoff could be as much as 150 percent higher in some urban areas; however, the lack of hydrometric data for watersheds undergoing urban development makes it virtually impossible at this time to quantify the impacts with any reasonable degree of accuracy.

Agriculture in the Great Lakes Basin is being, and will continue to be, subjected to severe social and environmental pressures. These pressures include the conversion of land to urban uses, the loss of fertile soil because of erosion and demands for higher productivity. With modern farming techniques, and an anticipated warming trend in the basin due to the greenhouse effect, agriculture may become economically feasible in the more northern parts of the basin. This would, however, require further deforestation of the basin and artificial irrigation/drainage of the new agricultural areas. The net effect of these changes on runoff into the Great Lakes is uncertain, since irrigation would tend to reduce the runoff, while deforestation and drainage would tend to increase the runoff. Another significant factor is that agricultural use of land generally results in considerable soil erosion. As the top layer of fertile moisture absorbing soil is eroded, the lower layer of less pervious sub-soil is exposed and runoff increases. Further work is required to accurately quantify the impacts of agriculture on future water supplies to the Great Lakes.

There is a need for ongoing investigations into the relationship of land-use changes to hydrology in the Great Lakes Basin. By looking at historical changes in land-uses and relating these to hydrologic uncertainties, we can begin to understand impacts of future changes, particularly on a local basis. Hopefully, with additional understanding, it will be possible to assess the aggregated impact of these land-use changes on large basins and ultimately on Great Lakes water levels.

STORM FORECASTING

Severe windstorms can cause short-term fluctuations in lake levels, which can be very destructive and affect all of the Great Lakes. It is not possible to predict when and where storms will occur and the degree of their severity. It is speculated, but not known, that doubling of atmospheric CO_2 will affect the severity or paths of future storms.

There have been recent efforts in both Canada and the United States to update the historical storm data base and undertake analyses of stormwater levels and wave conditions so that the experiences of the past 15-plus years can be used to better reflect what can be expected in the future. Open-coast flood levels for the entire shoreline of the lakes have or are being defined and mapped to identify flood risk areas. Possibilities for improved storm and wave forecasting and analysis exists through research efforts in both countries. Such information will aid in eliminating some of the uncertainties of Great Lakes hydrodynamic information and in better determinations of how fluctuating water levels interact with shoreline processes. These data will also be useful in assessing various possible future measures being considered for alleviating the impacts of fluctuating water levels.

RANGE OF FUTURE WATER LEVEL FLUCTUATIONS

Natural variations in precipitation and water supply to the Great Lakes cause seasonal, year to year and longer term fluctuations in lake levels. These fluctuations have occurred since the lakes formed, following the last retreat of the glaciers. These fluctuations are a likelihood of the future unless massive regulatory works, which would totally alter the watershed as we know it, were to be built. Since this is unlikely to materialize, an identification of anticipated water level fluctuations is necessary in order to plan and implement water management actions which may impact on future Great Lakes interests or activities that are affected by water level variations.

By their nature, the Great Lakes are considered to be one of the best naturally regulated watershed systems in the world. Despite this characteristic, water levels do vary considerably, with extended periods of dry and wet "weather" producing periods of lower or higher than "average" water levels throughout the system. The lake system can absorb short term basin-wide water supply variations of several months, or even several years and still maintain moderate level fluctuations. Similarly, extreme wet or dry conditions in one or two of the lakes can be buffered by the storage of the other lakes that experience less extreme or offsetting water supply conditions.

Given the above, what range of water level variations on the Great Lakes can be expected in the future, assuming no major change in artificial factors affecting water levels? Using the historic water level record as a guide to the future, reference is made to the range of levels, summarized in Table A-4-5, as experienced during the "above average supply" period, 1977 to 1986.

These data identify a range of levels of about 2-1/2 feet on Lake Superior to about 3-1/2 feet on Lakes Michigan-Huron and Erie. This envelope of level variation on the lakes could shift downwards in response to a trend to average or below average water supplies throughout the watershed. Conversely, the range of water level variation could shift higher, if future water supplies were to trend even higher than those recorded in the 20th century. The historic response of the lakes to a period of low water supplies following a high water period, 1952 to 1964, is worth noting. Neither the five to ten years leading up to 1952 or 1964 constituted the record wet or dry periods of the 20th century. Yet over this twelve year time frame a range of water level variation on the lakes from 2-1/2 feet to 6-1/4 feet was experienced on Lakes Superior to Lake Ontario, respectively. This is in comparison to the 1900-1986 water level range of 4 to 6-1/4 feet for the same lakes, as summarized on Table A-4-5.

