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Great Lakes Environmental Research Laboratory

GREAT LAKES - ST. LAWRENCE BASIN PROJECT

LE PROJET DU BASSIN DES GRANDS LACS ET DU SAINT-LAURENT

Climate Change Impacts on Western Lake Erie, Detroit River, and Lake St. Clair Water Levels.

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Abstract: The means and frequencies of Lake St. Clair, Detroit River, and western Lake Erie water levels are computed for a changed climate resulting from a doubling of atmospheric carbon dioxide, and compared to those of the present climate. Lake level frequencies for specific sites in the study areas, and potential movement of the shorelines due to decreases in mean lake levels, are illustrated by a series of maps. General surveys of impacts on wetlands, recreational boating, commercial navigation, and public water supply intakes are given. The intent of this work is to provide basic data to other researchers performing broader and more detailed impact studies as part of the Great Lakes - St. Lawrence Basin Project. With the changed climate scenario, the surface area and volume of Lake St. Clair decreases by 15% and 37%, respectively, relative to that of the present climate. Likewise, the surface area and volume of the western Lake Erie basin decreases by 4% and 20%. The surface area of the lower Detroit River decreases by 19%. The shoreline moves from less than 1 km to 6 km offshore from that of the present climate, with significant loss of freshwater estuaries and embayments.

Keywords: climate change, water levels, Lake St. Clair, Lake Erie, Detroit River, Long Point, Great Lakes - St. Lawrence Basin Project

Introduction

This study is a component of the Great Lakes - St. Lawrence Basin Project. The Project's prime objectives are to determine the impacts of climate variability and change in four theme areas: water management, land use and management, ecosystem health and human health, and to demonstrate how people, activities, and sectors can develop adaptation strategies to reduce vulnerability (Adapting to the Impacts of Climate Change and Variability, 1994).

This study contributes to the understanding of potential impacts of global warming on water quantity issues in the Lake Erie and Lake St. Clair basins. Our focus is on the water levels of the western basin of Lake Erie, the Detroit River, and Lake St. Clair: the change in their long-term means and frequency of occurrence, and the potential impacts on wetlands, recreational boating, commercial navigation, and public water supply intakes. Although not in the western basin of Lake Erie, impacts to Long Point are also evaluated due to the ecological importance of its wetlands. Figure 1 illustrates the study areas.

The limitations that apply to this study are those inherent in all modeling studies of climate change to date: lack of resolution and incorporation of fine-scale land surface-atmospheric interactions of the global climate models (GCMs), and uncertainties introduced through "down-scaling" GCM results or "nesting" of models, primarily the failure to capture changes in variability about the mean. Limitations specific to this study are our inability to quantitatively capture climate change effects on storm induced water levels: effects brought about by changes in wind intensity, duration, and direction; reductions in ice cover duration and extent; and decreases in bathymetric depths and fetch length. These limitations are addressed qualitatively.

Objectives

The objective of this study is to determine the means and frequencies of Lake St. Clair, the Detroit River, and western Lake Erie water levels given a changed climate resulting from a doubling of atmospheric carbon dioxide. The results presented here represent a steady-state changed climate - the effect on water levels during transition from the present climate to the changed climate is not considered. Lake level frequencies for specific sites in the study areas, and potential changes to shorelines due to decreases in mean lake levels are illustrated by a series of maps. A second objective is to postulate on impacts to wetlands, recreational boating, commercial navigation, and public water supply intakes resulting from changed water levels. General surveys of impacts are given to provide an overall sense of potential changes and their order of magnitude. The intent of this work is to provide basic data to other researchers performing broader and more detailed impact studies as part of the Great Lakes - St. Lawrence Basin Project.

