NOAA Technical Memorandum ERL GLERL-68

POTENTIAL VARIATION OF GREAT LAKES WATER LEVELS: A HYDROLOGIC RESPONSE ANALYSIS

Holly C. Hartmann

Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan
March 1988

UNITED STATES
DEPARTMENT OF COMMERCE

C.William Verity
Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

Environmental Research
Laboratories

Vernon E. Derr,
Director

NOTICE

Mention of a commercial company or product does not constitute an endorsement by NOAA Environmental Research Laboratories. Use for publicity or advertising purposes of information from this publication concerning proprietary products or the *tests of such products is not authorized.

For sale by the National Technical Information Service, 5285 Port Royal Road
Springfield, VA 22161

CONTENTS

FIGURES

Page

TABLES

POTENTIAL VARIATION OF GREAT LAKES WATER LEVELS: A HYDROLOGIC RESPONSE ANALYSIS[1]

Holly C. Hartmann

ABSTRACT. The potential for water level changes on Lakes Michigan, Huron, St. Clair, and Erie is examined, using the Great Lakes Environmental Research Laboratory's Hydrologic Response Model (HRM) in conjunction with several hydrometeorologic and water management scenarios. Of the scenarios examined, only a drought similar to that of the early 1960's could return the lakes to their normal levels of 1900-1969. If the regional climatology of 1971-1985 persists for several years, the lake level regime will average about 0.5 m higher than that of 1900-1969. The extreme water supply conditions of 1985 must be accompanied by 50% increases in Lake Superior outflows and persist for about 10 years to raise Lake Michigan and Huron levels 1.0 m above their 1986 record levels. The practice of increasing winter flows from Lake Superior to provide water storage in the spring and summer has practically no effect on downstream lake levels. The effect of a barge that accidentally lodged in the Niagara River in August 1986 raised levels on Lakes Michigan-Huron, St. Clair, and Erie by a maximum of 1, 4, and 5 cm, respectively; by June 1987 the effect had entirely dissipated. Elimination of the Long Lac and Ogoki diversions and increases of the Chicago and Welland Canal diversions to 283 m^3/s (10,000 ft^3/s) for a period of 7 to 8 years could reduce the levels on Lakes Michigan-Huron, St. Clair, and Erie by only 25, 21, and 18 cm, respectively; half of that lowering, however, would occur in 2 to 3 years. These scenarios suggest that Great Lakes interests should not count on lake levels returning to long-term (1900-1969) normal levels within the next several years.

1. INTRODUCTION

Continued high precipitation throughout the Great Lakes region since 1970 has created important water management problems associated with high lake levels (Croley, 1986; Quinn, 1986). At the beginning of 1985, Lakes Michigan, Huron, St. Clair, and Erie exceeded their long-term mean monthly levels by almost 0.5 m (U.S. Army Corps of Engineers, 1986a). Snowmelt and heavy precipitation during February and March 1985 caused record high monthly levels (since 1900) on Lakes Michigan, Huron, and St. Clair in April and May. Extremely heavy precipitation throughout the Great Lakes basin during September-November of that year caused the December water levels on Lakes Michigan and Huron to exceed their highest December levels experienced since 1900 by more than 0.22 m; Lakes St. Clair and Erie exceeded their previous

[1]GLERL Contribution No. 576

December high levels by more than 0.25 and 0.12 m, respectively. By October 1986, Lakes Michigan and Huron had set record monthly levels (since 1900) for 12 consecutive months and Lake St. Clair had set records for 13 consecutive months; Lake Erie had set record monthly levels each month since October 1985 except for April 1986 (U.S. Army Corps of Engineers, 1986d). In addition, recent geologic research (Larsen, 1985; Devine, 1987) has shown that several times during the last 2000 years, Lake Michigan levels have exceeded the 1986 record levels by over a meter, suggesting that even higher water levels are possible.

This report examines the potential for water level changes in the unregulated portion of the Great Lakes system, using the Hydrologic Response Model (HRM) of the Great Lakes Environmental Research Laboratory (GLERL) in conjunction with several hydrometeorologic and water management scenarios. First, the HRM is described briefly. Then, the model is used to examine the effect on lake levels of low, moderate, and high water-supply conditions. In addition, the model is used to evaluate the effect on lake levels of an increase in winter flows from Lake Superior, modifications of diversions in the Great Lakes system, an increase in the flow capacity of the Niagara River, and the effect on lake levels of a barge that lodged on a pier of the Peace Bridge in the Niagara River.

Many of these simulations were generated as part of special studies requested by Great Lakes interests outside of GLERL. Thus, not all simulation results are directly comparable. Admittedly, additional hydrometeorologic and water management scenarios are possible, but they are not examined herein. No probabilities of occurrence are expressed for any of the water supply or lake level scenarios.

2. HYDROLOGIC RESPONSE MODEL

GLERL's HRM considers overlake precipitation, basin runoff, lake evaporation, diversions, St. Marys River flows, and ice retardation of flows in the determination of water levels on Lakes Michigan-Huron, St. Clair, and Erie (Lakes Michigan and Huron are considered to be one lake hydraulically). It also determines flows through the St. Clair, Detroit, and Niagara Rivers. Quinn (1978) describes the model and its calibration in detail. Briefly, the HRM uses a second-order finite difference solution for a series of stage-fall-discharge equations for each of the connecting channels (Quinn, 1979) and, for each lake, an approximation of continuity:

$$0.5(I_1 + I_2)\Delta t - 0.5(O_1 + O_2)\Delta t = S_2 - S_1 \qquad (1)$$

where I = the rate of all inflows to a lake, O = the rate of all outflows from a lake, S = the storage volume of a lake, Δt = a specified time interval, and subscripts 1 and 2 = the beginning and end of the time interval, respectively. Model calibration determines the constants that represent the mean bottom elevation of each lake outlet in a set of standard discharge equations applied to each connecting channel:

$$Q = C(Z_1 - y_m)^2 (Z_1 - Z_2)^{0.5} \tag{2}$$

where Q = the flow rate in the connecting channel, C = a constant based partially on the application of Manning's equation to the connecting channel (Quinn, 1979), Z_1 and Z_2 = the water level of the lake above and below the connecting channel, respectively, and Ym = the mean bottom elevation of the connecting channel at the lake outlet. Because of ice effects, a single gage equation better estimates flows in the St. Clair River during the winter months. In addition, a single gage equation is appropriate for the Niagara River throughout the year, because the upper reach of the river so strongly controls the flows. Thus, the standard discharge equation used for these cases is slightly modified:

$$Q = C(Z_1 - y_m)^2 \tag{3}$$

Original model calibrations (Quinn, 1978) used monthly connecting channel flows and lake levels for three periods: 1950-1958, 1959-1961, and 1962-1975. However, when applied over 1962-1980, the model consistently underestimated monthly levels for Lake Michigan-Huron. Recalibration for 1962-1980, by a simple successive approximation of the mean bottom Lake St. Clair outlet elevation, improved the monthly water level estimates for Lake Michigan-Huron and had little effect on the levels of the other lakes or the flows through the connecting channels. Table 1 presents the parameter values used in each of the model applications described herein. Figures 1 and 2 show the frequency and magnitude of differences between model estimates and actual values of lake levels and connecting-channel flows, respectively, for the calibration period.

Table 1. --Hydrologic Response Model parameters

River	C*	Ym (m)
St. Clair		
Winter (Dec.-Feb.)	77.00	167.91
Non-winter (Mar.-Nov.)	38.90	165.40
Detroit	71.70	165.81
Niagara		
Summer (Jun.-Oct.	202.80	168.67
Non-summer (Nov.-May)	208.40	168.67

*For Detroit River and non-winter St. Clair River applications, units for C are $meters^{0.5}$/second; otherwise, units for C are meters/second.

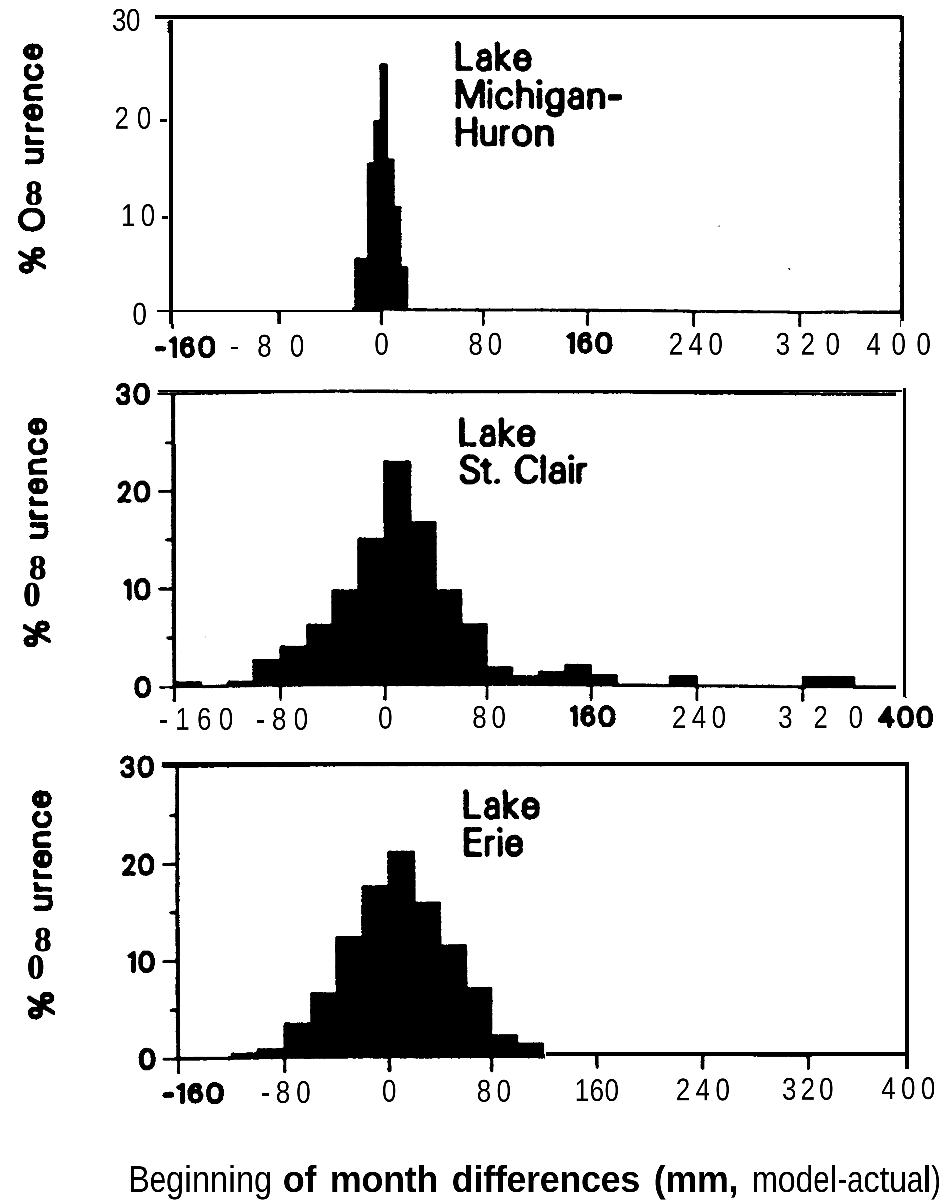

Figure 1. --Deviation between modeled and actual beginning-of-month lake levels for the calibration period.