Given that high water levels in the order of those experienced in 1885, 1929, 1952, 1973 and 1986 have roughly a 1 in 15 to 1 in 45 year return probability, as do the low water levels experienced in 1925, 1934 and 1964, then a water level range of at least 3 feet on Lake Superior and six feet on the lower lakes could be a future expectation. These ranges might be expected to increase marginally under the extreme wet and dry scenarios and decrease substantially under a potential climatic change as summarized in Table A-4-5.

Artificial factors affecting water supplies to the lakes in the form of increasing consumptive uses of water, management of existing diversions and land use modifications have caused impacts on the lake levels from several inches to more than a foot, as compared to the several feet of nature-induced impacts. Unless these forms of water supply modification were to change dramatically, they can be dismissed as generally insignificant and having no marked cumulative trend in one direction or another. The one exception is climatic change due to the so-called "greenhouse effect". If current forecasts of potential effects of climatic change were to occur in the Great Lakes region, then a very significant reduction in water supply to the lakes and a potential downward shift in the range of future water levels could result. The historically-experienced range of water level fluctuations may continue, but under a regime of possibly two or three feet less in an absolute sense. Additional societal responses could be expected to climatic change conditions in the watershed in the form of increased consumptive water use (domestic, industrial and agricultural), more rigorous diversion management, water use conservation and regulatory actions.

Table A-4-5
Hydrologic Summary of Past and Possible Future Water Levels (in feet) on the Great Lakes

	1977-1986[1]	1900-1986[1]	Modified Wet & Dry[2] (12-yr period)	Potential Climatic Change[3] (35-yr period)
Lake Superior				
mean	600.9	600.6	N/A	599.8
maximum	602.2	602.2	601.9	601.1
minimum	599.6	598.2	598.2	598.2
range	2.6	4.0	3.8	2.9
Lakes Mich-Huron				
mean	579.4	578.3	N/A	574.9
maximum	581.6	581.6	581.3	578.0
minimum	578.0	575.4	574.5	571.7
range	3.6	6.2	6.8	6.3
Lake Erie				
mean	571.9	570.5	N/A	567.8
maximum	573.7	573.7	573.2	570.7
minimum	570.4	567.5	567.2	564.8
range	3.3	6.2	6.0	5.9
Lake Ontario				
mean	245.1	244.7	Plan	Plan
maximum	246.7	248.1	1958-D	1958-D
minimum	243.7	241.5	fails	fails
range	3.0	6.6		

[1]Recorded at Marquette, Harbor Beach, Cleveland and Oswego, in feet (IGLD-1955).

[2]Based on receipt of 12-year modified wet and dry supplies.

[3]Basis-of-comparison data (routed with GLERL-computed supplies) less arithmetic average of the effects defined by the two least extreme (GISS and OSU) climatic change models (feet IGLD-1955).

SECTION 5

FINDINGS

1. The Great Lakes are considered to be one of the best naturally regulated watershed systems in the world. Nevertheless, unavoidable trends in water supply conditions of several years or more can cause persistent high or low water level and flow conditions throughout the watershed.

2. Historic 20th century water level variations on the Great Lakes range from about 4 feet on Lake Superior to 6 1/4 feet on Lakes Michigan, Huron and Erie and 6 1/2 feet on Lake Ontario. These ranges have been modified to about 3 1/2 feet on Lake Superior and 5-1/2 feet on Lake Ontario due to outflow regulation in the St. Marys and St. Lawrence Rivers. Similar modified lake level regimes should remain a future expectation barring major changes in regional water supply or lake outlet conditions.

3. Water level variations on the lakes, greater than, and less than those recorded in the 20th century have been identified as having occurred in the historical period prior to the 20th century, and could occur in the future. To identify the frequency of occurrence of lake levels outside the range of the 20th century record, is not possible.