Study Area

The study areas are comprised of Lake St. Clair, the Detroit River, the western basin of Lake Erie, and Long Point, as shown in Figure 1. The areas are located within the states of Michigan and Ohio, and the province of Ontario. Lake St. Clair is the smallest lake in the Great Lakes system with a total area of 1,114 km^2, 413 km of shoreline, and a mean natural depth of 3 m. Lake St. Clair is connected to the upper Great Lakes via the St. Clair River and the lower lakes via the Detroit River. The Detroit River is 50 km long with 212 km of shoreline (including islands). The upper portion of the river is narrow with a width of less than 1 km and depths to 15 m, but widens to a width of 6 km at its mouth where it enters Lake Erie with depths as shallow as 3 m. The western basin of Lake Erie lies west of the line from the tip of Cedar Point, Ohio, northward to Point Pelee, Ontario. Bedrock islands and shoals partially separate it from the central Lake Erie basin. The western basin has an area of 3,284 km^2, 445 km of shoreline, and depths mostly varying between 8 and 11 m (Bolsenga and Herdendorf, 1993).

Long Point, located on the northern shore of Lake Erie, partially separates the central basin of Lake Erie from the eastern basin. The point is the creation of converging alongshore currents depositing sediments. This sandy spit is 32 km long, reaching out into the deepest part of Lake Erie (Bolsenga and Herdendorf, 1993).

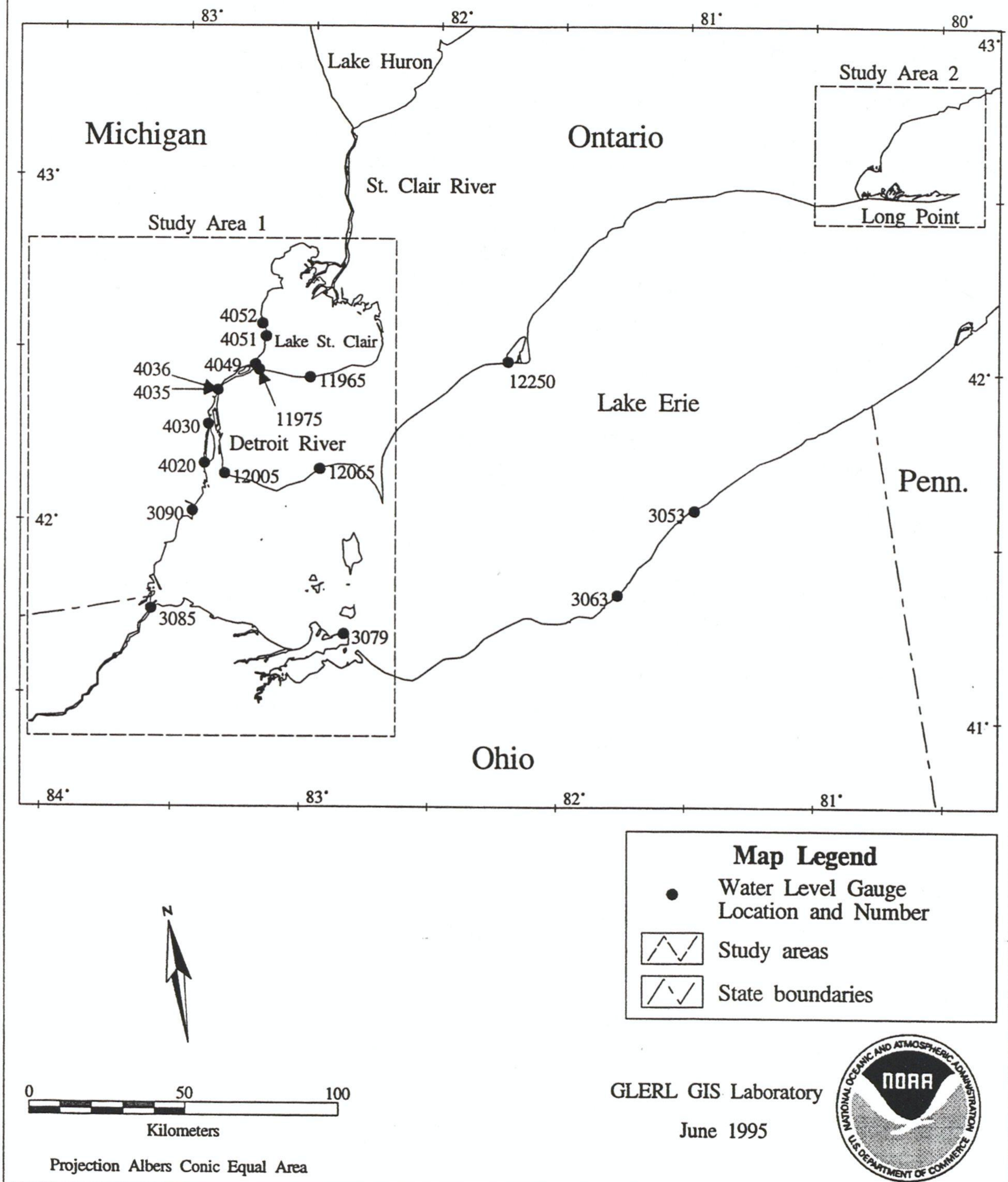
Many rich and sensitive wetlands are found in the study areas: the St. Clair Flats, Mouille Marsh, Long Point, and many others. They are home to diverse flora and fauna. The St. Clair Flats are an important resource for resident Native Americans. Long Point, with its series of dune ridges and intervening lagoons, provides significant marsh habitats.