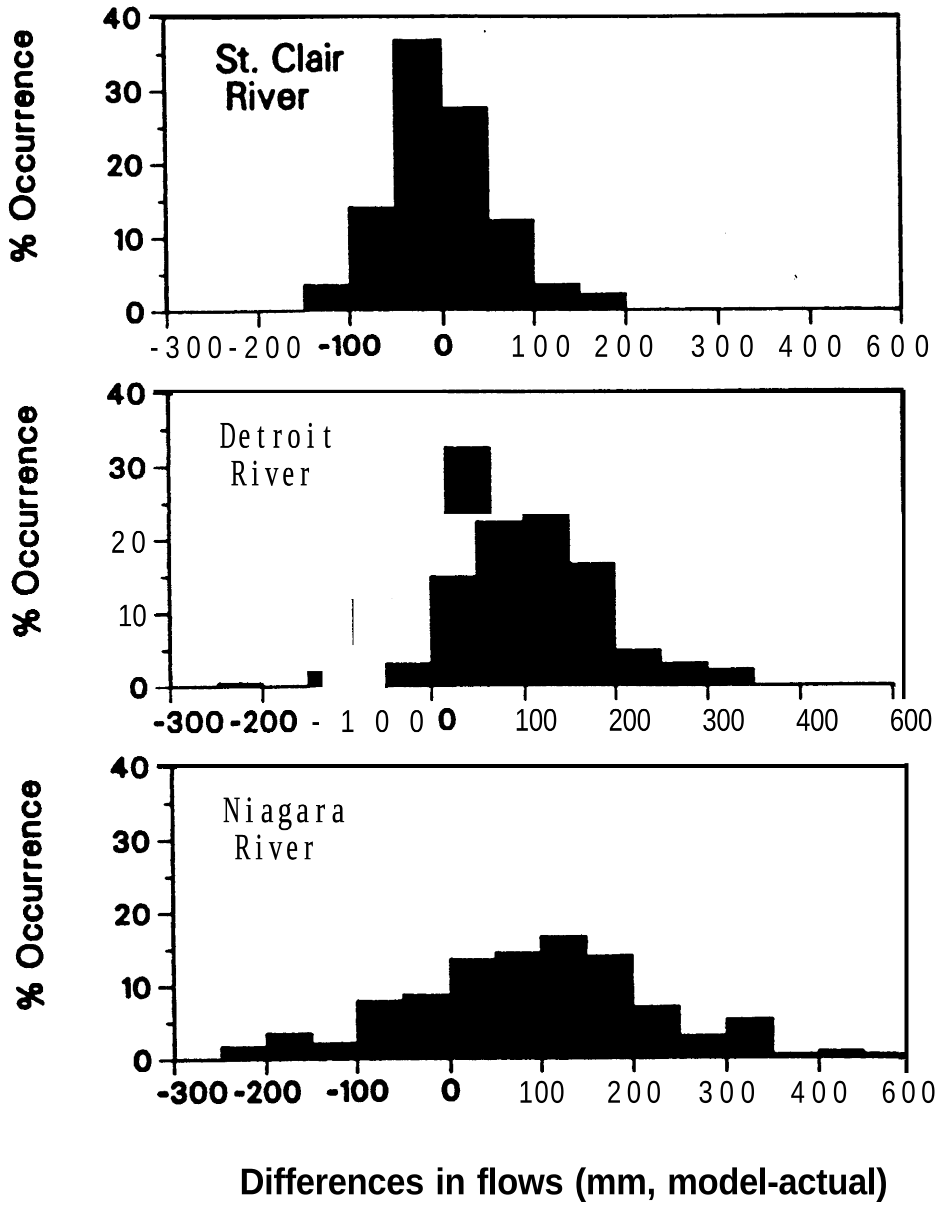

Figure 2. --Deviation between modeled and actual monthly connecting-channel flows for the calibration period.

3. CLIMATIC EFFECTS ON LAKE LEVELS

Between 1900 and 1985, annual water levels of the middle Great Lakes fluctuated over a range of about 1.43 m (Fig. 3). In addition, maximum monthly levels for each year ranged over 1.54 m on Lakes Michigan-Huron and Erie, and 1.33 m on Lake St. Clair (Fig. 4). Mean water level conditions computed for 1900-1985 and 1900-1969 are presented in Table 2 for each of the unregulated Great Lakes; the levels are presented as elevations above the International Great Lakes Datum of 1955 (IGLD55). The 1900-1969 mean annual and mean maximum monthly levels in the table are used to provide a perspective on subsequent lake level simulations because the conditions for the 1900-1969 period, when much of the development along the Great Lakes shoreline took place, often are considered "normal" (Croley, 1986; Quinn, 1986). This is due to the distinct change in the Great Lakes region's climatology that began about 1970. Figures 3 and 4 show that the lake levels have been consistently high since the early 1970's; the high levels are primarily due to the persistent high precipitation the Great Lakes region has received since about 1970 (Croley, 1986; Quinn, 1986). Although subsequent lake level simulations are compared with the 1900-1969 mean levels, the 1900-1985 mean levels are also presented in Table 2 because they more accurately represent the long-term behavior of the Great Lakes levels.

Table 2. --Normal* water level conditions on the unregulated Great Lakes

Lake	Mean annual levels (m above IGLD55!)		Mean maximum monthly levels (m above IGLD55!)	
	1900-1969	1900-1985	1900-1969	1900-1985
Michigan-Huron	176.18	176.26	176.36	176.44
St. Clair	174.66	174.76	174.88	174.97
Erie	173.78	173.88	174.01	174.11

* Normal determined as a mean for the period.
! International Great Lakes Datum of 1955.

Great Lakes water level variations are linked closely to the regional climate. Thus, forecasts of lake levels can be no better than the weather forecasts on which they are based. Although reliable long-range forecasts of climatic variations are not available, use of a range of hydrometeorologic conditions derived from historical records can provide a perspective on the potential for water level variations. All applications of the HRM described in this section begin with actual January 1986 beginning-of-month levels for Lakes Michigan-Huron, St. Clair, and Erie (176.97, 175.69, and 174.45 m, respectively), based on levels at the master gage for each lake (Harbor Beach and St. Clair Shores, Michigan, and Cleveland, Ohio, respectively). Except where noted, all simulations use mean monthly hydrometeorologic data from Quinn and Kelley (1983) where available. Although the HRM can consider variations in individual net basin supply components (basin runoff, overlake

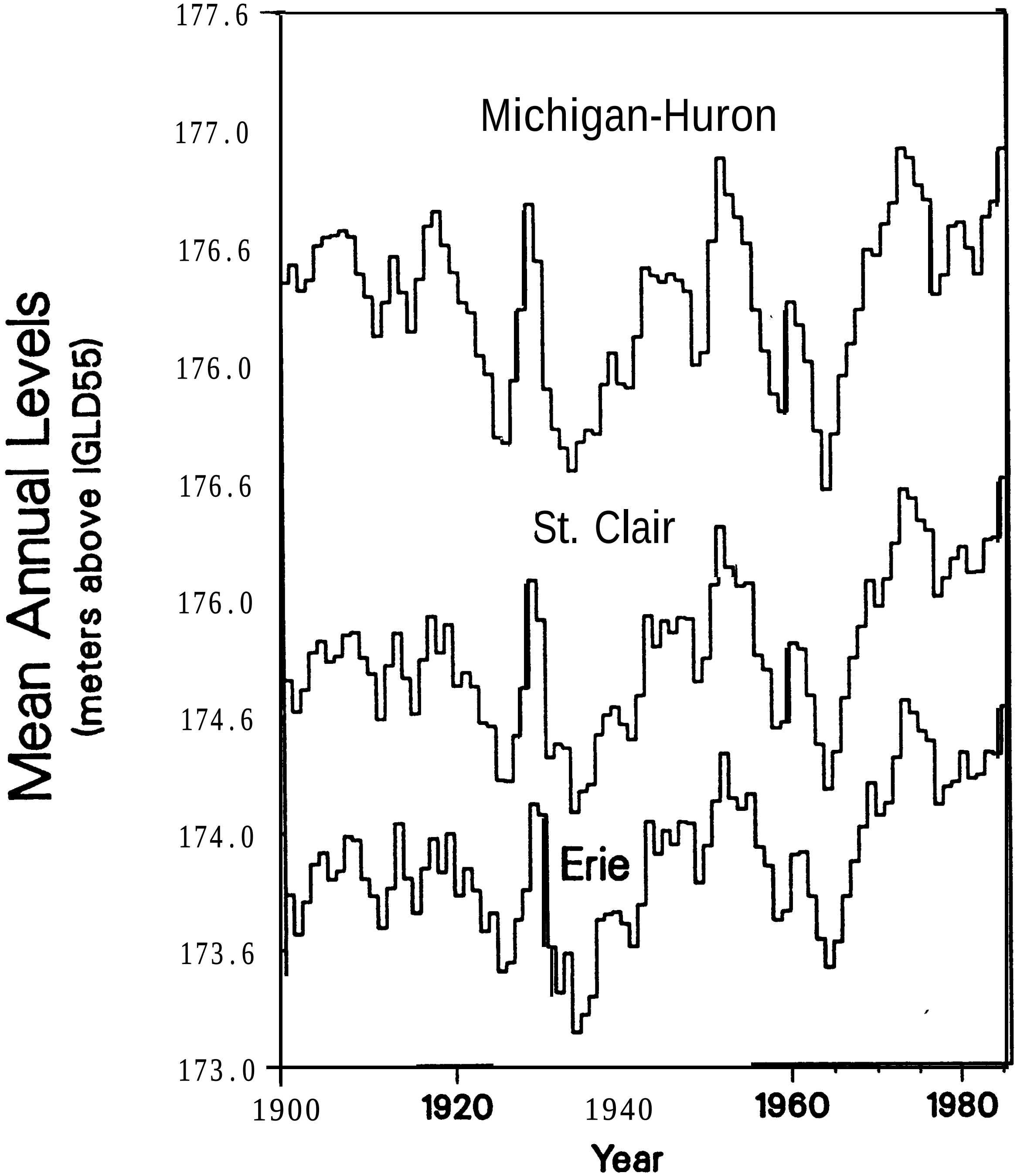

Figure 3. --Mean annual water levels of Lakes Michigan-Huron, St. Clair, and Erie for 1900-1985.