4. It appears probable that anticipated future climatic change conditions which have never been experienced during the history of the Great Lakes, could cause a reduction in water supplies to the lakes which in turn would result in a potential for considerable reduction in future lake levels. To identify the time of occurrence or probability of this is not yet possible.

5. The water levels of the past 20 years or so have ranged from average to well above average with new record highs being established twice. Future recurrence of levels in the same range or even higher can be expected, but the occurrence of lower levels, on the order of one to three feet below the long-term averages, may also occur with no definite probability or forecasted time of occurrence.

6. Short-term water level rises at the downwind extremities of the lakes during storm conditions can approach 3-1/2, 3-1/2, 3, 8 and 2-3/4 feet, respectively, on Lakes Superior, Michigan, Huron, Erie and Ontario. Opposite extremities of the lakes experience water level lowerings of similar magnitudes during these events.

7. Currently, society's capabilities and actions to modulate water level fluctuations on all lakes, excepting Lake Ontario, can be measured in inches as compared to the three to six foot natural range of levels that, depending on the lake, can be expected to occur. Artificial effects due to lake regulation, diversions, channel dredging and other lake outlet modifications have caused a net change in maximum, mean and minimum water levels on the lakes.

8. Regulation of Lakes Erie and Michigan-Huron outflows is technically possible and could reduce the range of levels on those Lakes. With the addition of regulation of Lake Erie outflows, the current 6-1/4 foot still-water range of levels on Lake Erie could change to a 3 to 4 foot range, depending upon the size and extent of the structures installed in the Niagara River. Any regulatory devices placed in the outlets of any of the presently unregulated middle lakes will in turn, not only increase flow variations in the connecting channels, but will also, unless counteracting steps are taken, increase the range of fluctuations in Lake Ontario levels and increase the St. Lawrence River flows.

9. To maintain the current Lake Ontario water level regime conditions under middle lake regulation scenarios, (i.e., those which would discharge an additional 25,000 to 50,000 cfs into Lake Ontario) would require extensive channel modifications in the St. Lawrence River as well as restructuring of the Lake Ontario Regulation Plan.

10. Scaled down regulatory scenarios, or combinations thereof, having lesser initial costs and resulting in less effect on water levels and the environment, as well as creating less of an impact on the overall management of the Great Lakes - St. Lawrence River System, may be socially, economically and politically more attractive to both governments and other Great Lakes interests.

11. To further enhance any potential lake regulation schemes for the Great Lakes, the following steps may be considered:

a. Refine improvements to the existing regulation plans for Lakes Superior and Ontario.

b. Development of a five-lake system-wide regulation plan.

c. Systemic optimization of lake outflow regulation.

d. Improvements in hydrometeorologic monitoring and water supply forecasting.

e. Development of a Great Lakes Hydrodynamic Wave and Storm Surge data base.

APPENDIX A-1

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APPENDIX A-2

GLOSSARY OF TERMS

Note: The hydrology and hydraulic terms are defined within the context of the Great Lakes.

Accretion — May be either natural or artificial. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a beach by deposition of water or redistribution of material by wind. Artificial accretion is a similar buildup of land by reason of an act of society such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means.

Bathymetry — The topography or relief of the lake bottom, as in the measurement of depths of water in oceans, seas and lakes; also information derived from such measurements.

Control Works — Hydraulic structures (channel improvements, locks, powerhouses, or dams) built to control outflows and levels of a lake or lake system.

Connecting Channels — A natural or artificial waterway of perceptible extent, which either periodically or continuously contains moving water, or which forms a connecting link between two bodies of water. The Detroit River, Lake St. Clair and the St. Clair River comprise the connecting channels between Lake Huron and Lake Erie. Between Lake Superior and Lake Huron, the connecting channel is the St. Marys River.

Consumptive Use — The quantity of water withdrawn or withheld from the Great Lakes and assumed to be lost or otherwise not returned to them, due to evaporation during use, leakage, incorporation into manufactured products or otherwise consumed in various processes.

Convergent Shores — The phenomena of converging shorelines; such as Saginaw Bay. Water-level fluctuations are exaggerated as shorelines converge.

Crustal Movement — The change in level of the earth's surface at a location with respect to another location. Crustal movement is expressed as a differential rate of the change in level over time. This process is still continuing and affects differences in elevations.