The region surrounding the study areas is also home to the highly populated Detroit Metropolitan area, and the major cities of Toledo, Ohio and Windsor, Ontario. Their industries and municipalities depend in part on the lakes and river for water supply.

The Canadian peninsula bounded by the lakes and river is an important agricultural region. The peninsula is predominantly of low relief, and where it borders the waters of the Great Lakes system, is lined with residential development.

Both commercial navigation and recreational boating utilize the lakes and river. An 8 m dredged channel in the St. Clair River, the Detroit River, and Lake St. Clair provide a link for commercial navigation between the upper and lower lakes. Lake St. Clair, the western Lake Erie basin, and Long Point are intensively used for recreational boating, and their shores are host to many marinas and public and private beaches.

Figure 1 - Map of Study Areas



Methods

Background

Great Lakes water levels are a result of the basin's hydrologic processes. The water levels fluctuate due to changes in the net supply of water on a seasonal and annual basis. Seasonal fluctuations are a result of normal cycles in precipitation and temperature, and annual fluctuations occur in response to climate trends. The water levels of the Great Lakes rise in the spring and summer as water stored on the basin in the form of snow begins to enter the lakes. The levels fall through the autumn and winter due to increased evaporation when cool dry air crosses over the warmer lakes, and precipitation is stored as snow. The seasonal change in water levels is about 0.4 m for Lakes St. Clair and Erie. The annual average levels of the lakes also rise and fall depending on the total water supply to the lakes from year to year. Extended periods of above average precipitation and low evaporation cause levels to rise, while severe droughts can result in rapidly falling water levels. Recorded long-term annual fluctuations of Lakes St. Clair and Erie are about 1.4 m. It is interesting to note that Lake St. Clair and Lake Erie receive the majority of their water supply (97% and 80%, respectively) from the upstream lakes via the connecting channels (the St. Clair and Detroit Rivers).

Water levels in the Detroit River are primarily a function of Lake St. Clair and Lake Erie water levels. Because of the mild slope of the river, a significant backwater effect is transmitted from Lake Erie to Lake St. Clair.

Another factor that affects lake and connecting channel levels is storms. Storms, with accompanying changes in barometric pressure and high winds, cause lake levels to fluctuate over a small time period (an hour to several days) through wind setup, storm surges, seiches, and waves. The magnitude of the short-term fluctuations vary depending on shoreline location and configuration, and storm direction, duration, and intensity. The fluctuations can be positive (storm surge) or negative (storm set down) relative to the hydrologic lake level (i.e. they can increase or decrease the undisturbed lake level). The fluctuations are most pronounced on Lake Erie due to its shallowness and parallel orientation to the predominant storm direction. Storms have caused as much as a 4 m differential in levels between Buffalo, New York and Toledo, Ohio.