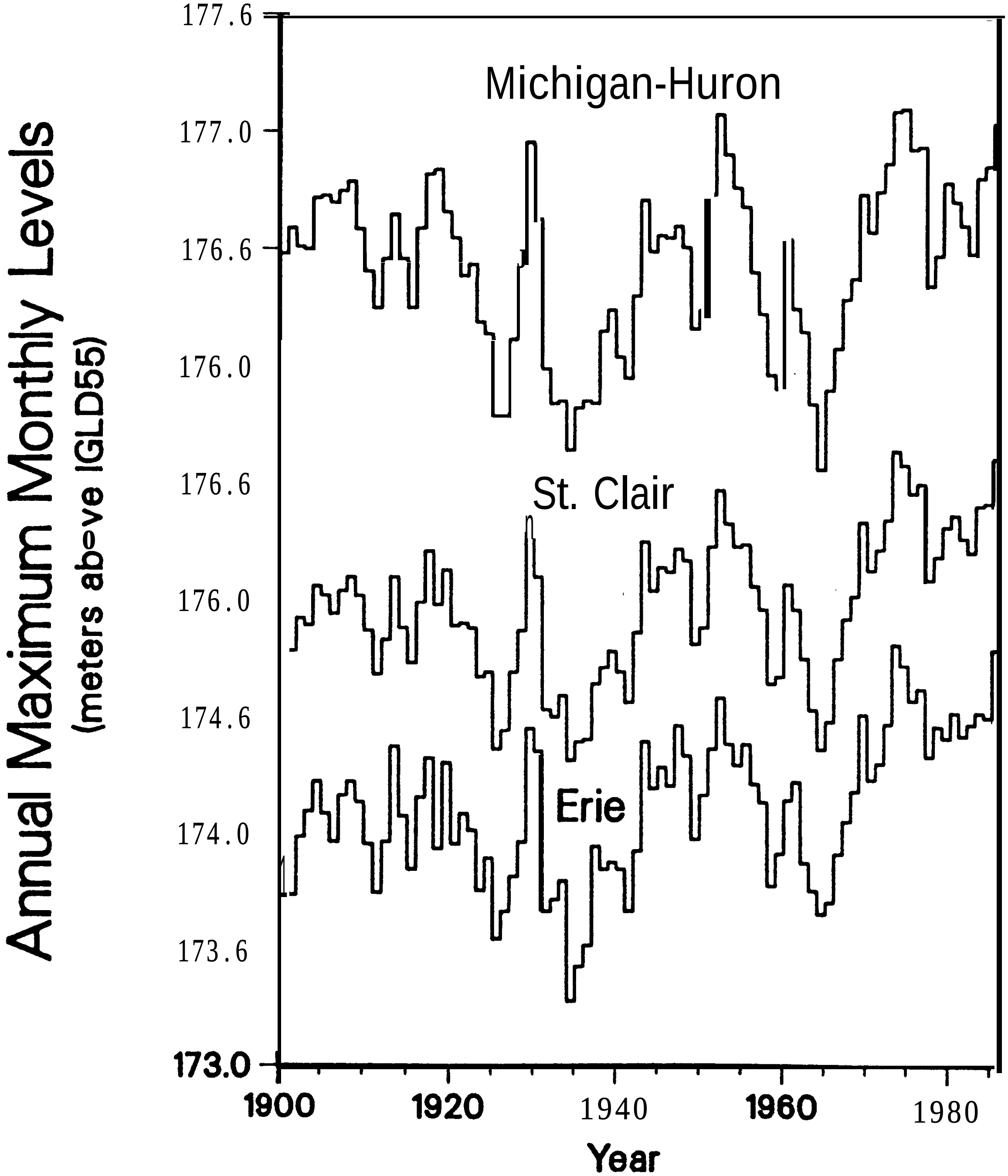

Figure 4. --Annual maximum monthly water levels of Lakes Michigan-Huron, St. Clair, and Erie for 1900-1985.

precipitation, lake evaporation), such data are complete only through 1979. Thus, except where noted, all simulations simply use net basin supplies derived from a water balance based on connecting channel flows and lake levels. Mean annual net basin supplies to each of the lakes are shown as an equivalent depth over the lake in Fig. 5 for 1900-1985; note that Lake St. Clair net basin supplies begin only in 1910. The simulations also use mean monthly inflows from the St. Marys River. The Chicago and the Welland Canal are considered only after 1939 and 1944, respectively, since their diversion regimes were quite different prior to those dates. Similarly, all runs use mean ice retardation rates only for 1937-1981 for the St. Clair and Detroit Rivers, since the effects of ice on flows through those rivers have not been determined for other periods. No ice effects are considered for the Niagara River, because the ice boom effectively eliminates ice retardation of flows in that river.

The effects on subsequent lake level simulations of using these shortened periods of data for determining mean diversions, ice retardation rates, and Lake St. Clair net basin supplies are difficult to estimate. The diversions and Niagara River ice retardation rates for the periods described herein are more appropriate than using the entire period of record since they better represent expected future conditions. However, the mean Lake St. Clair net basin supplies described herein probably cause simulated lake levels to be slightly higher than if supplies for 1900-1909 were available, since the 1900-1909 supplies probably were below normal as suggested by Lake Michigan-Huron and Erie net basin supplies over that period. The use of the relatively short period of ice retardation rates for the St. Clair and Detroit Rivers probably has little effect on simulated mean annual levels and annual maximum monthly levels, because ice jams generally have little effect on large Lake Michigan-Huron and have only transitory effects during late winter or early spring on Lake St. Clair.

3.1 Falling Lake Levels

To examine the potential for the unregulated Great Lakes to return to more moderate levels, four hydrometeorologic simulations were used with the HRM (Figs. 6-8). The first simulation considered water supplies trending toward the long-term average. Mean monthly values of St. Marys River flows and net basin supplies to Lakes Michigan-Huron, St. Clair, and Erie were computed for 1900-1985 and used as a continuously repeating water supply scenario for a 20-year period beginning in 1986. As noted previously, the Lake St. Clair net basin supplies, Chicago and Welland Canal diversions, and ice retardation means are based on somewhat different periods owing to data applicability and availability constraints. Figure 6 ("OO-85") shows the monthly net basin supplies to Lakes Michigan-Huron, St. Clair, and Erie used as input for the simulation. Figures 7 and 8 ("1900-1985") show the effect on lake levels of receiving monthly water supplies equivalent to the mean monthly supplies of 1900-1985. Under this scenario, Lake Michigan-Huron falls to within 0.15 m of the 1900-1969 mean annual level ("Normal") after 6 years, whereas for such a drop in Lake St. Clair and Erie levels 9 to 10 years are required. Because of the constant annual supplies used each year in the simulation, the system eventually reaches steady state. Each of the lakes

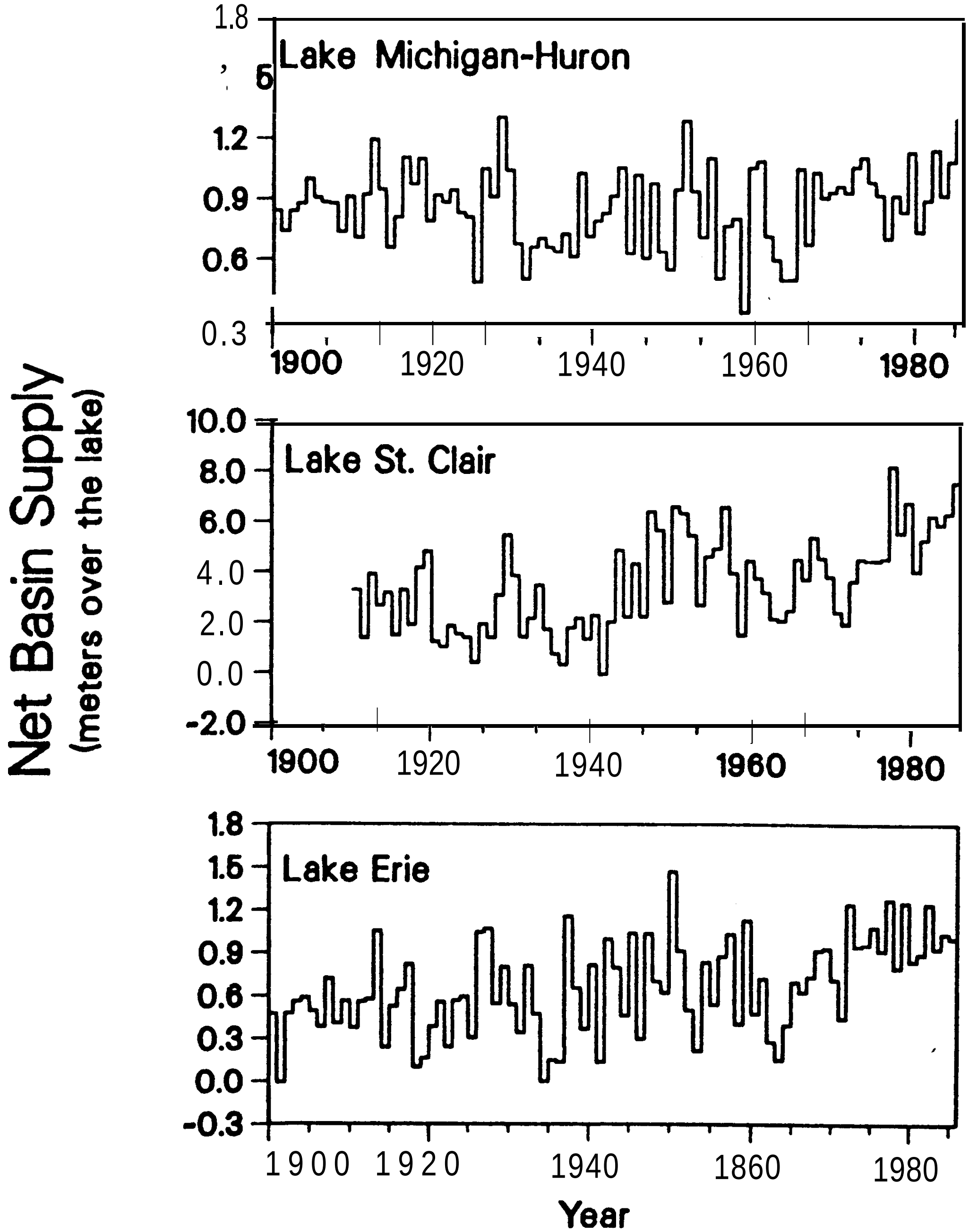

Figure 5. --Mean annual net basin supplies to Lakes Michigan-Huron, St. Clair, and Erie for 1900-1985.

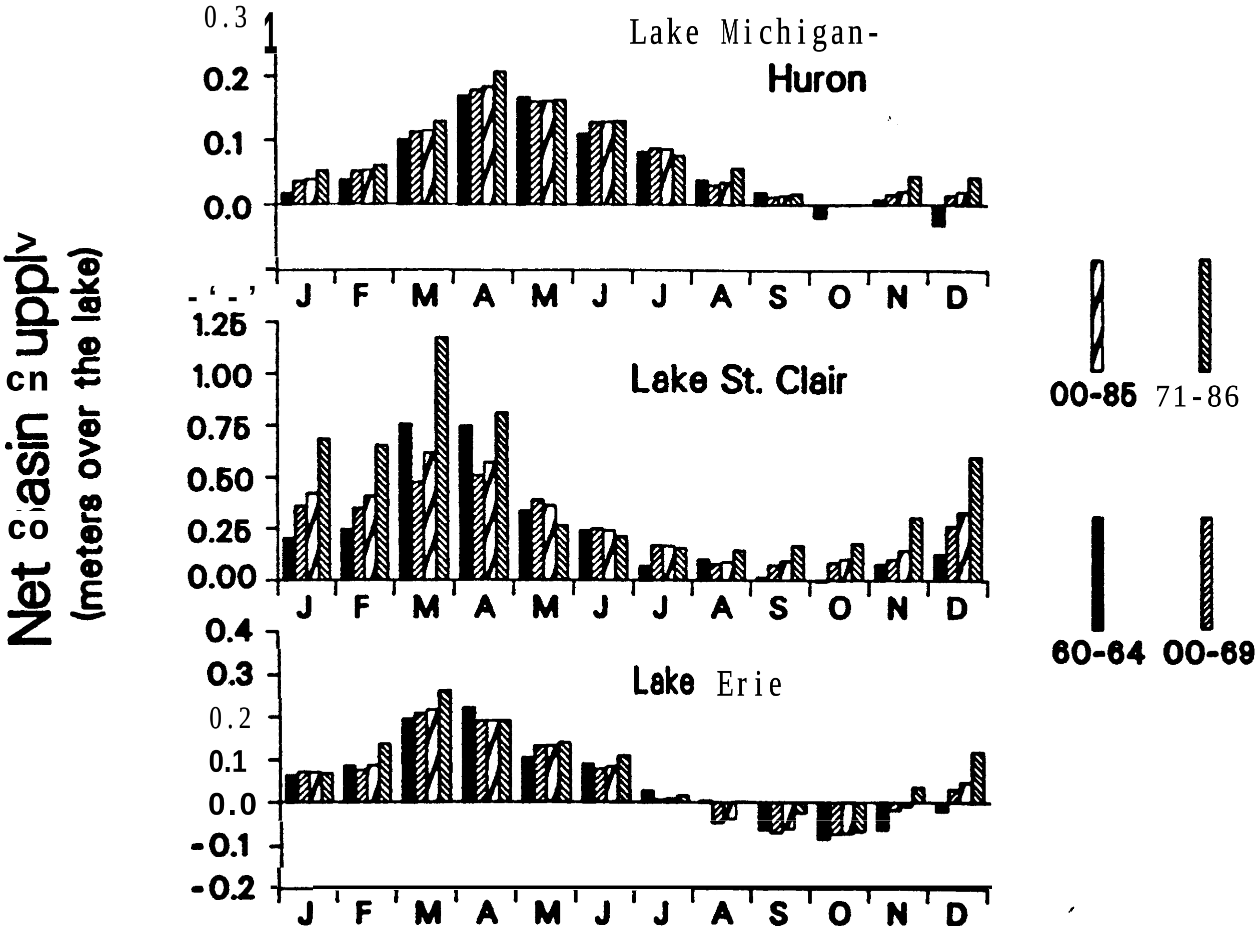

Figure 6. --Monthly net basin supplies to Lakes Michigan-Huron, St. Clair, and Erie used in simulations of falling lake levels.