Diurnal Tide	A tide with one high water and one low water in a tidal day.
Diversions	A transfer of water either into the Great Lakes watershed from an adjacent watershed, or vice versa, or from the watershed of one of the Great Lakes into that of another.
Drainage Basin	That part of the surface of the earth that is occupied by a drainage system of rivers and lakes.
Empirical	Relying or based solely on experiment and observation rather than theory.
Erosion	The wearing away of the shoreline and lake or riverbed by the action of waves and currents. Shoreline erosion on the Great Lakes is most often a result of the combined action of waves, currents and water levels.
Evapotranspiration	The loss of water from the soil by evaporation and transpiration (the passage of water from plants through membranes or pores).
Groundwater	Subsurface water occupying the zone of saturation. In a strict sense, the term is applied only to water below the water table.
Hanging Dam	A form of ice jam.
Hydrodynamics	A branch of science that deals with the motion of fluids and the forces acting on solid bodies immersed in fluids and in motion relative to them.
Hydrometeorology	A branch of science concerned with the study of the atmospheric and land phases of the hydrological cycle, with emphasis on the interrelationships involved.
Ice Boom	A structure installed to aid in the formation and maintenance of an ice arch at the head of a river, and thus reduce the adverse effects of ice on river levels and flows.
Ice Jam	An accumulation of river ice, in any form, which obstructs the normal riverflow.
Ice Retardation	The difference between the amount of water discharged at given lake and river stages under open water conditions and under ice conditions.

Infiltration	Movement of water through the soil surface and into the soil.
Lake Years	A hydrologic year considered to begin in August.
Low Water Datum	The plane on each lake to which navigation chart depths and Federal navigation improvement depths are referred. Also referred to as Chart Datum.
Marsh	(See Wetlands)
Meteorologic	Pertaining to the atmosphere or atmospheric phenomena; of weather or climate.
Mass Transfer Relationship for Evaporation	An application of Dalton's Law, where evaporation is considered to be a function of the wind speed and the difference between the vapor pressure of saturated air at the water surface and the vapor pressure of the air above.
Net Basin Supply	Represents the supply of water a lake receives from its own basin less the losses by evaporation from the lake surface and loss or gain due to seepage, and the inflows to the lake and the outflows from it.
Physiography	A descriptive study of the earth's surface.
Riparians	Persons residing on the banks of a body of water.
Regression Equation	A mathematical expression which statistically relates two or more physical variables.
Runoff	The portion of precipitation on the land that ultimately reaches streams.
Seiche	A standing wave oscillation of a body of water that continues, pendulum fashion, after the cessation of the originating force.
Snowpack Water Equivalent	The depth of water which would result from the melting of the snow cover of a given area.
Socio-economic Conditions	Pertaining to the demographics of a region.
Steady-state	No change over time.
Urbanization	The change of character of land from rural to urban.

Watershed	The area drained by a river or lake system.
Water Supply	Water reaching the Great Lakes as a direct result of precipitation, less evaporation from land and lake surfaces.
Wetlands	"Lands where the water tables is at, near or above the land surface long enough each year to support the growth of hydrophytes (plants which prefer wet conditions), as long as other environmental variables are favorable." (Cowardin, et.al., 1977) Along the Great Lakes shoreline they include marshes, swamps and other lands generally considered to be potential havens for fish and wildlife areas.

APPENDIX A-3

LIST OF ACRONYMS

GCM	Global Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies
GLERL	Great Lakes Environmental Research Laboratory
IGLD	International Great Lakes Datum
IJC	International Joint Commission
ILSBC	International Lake Superior Board of Control
NOAA	National Oceanic and Atmospheric Administration
OSU	Oregon State University
2xCO2	Double Atmospheric Carbon Dioxide
USGS	United States Geological Survey

APPENDIX A-4

CONVERSION FACTORS
(English to Metric Units)

1 cubic foot per second (cfs) = 0.02832 cubic meter per second (cms)

1 gallon (U.S.) = 0.003785 cubic meter

1 foot = 0.3048 meter

1 inch = 2.54 centimeters

1 mile (statute) = 1.609 kilometers

1 square mile = 2.59 square kilometers

1 cubic mile = 4.167 cubic kilometers

1 acre = 4047 square meters

1 acre-foot = 1234 cubic meters

Temperature in °F = 9/5°C + 32

APPENDIX A-5

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