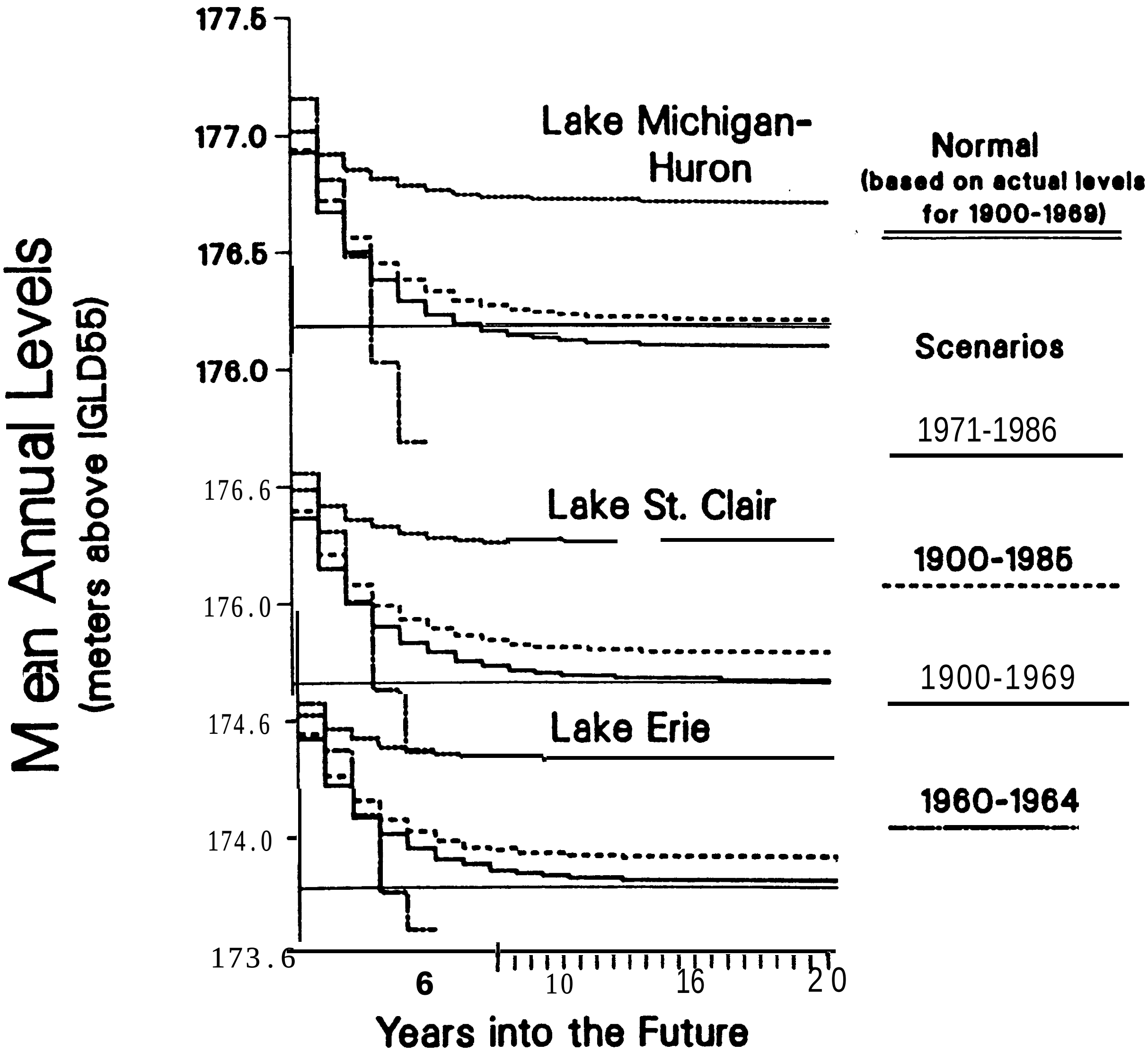

Figure 7. --Mean annual water levels of Lakes Michigan-Huron, St. Clair, and Erie resulting from scenarios of low and moderate water supplies.

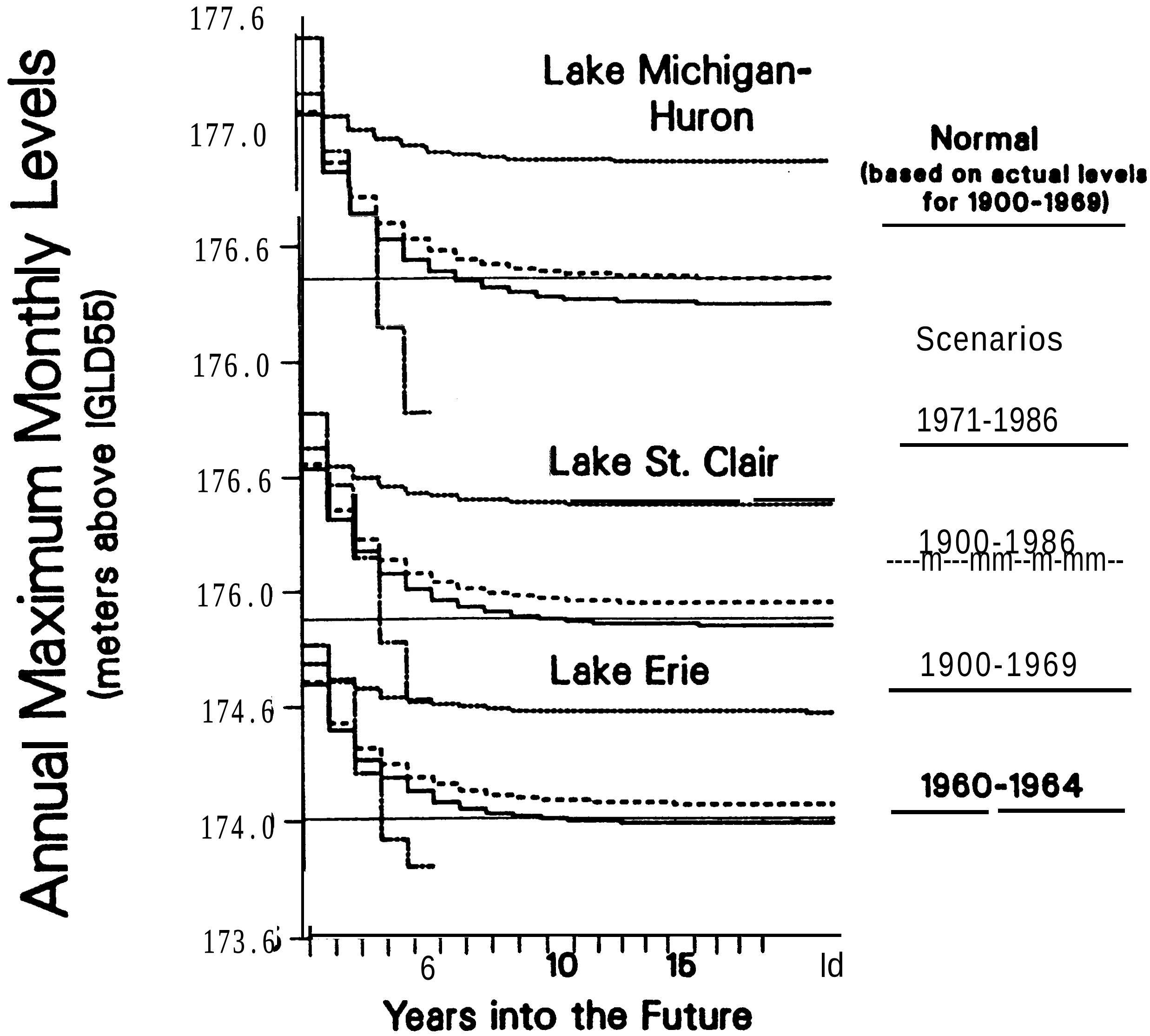

Figure 8. --Annual maximum monthly water levels of Lakes Michigan-Huron, St. Clair, and Erie resulting from scenarios of low and moderate water supplies.

remains above its 1900-1969 mean annual level; Lake Michigan-Huron exceeds it by about 0.03 m, and Lakes St. Clair and Erie exceed them by 0.12 to 0.13 m. Whereas annual maximum monthly levels (Fig. 8) on Lake Michigan-Huron return to the 1900-1969 mean maximum level ("Normal"), those on Lakes St. Clair and Erie remain 0.06 to 0.07 m above the mean maximum levels. Lake Michigan-Huron falls farther than the other lakes in relation to the 1900-1985 and 1900-1969 normal levels; this results because the Michigan-Huron "normal" levels are higher than could be reached currently under similar water supply conditions, owing to the smaller discharge capacity of the St. Clair River during the early 1900s (Derecki, 1985).

The second simulation considers average water supply conditions prior to the change in the Great Lakes region's climatic regime. Mean monthly St. Marys River flows and net basin supplies were computed for 1900-1969 and used as a repetitive water supply scenario for a 20-year period beginning January 1986. As before, net basin supplies for Lake St. Clair, diversions, and ice retardation means are based on somewhat different periods. Figure 6 ("00-69") shows the monthly net basin supplies to each of the lakes used in this simulation. Figures 7 and 8 ("1900-1969") show the effect on lake levels of receiving monthly water supplies equivalent to the mean monthly supplies of 1900-1969. Under this scenario, Lake Michigan-Huron returns to its 1900-1969 mean annual level ("Normal") within 7 years, and the remaining lakes require 9 to 11 years to return to within 0.05 m of their 1900-1969 mean annual levels ("Normal"). Lake Michigan-Huron maximum monthly levels fall to the 1900-1969 mean maximum monthly level ("Normal") within 6 years. Lake St. Clair and Erie maximum monthly levels return to the 1900-1969 mean maximum monthly levels ("Normal") within about 9 years.

The third simulation considers the effect on water levels of a drought like that experienced in the early 1960s. Mean supplies are not used over this short period; rather, the actual sequence of water supplies experienced during 1960-1964 are used directly. Additionally, since net basin supply components are available throughout this period, they are used rather than the net basin supplies derived from the water balance. Likewise, actual diversions and ice retardation rates for 1960-1964 are used in the simulation. Precipitation over the Lake Michigan-Huron, St. Clair, and Erie basins throughout this period was about 7% less than the 1900-1985 mean. Figure 6 ("60-64") shows the mean of the monthly supplies used in the simulation. Figures 7 and 8 ("1960-1964") show the effect on lake levels of water supplies like those received for 1960-1964. Under this scenario, each lake drops to its 1900-1969 mean annual level ("Normal") within 4 years. After 5 years, Lakes Michigan-Huron, St. Clair, and Erie are 0.49, 0.29, and 0.18 m, respectively, below their 1900-1969 mean annual levels. Under these drought conditions, the maximum monthly levels fall at a similar rate, and after 5 years drop to 0.58, 0.35, and 0.21 m below the 1900-1969 mean maximum monthly levels ("Normal") for Lakes Michigan-Huron, St. Clair, and Erie, respectively. However, Figs. 7 and 8 show that this scenario produces higher water levels during the first year than other scenarios; this is due to the relatively high precipitation of 1960, although 1960-1964 is considered a period of drought. Thus, the lakes may fall to the 1900-1969 mean levels within only about 3 years, if a drought like that of 1961-1964 is not preceded by a year like 1960.

The fourth simulation reflects water supply conditions trending toward the recent average. Mean monthly values of St. Marys River flows, net basin supplies, and the Chicago and Welland Canal diversions were computed for 1971-1985, and used as a continuous water supply sequence for a 20-year period beginning January 1986; ice retardation of flows was determined as for the first two simulations. Precipitation over the Lake Michigan-Huron, St. Clair, and Erie basins throughout this period was about 7% greater than the 1900-1985 mean and about 9% greater than the 1900-1969 mean. Figure 6 ("71-85") shows the monthly net basin supplies to each of the lakes used as input for the simulation. Figures 7 and 8 ("1971-1985") show the effect of receiving monthly water supplies equivalent to the mean monthly supplies of 1971-1985. Under this scenario, lake levels fall slowly, but never return to the 1900-1969 mean annual levels. The system reaches equilibrium in 9 to 14 years, and Lakes Michigan-Huron, St. Clair, and Erie stabilize at 0.53, 0.59, and 0.54 m, respectively, above their 1900-1969 mean annual levels ("Normal"). Likewise, the maximum monthly levels stabilize at 0.50, 0.50, and 0.47 m above the 1900-1969 mean maximum monthly levels ("Normal") for Lakes Michigan-Huron, St. Clair, and Erie, respectively.

The four preceding simulations suggest that persistent extreme drought conditions, such as those occurring in the early 1960s, are required for the unregulated Great Lakes to return to their perceived normal water levels (mean levels for 1900-1969). The fastest the lakes can be expected to fall in a single year, as indicated by the drought scenario, is 0.50, 0.37, and 0.40 m, respectively, for Lakes Michigan-Huron, St. Clair, and Erie. However, if the recent (1971-1985) Great Lakes climate actually is more typical of the long-term regional climatology than the climate of the first 70 years of this century, the resulting lake level regime could be about 0.5 m above the perceived normal lake levels. Even without reliable weather forecasts for the next 5 years, these scenarios suggest that riparians should not count on lake levels returning to their perceived normal levels within the next several years unless we have an abnormally dry period.

3.2 Rising Lake Levels

In 1986, Lakes Michigan-Huron, St. Clair, and Erie reached their highest monthly levels recorded this century (U.S. Army Corps of Engineers, 1986a,b,c,d); these record monthly levels and the highest annual levels experienced since 1900 are listed in Table 3. Geologic evaluations of ancient Lake Michigan shorelines (Larsen, 1985; Devine, 1987) suggest that water levels on that lake have exceeded the 1986 high levels by more than a meter several times during the last 2000 years, prompting concerns that the lakes may continue to rise above their present high levels. The potential response of the middle Great Lakes to continued high water supplies is indicated by using the HRM for five water supply simulations.

The first simulation considers water supplies similar to those of 1985. Actual monthly values of net basin supplies, St. Marys River flows, and diversions for 1985 were used as a continuously repeating water supply sequence for a 20-year period beginning January 1986. As for earlier simulations, flow retardations due to ice were computed as the mean monthly

Table 3. --Highest lake levels recorded for 1900-1986

Lake	Annual water level (m above IGLD55*)	Monthly water level (m above IGLD55*)
Michigan-Huron	177.08 (1986)	177.28 (Oct. 1986)
St. Clair	175.66 (1986)	175.77 (Oct. 1986)
Erie	174.71 (1986)	174.86 (Jun. 1986)

* International Great Lakes Datum of 1955.

values for 1937-1981 for the St. Clair and Detroit Rivers, and were considered negligible for the Niagara River. During 1985, precipitation over the Lake Michigan-Huron, St. Clair, and Erie basins was about 26% above the 1900-1985 mean and about 28% above the 1900-1969 mean. However, combined net basin supplies to the lakes were about 53% above the 1900-1985 mean and about 60% above the 1900-1969 mean. Figure 9 ("1985") shows the monthly net basin supplies to Lakes Michigan-Huron, St. Clair, and Erie used as input for the simulation. Under this scenario, Lakes Michigan-Huron and St. Clair rise to 1.0 m above their 1900-1969 mean annual levels of Table 2 within 2 years, whereas Lake Erie reaches 1.0 m above its 1900-1969 mean annual level of Table 2 within 4 years. The lakes stabilize in 10 to 11 years at about 1.4, 1.3, and 1.1 m, respectively, above their 1900-1969 mean annual levels of Table 2. The curves "1985" in Figs. 10 and 11 compare the simulated lake levels with the record high levels of Table 3 ("Record" in Figs. 10 and 11). Each lake meets or exceeds its highest monthly level experienced since 1900; Lake Michigan-Huron does so in the first year, Lake St. Clair in the second, and Lake Erie in the third. When the system reaches equilibrium, maximum monthly levels on each lake are 0.46, 0.31, and 0.19 m, respectively, above the highest monthly levels experienced since 1900, and the annual levels are 0.46, 0.26, and 0.16 m, respectively, above the highest annual levels experienced since 1900.

The second simulation considers water supplies that are moderately more extreme than the long-term average. The mean monthly St. Marys River flows and net basin supplies, determined for 1900-1985, were increased by 25% and used as a continuously repeating water supply scenario for a 20-year period beginning January 1986. Monthly mean diversions and ice retardation of flows, based on somewhat different periods because of the data applicability and availability constraints described earlier, remained unchanged from earlier simulations. Figure 9 ("+25%") shows the monthly net basin supplies to each of the lakes used as input for the simulation. Under this scenario, annual levels and maximum monthly levels on each of the lakes stabilize practically within the first year. Both'mean annual and maximum monthly levels on Lakes Michigan-Huron, St. Clair, and Erie stay at about 1.0, 0.9, and 0.8 m above their 1900-1969 means of Table 2, respectively. The curves "+25%" in Figs. 10 and 11 compare the simulated lake levels with the record high levels of Table

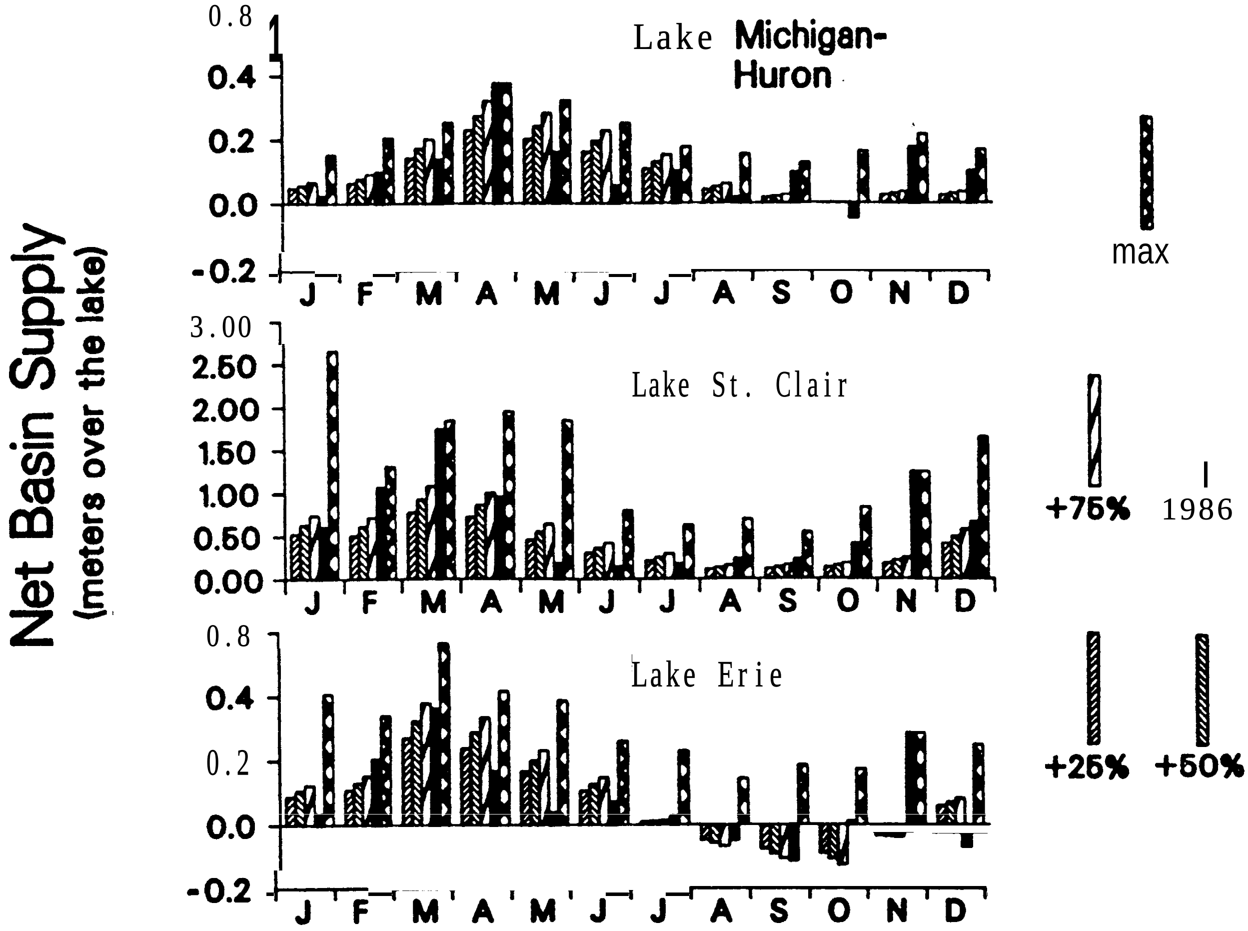

Figure 9. --Monthly net basin supplies to Lakes Michigan-Huron, St. Clair, and Erie used in simulations of rising lake levels.

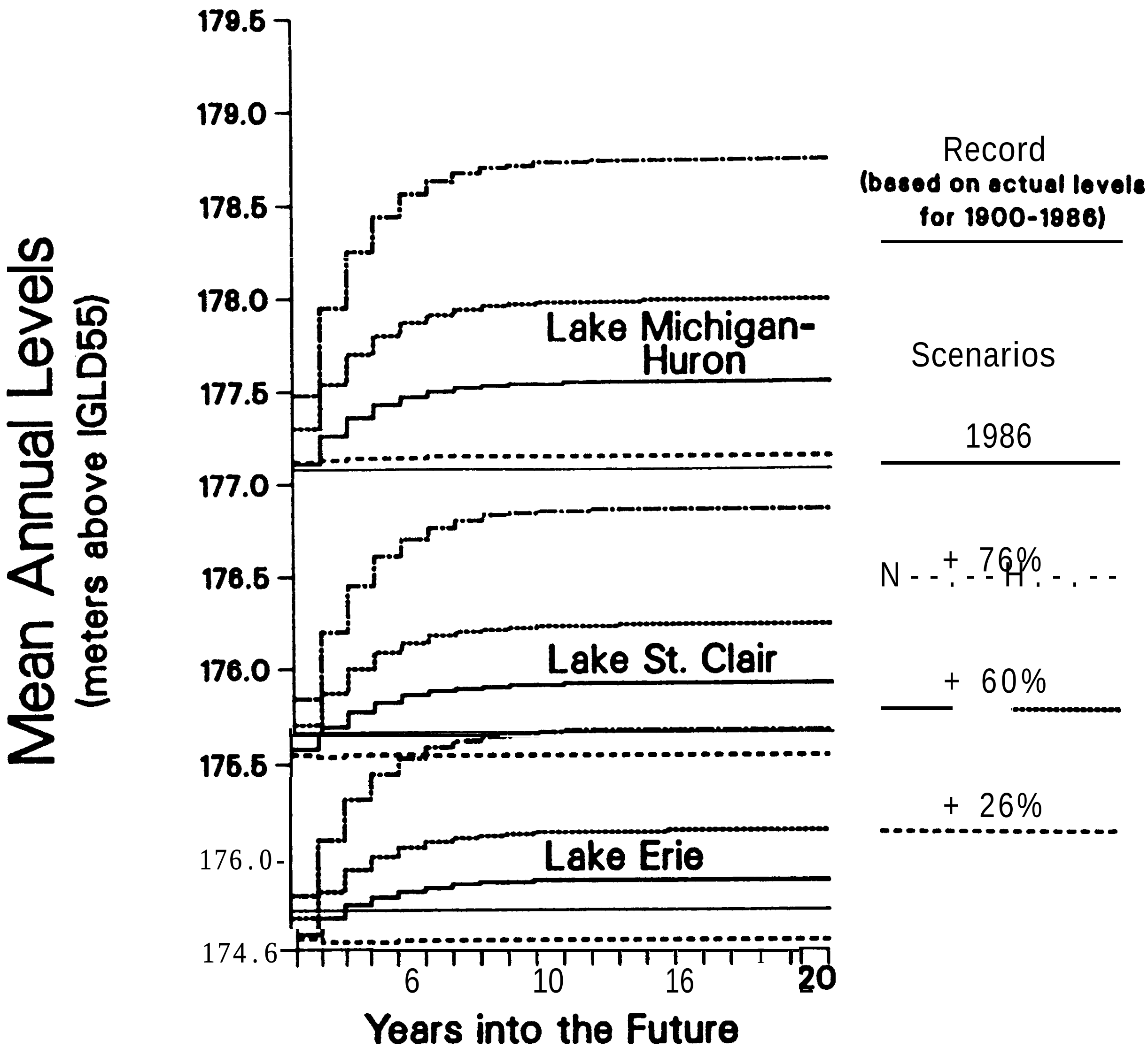

Figure 10.--Mean annual water levels on Lakes Michigan-Huron, St. Clair, and Erie resulting from scenarios of high water supplies.

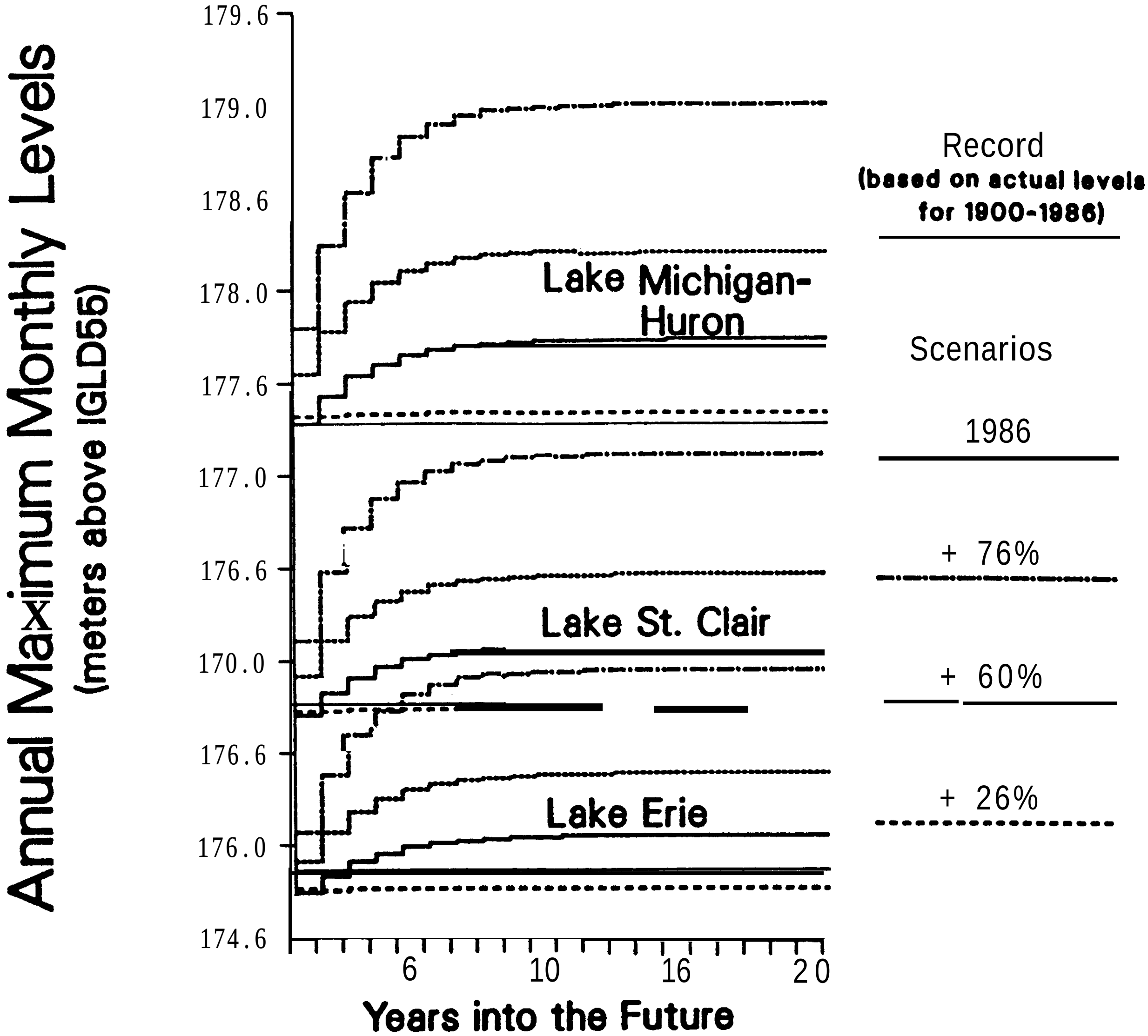

Figure 11. --Annual maximum monthly water levels on Lakes Michigan-Huron, St. Clair, and Erie resulting from scenarios of high water supplies.

3 ("Record" in Figs. 10 and 11). Annual levels on Lake Michigan-Huron rise to only 0.07 m above the highest annual level experienced since 1900, and annual levels on Lake St. Clair and Erie, respectively, remain 0.11 and 0.16 m below their highest annual levels. Maximum monthly levels on Lake Michigan-Huron rise to only about 0.06 m above the highest monthly level experienced since 1900, and maximum monthly levels on Lakes St. Clair and Erie, respectively, remain 0.03 and 0.10 m below the highest monthly levels experienced on those lakes.

The third simulation reflects water supply conditions significantly more extreme than the long-term average. The 1900-1985 mean monthly St. Marys River flows and net basin supplies were increased by 50% and used as a repetitive water supply scenario for a 20-year period beginning January 1986. As before, diversions and ice retardation of flows remained unchanged. Figure 9 ("+50%") shows the monthly net basin supplies to each of the lakes used as input for the simulation. This scenario results in higher levels than a repeat of the 1985 net basin supply conditions, since the St. Marys River flows are increased as well. The annual levels of Lakes Michigan-Huron and St. Clair rise to about 1.5 m above their 1900-1969 mean annual levels of Table 2 within 3 and 6 years, respectively. Lakes Michigan-Huron, St. Clair, and Erie stabilize at about 1.8, 1.6, and 1.4 m, respectively, above their 1900-1969 mean annual levels of Table 2 and about 0.9, 0.6, and 0.4 m, respectively, above their highest annual levels experienced since 1900 (Table 3 and Fig. 10). The curves "+50%" in Figs. 10 and 11 compare the simulated lake levels with the record high levels of Table 3 ("Record" in Figs. 10 and 11). Each lake sets new monthly water level records within the first year of the simulation. Monthly levels on Lakes Michigan-Huron, St. Clair, and Erie exceed their highest levels experienced since 1900 by 0.5 m in 2, 4, and 8 years, respectively. At equilibrium, the maximum monthly levels for each lake exceed the highest monthly levels experienced since 1900 by 0.94, 0.70, and 0.53 m, respectively.

The fourth simulation considers water supplies very much more extreme than the long-term average. The 1900-1985 mean monthly St. Marys River flows and net basin supplies were increased by 75% and used as a repetitive water supply scenario for a 20-year period beginning January 1986; diversions and ice effects remained unchanged. Figure 9 ("+75%") shows the monthly net basin supplies to each of the lakes used as input for the simulation. Annual levels of Lakes Michigan-Huron and St. Clair rise to 2.0 m above the 1900-1969 mean annual levels of Table 2 within 3 and 5 years, respectively. Lakes Michigan-Huron, St. Clair, and Erie stabilize at about 2.6, 2.2, and 1.9 m, respectively, above their 1900-1969 mean annual levels of Table 2 and about 1.8, 1.2, and 1.0 m, respectively, above their highest annual levels experienced since 1900 (Table 3 and Fig. 10). The curves "+75%" in Figs. 10 and 11 compare the simulated lake levels with the record high levels of Table 3 ("Record" in Figs. 10 and 11). Monthly levels on Lakes Michigan-Huron, St. Clair, and Erie exceed the highest monthly levels experienced since 1900 by 0.5 m in 1, 2, and 3 years, respectively. At equilibrium, the maximum monthly levels for each lake exceed the highest monthly levels experienced since 1900 by about 1.7, 1.4, and 1.1 m, respectively.

The fifth simulation reflects some sort of "worst case" water supply scenario. Maximum monthly St. Marys River flows and net basin supplies first were determined for 1900-1985. Then, the respective maximums for each month were used as a continuous water supply scenario for a 20-year period beginning January 1986. Diversions and ice effects remain unchanged from previous simulations. Figure 9 ("max") shows the monthly net basin supplies to each of the lakes used as input for the simulation. Each lake's annual level exceeds its respective 1900-1969 mean annual level of Table 2 by 2.0 m within 3 years. Their annual levels eventually reach about 4.5, 4.0, and 3.7 m higher, respectively, than their 1900-1969 mean annual levels of Table 2. Although the simulated lake levels are not shown, they are compared herein with the record high levels of Table 3. Each lake's annual level rises to more than 2.0 m above the highest annual level experienced since 1900 within 2 years, and stabilizes at about 3.6, 3.0, and 2.7 m, respectively, above the highest annual levels experienced since 1900. The maximum monthly levels for each of the lakes exceed the levels resulting from any of the other simulations. Lake Michigan-Huron eventually reaches a monthly elevation of 180.87 m, exceeding by about 3.6 m the highest monthly level experienced on that lake since 1900. Lake St. Clair eventually exceeds its previous record monthly level by about 3.1 m. Lake Erie finally reaches an elevation of 177.62 m; not only does this level exceed the previous Lake Erie monthly water level record by about 2.8 m, it also exceeds by about 0.34 m the highest Lake Michigan-Huron monthly level experienced since 1900.

These five simulations indicate the extreme nature of water supply conditions required to raise the middle Great Lakes to levels that the geologic record suggests have occurred several times in the past 2000 years. Under each of the scenarios, Lake Michigan-Huron rises more than Lakes St. Clair and Erie. A persistent recurrence of the water supply conditions of 1985 would raise Lake Michigan-Huron only about 0.5 m above the record monthly level experienced in 1986. To raise the lake 1.0 m above 1986's record monthly level, the conditions of 1985 would have to be augmented by a 50% increase in outflows from Lake Superior, and such extreme conditions would have *to* persist for about 10 years. Even if Lake Superior outflows and net basin supplies to the unregulated lakes were 75% above the long-term (1900-1985) average, such extreme conditions would have to occur consecutively for 2 years to raise Lake Michigan-Huron by even 0.5 m.

4. HUMAN EFFECTS ON LAKE LEVELS

4.1 Lake Superior Regulation Modifications

In 1977, the International Joint Commission (IJC) mandated that the International Lake Superior Board of Control (ILSBC) devise an updated regulation plan for Lake Superior that would consider the effects of the regulations on Lake Michigan-Huron, in addition to the requirements of the 1914 IJC Orders of Approval (ILSBC, 1982). The ILSBC developed Plan 1977, which includes an operational restriction that Lake Superior outflows from December through April must not exceed 2407 m^3/s (85,000 ft^3/s). During the winter, Great Lakes levels are lowest (Croley, 1986), being on average about 37, 54, and 52 cm lower than the seasonal peak levels on Lakes Michigan-Huron, St. Clair, and Erie, respectively. Suggestions have been made that maximum monthly water levels on the lower Great Lakes may be reduced by increasing the passage of water through the system during seasonal periods of relatively low water levels (F. Quinn, GLERL, personal communication, 1987).

One proposal calls for increasing Lake Superior outflows to 2690 m^3/s (95,000 ft 3/s) from December through March and then storing water on Lake Superior from April through July, by an amount equivalent to the excess water released in the winter. To assess the effects of such a change in Lake Superior regulations, a base simulation first was generated starting with actual lake levels of 1 August 1979 and using average monthly net basin supplies, diversions, and St. Marys River flows determined for 1980-1986; St. Clair and Detroit River ice retardation rates were determined for 1937-1981, and no ice retardation was considered for the Niagara River, for reasons described previously. St. Marys River flows for December through March, respectively, averaged 2174 m^3/s (77,000 ft^3/s), 2042 m^3/s (72,000 ft^3/s), 2028 m^3/s (72,000 ft^3/s), and 2065 m^3/s (73,000 ft^3/s). In a subsequent simulation, net basin supplies, diversions, and ice retardations remained identical, but the St. Marys River flows for December through March were adjusted to a constant rate of 2690 m^3/s (95,000 ft^3/s). One-quarter of the total departure between the adjusted winter flows and the 1980-1986 monthly means was then subtracted from the mean monthly flows for each of the 4 subsequent months (April through July) to simulate storage of water on Lake Superior.

This scenario produces no practical difference in either annual lake levels or peak monthly levels. Annual levels are raised by 1 cm on each of the lakes. The peak monthly level on Lake Michigan-Huron is decreased by 1 cm, but peak monthly levels are raised by 1 cm on Lakes St. Clair and Erie.

4.2 Diversion Modifications

Great Lakes levels are affected by several diversions to, from, and within the system. The Long Lac and Ogoki diversions route water from the Hudson Bay watershed into Lake Superior, at a combined rate that averages about 159 m^3/s (5600 ft^3/s). The Chicago diversion routes water from Lake Michigan-Huron into the Mississippi River basin, at an average rate of about 91 m^3/s (3200 ft^3/s). The Welland Canal diversion effectively increases Lake Erie outflows into Lake Ontario by providing an alternate route that bypasses Niagara Falls; the Welland Canal diversion rate has recently averaged about 261 m^3/s (9200 ft^3/s). Table 4 presents the increase in long-term water levels of Lakes Michigan-Huron and Erie due to these diversions.

During the period of high water levels in 1985 and 1986, proposals were made for lowering Great Lakes levels by modifying the rates of the existing diversions (Great Lakes Coalition, 1986; Ozanne, 1987; Urquhart, 1987). Proposed strategies have included eliminating the diversions into Lake Superior, increasing the Chicago diversion to 283 m^3/s (10,000 ft^3/s), and increasing flows through the Welland Canal to the maximum possible, about 283 m^3/s (10,000 ft^3/s) (D. Schweigert, USACE, personal communication, 1987). To compare the effects of these diversion changes, a base simulation first was generated using actual net basin supplies, St. Marys River flows, diversions,

Table 4.--Increase in long-term Great Lakes mean water levels due to existing diversions*

Diversion	Rate (m^3/s)	Lake Michigan-Huron (cm)	Lake Erie (cm)
Long Lac/Ogoki	159	+11.3	+7.6
Chicago	91	-6.4	-4.3
Welland Canal	266!	-5.5	-13.4
Combined		-0.6	-10.1

* From IJC (1985).
! Although the IJC (1985) evaluated a Welland Canal diversion rate of 266 m^3/s, the present rate of 260 m^3/s has practically identical effects.

and ice retardations for 1962-1980. Then, each of the diversion changes was considered separately; the Long Lac-Ogoki diversion change was reflected by decreasing St. Marys River flows by 159 m^3/s (5,600 ft^3/s) each month. Additionally, another simulation was generated, which incorporated all three diversion modifications.

The full effect of a change in diversions does not occur immediately after the change is made; instead, some time is required for the lake levels and lake outflows to adjust to the new diversion regime and for the ultimate effect of the diversion change to be realized. Because of the extremely large volumes of the Great Lakes relative to their connecting channel flow capacities, the lakes generally respond very slowly to changes in diversions. Because the scenarios examined herein are compared with a base case using actual diversion rates that vary from month to month, the effects of the diversion changes do not reach equilibrium. Thus, the scenarios provide only an indication of the magnitude of the effects of diversion modifications, rather than the expected ultimate effect on levels should the diversion changes be instituted.

Of the scenarios examined herein, the most rapid change in lake levels results from the increase of Welland Canal diversions, but the effects are quite small. The largest effect occurs on Lake Erie in 1964, where the annual water level is lowered by 4.5 cm; thereafter, Lake Erie annual levels fluctuate between 1.9 and 4.2 cm lower; Lake St. Clair, between 1.4 and 2.9 cm lower; and Lake Michigan-H&on between 0.8 and 1.2 cm lower. Increases in the Chicago diversion lower the lake levels more slowly; about 50% of the total effect occurs in 2 to 3 years. After about 7 years, additional lowering of the lake levels due to the diversion change is very small; after 7 years, the decline in the annual levels of Lakes Michigan-Huron, St. Clair, and Erie, respectively, varies between 13.0 and 13.7 cm, 9.9 and 10.5 cm, and 8.0 and 8.7 cm. Elimination of the Long Lac and Ogoki diversions also requires about 2 to 3 years for 50% of the total effect on lake levels to be realized, and after about 7 years further effects of the diversion elimination are very small. After 7 years, the decline in the annual levels of Lakes Michigan-Huron, St. Clair, and Erie, respectively, varied between 10.7 and 11.1 cm, 8.2 and 8.6 cm, and 6.6 and 7.1 cm. As expected, the largest lowering of Great

Lakes levels results from the combined effect of all three diversion scenarios, but still only half the effect occurs within 2 to 3 years, and after about 7 years any further lowering of the lake levels is very small. After 7 years, the decline in the annual levels of Lakes Michigan-Huron, St. Clair, and Erie, respectively, varies between 25.0 and 26.0 cm, 20.2 and 21.4 cm, and 17.3 and 18.9 cm. These scenarios represent maximum effects since actual implementation of the diversion strategies would be constrained by other considerations. Even closed completely, the long Lac and Ogoki diversion structures would probably leak about 23 m^3/s (800 ft^3/s); Chicago diversions would probably be limited to only about 246 m^3/s (8700 ft^3/s) as a result of potential flooding along the Illinois River.

Previous reports (Croley, 1986; Kirshner, 1968; Quinn, 1985) have indicated that 12 to 15 years are required for the entire effect to be felt from a diversion change from Lake Michigan-Huron. In theory, the progressive effect of a diversion change increases asymptotically toward a value that is never quite realized. Practically, however, after several years further changes in levels become so small that the system appears to have stabilized at a new equilibrium. Additionally, because the relationship between lake levels and connecting channel outflows is nonlinear, the effect of a diversion change depends on the levels of the lakes. This is shown by comparing the effects of increased Chicago diversions under scenarios of both high and low lake levels. First, a base simulation was generated using the actual monthly net basin supplies, St. Marys River flows, Welland Canal diversions, and ice retardations for 1973 (a period of high water supplies and lake levels) as a continuously repeating water supply scenario for a 19-year period beginning in January 1973. The base simulation used actual lake levels of January 1973 as initial conditions and a constant Chicago diversion of 91 m^3/s (3,200 ft/s). Then, the simulation was repeated, but using a constant Chicago diversion of 283 m^3/s (10,000 ft^3/s). A second base simulation was generated using actual monthly net basin supplies, St. Marys River flows, Welland Canal diversions, and ice retardations for 1962 (a period of low water supplies and lake levels) as a continuously repeating water supply scenario for a 19-year period beginning in January 1962. This base simulation used actual lake levels of January 1962 as initial conditions, but as before used a constant Chicago diversion of 91 m^3/s (3,200 ft^3/s). Then the simulation was repeated with a constant Chicago diversion of 283 m^3/s (10,000 ft/s).

Table 5 shows the progressive effect on Lake Michigan-Huron's annual levels of increasing the Chicago diversion under these high and low lake level conditions. For both cases, although the progressive effect of the additional diversion continues to increase throughout the simulation period, after several years the additional effects become quite small. For the high lake level period of 1973, Lake Michigan-Huron's annual levels are lowered by 5.6 cm in the second year, 11.8 cm in the seventh year, and 12.9 cm in the nineteenth year. However, using the low lake level period of 1962, the lake's levels are lowered by 5.8 cm in the second year, 13.6 cm in the seventh year, and 16.3 cm in the nineteenth year. Thus, although effects of diversion changes are greater for low lake levels, the ultimate effect is approached more rapidly at high lake levels. The greater effect during periods of low lake levels results because the stage-discharge relationships for the unregulated Great Lakes are not linear; lake levels are more sensitive to changes in outflows at low levels than at high levels (increased diversions correspond to increased outflows).

Table 5. --Decrease in the annual levels of Lake Michigan-Huron resulting from an increase in the Chicago diversion from 91 m^3/s to 283 m^3/s using 1962 and 1973 for water supply and initial lake levels

Years into the future	1962 (cm)	1973 (cm)
1	2.3	2.1
2	5.8	5.6
3	8.4	7.9
5	11.7	10.6
7	13.6	11.8
12	15.7	12.7
15	16.1	12.8
19	16.3	12.9

Hartmann and Croley (1987) also examined the effects on water levels of modified diversions. They integrated rainfall-runoff models (Croley, 1983; Croley and Hartmann, 1984) for each lake basin, past sequences of daily meteorology, and the Lake Superior regulation plan in conjunction with the HRM to assess the effect of reducing the Long Lac and Ogoki diversions to 23 m^3/s (800 ft^3/s), increasing the Chicago diversion to 246 m^3/s (8700 ft^3/s), and increasing flows through the Welland Canal to 283 m^3/s (10,000 ft^3/s). Errors in the implementation of the regulation plan resulted in smaller effects on lake levels than would actually occur; updated results are presented herein. Effects of the diversion changes were compared with a probabilistic evaluation of 1986 lake levels (Hartmann and Croley, 1987). As a result of the large size of the Great Lakes relative to their outflow capacities and compensation of the regulated outflows from Lake Superior, the diversion strategy produced levels only slightly lower than the levels expected on the basis of past meteorology. For 1986, the modified diversions would have lowered expected levels on Lake Superior, Michigan-Huron, St. Clair, and Erie, respectively, by a maximum of 4.6, 5.3, 3.7, and 2.9 cm. An additional 283 m^3/s (10,000 ft^3/s) diversion out of Lake Michigan-Huron had slightly larger effects on the expected lake levels of 1986, producing maximum lowerings on Lakes Superior, Michigan-Huron, St. Clair, and Erie, respectively, of 4.6, 10.4, 7.1, and 5.5 cm. These effects are much smaller than the potential effects of meteorologic variability (due to recurrence of wet or dry historical meteorologic sequences) shown by Hartmann and Croley (1987), which were greater than 48, 52, 64, and 42 cm on Lakes Superior, Michigan-Huron, St. Clair, and Erie, respectively.

To evaluate the potential long-term effect of the diversion changes, Hartmann and Croley (1987) used the integrated models but with a single historical meteorologic sequence; they selected the 26-year sequence of

1954-1979 as one possible scenario. The diversion changes reduced lake levels by a maximum of 18, 25, 19, and 16 cm on Lakes Superior, Michigan-Huron, St. Clair, and Erie, respectively. During the drought conditions of the early 1960's, the diversion changes reduced levels by a maximum of 20 cm on Lake Michigan-Huron, compared with levels expected if no diversion changes were implemented; water levels remained above the record minimum levels by 28, 33, 41, and 46 cm, on Lakes Superior, Michigan-Huron, St. Clair, and Erie, respectively. If lake level thresholds (e.g., dropping below a level of 176.63 m [579.5 ft] on Lake Michigan-Huron) were used to trigger restoration of normal diversion rates, the effects of the diversion changes would be smaller. With an additional 283 m^3/s diversion out of Lake Michigan-Huron, maximum lake level reductions of 25, 45, 35, and 29 cm occur on Lakes Superior, Michigan-Huron, St. Clair, and Erie, respectively; effects during the drought conditions of the 1960's are somewhat smaller (17, 42, 33, and 27 cm, respectively). The levels still remained above record lows by 22, 13, 26, and 33 cm, respectively. Recurrence of the record of low levels of 1964 on Lake Michigan-Huron is avoided, even under a repeat of the drought meteorologic conditions, because the present Lake Superior regulation plan (Plan 1977) considers levels on Lake Michigan-Huron in determining outflows from Lake Superior. Previous regulation plans considered only Lake Superior levels. Because Plan 1977 tries to maintain both lakes near their respective long-term monthly levels, any lowering of the downstream lakes due to reduced water supplies (from drought conditions or increased diversions) results in increased Lake Superior outflows.

The diversion scenarios presented in this section suggest that even if the Long Lac and Ogoki diversions had been eliminated and the Chicago and Welland Canal diversions had been maintained at 283 m^3/s, the water levels of 1985 and 1986 still would have been very high. The small effects of the diversions (relative to natural fluctuations) and the long response time of the Great Lakes system preclude water level management by means of diversions. However, if the diversion changes are instituted, the Lake Superior regulation plan may help mitigate undue lowering of levels during periods of extended drought.

4.3 Niagara River Modifications

In response to the high Great Lakes water levels of the 1970s, the International Lake Erie Regulation Study Board (ILERSB) developed several plans for the limited regulation of Lake Erie (ILERSB, 1981). One of the plans, Niagara Plan 25-N, has received support by riparian interests (Great Lakes Coalition, 1986; Ozanne, 1987). Niagara Plan 25-N would increase the discharge capacity of the Niagara River by about 708 m^3/s (25,000 ft^3/s). To compare the effects of this scenario, a base simulation first was generated using actual net basin supplies, St. Marys River flows, diversions, and ice retardation rates for 1962-1980. Then, the discharge equation constants [C in Eq.(3)] for the Niagara River were increased by 10%, and another simulation was generated for the same period, representing a 10% increase in the Niagara River flow capacity. The largest reductions in water levels result for Lake Erie; the annual lake levels fall by 19 cm in 2 years, 22 cm in 5 years, and stabilize at 25 to 27 cm lower in 11 to 12 years. Lake St. Clair annual levels fall 12 cm in 2 years, 15 cm in 5 years, and stabilize at 17 to 19 cm lower in 12 years. Lake Michigan-Huron annual levels fall only 4 cm in 2 years and stabilize at 10 to 11 cm lower in 15 to 17 years. Maximum monthly levels fall at similar rates.

Had Plan 25-N been implemented in 1979 and used *to* continuously maintain a 10% increase in Niagara River flows through 1986, the highest monthly levels experienced on Lakes Michigan-Huron, St. Clair, and Erie in 1986 would have been 9, 16, and 24 cm lower, respectively. That effect on lake levels, however, would not have been sufficient to preclude high water levels during 1986. Maximum monthly levels on Lakes Michigan-Huron, St. Clair, and Erie in 1986, as affected by Plan 25-N, still would have been 83, 73, and 61 cm above each lake's respective 1900-1969 mean maximum monthly level.

4.4 The 1986 Barge Accident

on 7 August 1986, a shipping accident in the Niagara River caused a barge to lodge against the center pier of the Peace Bridge between Buffalo, New York, and Fort Erie, Ontario. High flow rates, storms, and equipment problems delayed removal of the barge until 19 December 1986. While lodged, the barge impeded flows in the Niagara River by about 198 m^3/s (7000 ft^3/s) (Pratt, 1987). To assess the effects of the barge on the levels of Lakes Michigan-Huron, St. Clair, and Erie, a base simulation first was generated for August 1986 through June 1987, using actual St. Marys River flows and net basin supplies to each of the lakes, constant Welland Canal and Chicago diversion rates of 261 m^3/s (9200 ft^3/s) and 91 m^3/s (3200 ft^3/s), respectively, and no ice retardation of flows for the simulation period. Then, the Niagara River discharge equation constants [C in Eq. (3)] were adjusted to reflect a 198 m^3/s reduction in the channel capacity at a water level of 174.75 m from August through December, and another simulation was generated for the same period. Thus, in the adjusted simulation, for the months of August through October, in Eq. (3) for the Niagara River, C = 197.44 m/s; for November and December, C = 203.04 m/s.

The two simulations show that the barge had only a minor and temporary effect on the levels of the unregulated Great Lakes; Lake Erie was most affected. Within 2 months after the barge was stranded, Lake Erie levels had risen by 3 cm because of the reduction in the Niagara River flow capacity. The maximum effect of the barge occurred in January 1987 when Lake Erie levels had been raised by 5 cm; by June, the effect of the barge had dissipated and Lake Erie levels were only 1 cm higher than if the barge accident had not occurred. In January 1987, Lakes St. Clair and Michigan-Huron levels had been raised by only 4 and 1 cm, respectively; by June, the effect of the barge was nil.

5. SUMMARY

The potential for Great Lakes water level changes was examined by using the GLERL Hydrologic Response Model with several hydrometeorologic and water management scenarios. No probabilities of occurrence are expressed for any of the hydrometeorologic scenarios. However, these scenarios suggest that Great

Lakes interests should not count on lake levels returning to long-term (1900-1969) normal levels within the next several years. Of the scenarios examined, only a drought similar to that of the early 1960's could return the Great Lakes to their normal levels of 1900-1969. If the Great Lakes regional climatology of 1971-1985 persists for several more years, riparians may have to adjust to "normal" levels about 0.5 m above the 1900-1969 mean levels. However, these scenarios also indicate the extreme nature of water supply conditions required to raise the Great Lakes to levels that the geologic record suggests have occurred several times in the past 2000 years; to raise Lake Michigan-Huron 1.0 m above its 1986 record monthly level, net basin supplies 50% above the long-term (1900-1985) average (similar to the conditions of 1985) would have to be accompanied by a 50% increase in outflows from Lake Superior, and such extreme conditions would have to persist for about 10 years.

Human effects can reduce Great Lakes levels only relatively little (compared with natural fluctuations) over the next several years. Increasing winter flows from Lake Superior to enable water storage on that lake in the spring and summer has practically no effect on lake levels. Likewise, the barge that accidentally was caught on the Peace Bridge in the Niagara River had no appreciable effect on lake levels, and the small effect has dissipated. Changes in Great Lakes diversions can reduce water levels, but the largest expected decreases in levels on Lakes Michigan-Huron, St. Clair, and Erie amount to only 25, 21, and 18 cm, respectively. That lowering requires the elimination of the Long Lac and Ogoki diversions and the increase of the Chicago and Welland Canal diversions to 283 m^3/s (10,000 ft^3/s), for a period of 7 to 8 years; half of the lowering would occur, however, in 2 to 3 years.

6. REFERENCES

Croley, T.E., II, 1983. Great Lakes basins (U.S.A.-Canada) runoff modeling. J. Hvdrol. 64:135-158.

Croley, T.E., II, 1986. Understanding recent high Great Lakes water levels. Proceedings of the Great Lakes Symposium. Ohio State University, Columbus, OH, 60-70.

Croley, T.E., II, and Hartmann, H.C., 1984. Lake Superior basin runoff modeling. NOAA Technical Memorandum ERL GLERL-50, Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 284 pp.

Derecki, J.A., 1985. Effect of channel changes in the St. Clair River during the present century. J. Great Lakes Res. 11(3):201-207.

Devine, J.F., 1987. Testimony regarding the record high levels of the Great Lakes. Hearings before the Subcommittee on Water Resources of the Committee on Public Works and Transportation, U.S. House of Representatives, Washington, DC, 520-523.

Great Lakes Coalition, 1986. Position paper on Great Lakes water level regulation and management. Wisconsin Lake Michigan Shoreline Chapter, Great Lakes Coalition, Sheboygan, WI, 34 pp.

Hartmann, H.C., and Croley, T.E., II, 1987. Great Lakes water management: Modeling hydrologic impacts. Preprint Volume of the Seventh Conference on Hydrometeorology. American Meteorological Society, Boston, MA, 174-177.

IJC (International Joint Commission), 1985. Great Lakes diversions and consumptive uses. Washington, DC, 82 pp.

ILERSB (International Lake Erie Regulation Study Board), 1981. Lake Erie water level study. International Joint Commission, Washington, DC, 231 pp.

ILSBC (International Lake Superior Board of Control), 1982. Operational guides of Plan 1977. International Joint Commission, Washington, DC, 52 pp.

Kirshner, L.D., 1968. Effects of diversions on the Great Lakes. Miscellaneous Paper 68-7, U.S. Lake Survey, U.S. Army Corps of Engineers, Detroit, MI, 34 pp.

Larsen, C.E., 1985. A stratigraphic study of beach features on the southwestern shore of Lake Michigan: New evidence of Holocene lake level fluctuations. Environmental Geology Notes 112, State Geological Survey Division, Illinois Department of Energy and Natural Resources, Champaign, IL, 31 pp.

Ozanne, R.W., 1987. Completing the regulation of the Great Lakes water levels. Wisconsin Lake Michigan Shoreline Chapter, Great Lakes Coalition, Sheboygan, WI, 5 pp.

Pratt, J., 1987. Great Lakes levels update no. 18. In Monthly Bulletin of Lake Levels for the Great Lakes. January 1987. U.S Army Corps of Engineers, Detroit District, Detroit, MI, 3-9.

Quinn, F.H., 1978. Hydrologic response model of the North American Great Lakes. J. Hydrol. 37:295-307.

Quinn, F.H., 1979. Derivation and calibration of stage-fall-discharge equations for the Great Lakes connecting channels. GLERL Open File Report No. 134, Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 4 pp.

Quinn, F.H., 1985. Great Lakes overview. In Great Lakes Water Levels: Briefing of Senators and Representatives From the Great Lakes Basin, U.S. Army Corps of Engineers, Detroit, MI, 1-24.

Quinn, F.H., 1986. Causes and consequences of the record high 1985 Great Lakes water levels. Preprint Volume of the Conference on the Human

Consequences of 1985's Climate. American Meteorological Society, Boston, MA, 281-284.

Quinn, F.H. and Kelley, R.N., 1983. Great Lakes monthly hydrologic data. NOAA Data Report ERL GLERL-26, Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 79 pp.

Urquhart, J., 1987. "Canada is proposing several measures to reduce water level of Great Lakes." Wall Street Journal, 22 April 1987.

U.S. Army Corps of Engineers, 1986a. Monthlv Bulletin of Lake Levels for the Great Lakes. Januarv 1986. U.S. Army Corps of Engineers, Detroit District, Detroit, MI, 5 pp.

U.S. Army Corps of Engineers, 1986b. Monthlv Bulletin of Lake Levels for the Great Lakes. Julv 1986. U.S. Army Corps-of Engineers, Detroit District, Detroit, MI, 5 pp.

U.S. Army Corps of Engineers, 1986c. Monthly Bulletin of Lake Levels for the Great Lakes, October 1986. U.S. Army Corps of Engineers, Detroit District, Detroit, MI, 5 pp.

U.S. Army Corps of Engineers, 1986d. Monthlv Bulletin of Lake Levels for the Great Lakes, November 1986. U.S. Army Corps of Engineers, Detroit District, Detroit, MI, 5 pp.