Storm surges and set downs imposed upon hydrologic lake levels result in the total instantaneous lake level. Because the instantaneous lake level is a function of these two independent components, the following method is required to compute their combined frequency of occurrence.

Computation of Lake Level Frequencies

Given two independent variables, X (hydrologic lake levels) and Y (storm fluctuations), that are continuous random variables, and have the relationship Z (instantaneous lake levels) = X + Y , then

$$P(Z) = \iint p(X)\ p(Y)\ dX\ dY \tag{1}$$

where P(Z)is the cumulative probability of instantaneous level Z and p(X) and p(Y) are probability density functions of variables X and Y. To solve this integral, the Combined Frequencies Program (CFP) uses a convolution formula and discretization to integrate the convolution integral using numerical approximation (Chow et al., 1994). For discrete variables, the integral becomes

$$P(Z) = \sum_{X} p(X)\ p(Z - X) \tag{2}$$

CFP provides five probability distributions to determine the cumulative probability functions of X and Y. They are the normal, lognormal, Gumbel, log-Pearson type 3 and general extreme value distributions.

In light of the demonstrated bias exhibited when using least squares analysis to select the "best fitting" distribution function (Chow et al., 1994), the Akaike information criteria (AIC) [Akaike, 1974] is used as proposed by Chow and Watt (1992). The AIC measures the value of improving the fit with additional parameters. If more than one distribution is fit to the observed data, the model that has the minimum AIC is selected. For example, the use of a three-parameter distribution is justified, as opposed to a two-parameter distribution, only if the improved fit compensates for the penalty due to the additional parameter.

A brief description of the CFP procedure for combining the probability distributions follows. First, the program attempts to determine a possible range of Z values in which the cumulative probability can be obtained using equation (2). The range of Z values is determined using the values of X and Y with a cumulative probability of 99.5% from their 'best-fit' distributions. Normally, this estimated Z value has a return period of about 200 years. The minimum Z value is estimated in the same manner using the X and Y values with a cumulative probability of 0.5%. The range of the Z value is then divided into 50 equal intervals. The cumulative probabilities of these fifty Z values are then estimated using equation (2). The fitted X and Y distributions were used to compute exact solutions of their respective cumulative probabilities used in equation (2). The Z values and their computed cumulative probabilities should be considered to be the 'true' frequency curves for the instantaneous levels Z. No distributions are fitted to the Z values to avoid under- or over-estimation of the instantaneous levels.

Data

Climate Change Scenario - Hydrologic Lake and River Levels

The climate change scenario used here was developed for Phase II of the International Joint Commission Levels Reference Study (International Joint Commission, 1993). The development of the climate change data set by the Canadian Climate Centre, and its interpolation over the Great Lakes Basin, is described by Louie (1991). Croley (1991) applied the climate data set to his conceptual hydrologic and thermodynamic models of the Great Lakes and their basins to develop a water supply scenario for each lake. These water supplies were routed through regulation and hydrologic response models to obtain a 38-year series of monthly lake levels and outflows.

To obtain a comparable series of levels for locations along the Detroit River, we used stage-discharge relationships developed by the U.S. Army Corps of Engineers. The climate change Lake St. Clair and Lake Erie water levels and Detroit River flows were used to solve the relationships for monthly water levels at four gauge locations (Gibraltar - 4020, Wyandotte - 4030, Fort Wayne - 4035/4036, and Windmill Point - 4049; see Figure 1). The effects of ice and weed retardation were neglected in the computation of these levels. Ice retardation could be expected to diminish as a result of the warmer air and water temperatures given a changed climate. Weed retardation could be expected to increase due to the warmer water temperatures and increased light penetration due to lower lake levels, resulting in an extension of the weed growth season and increased weed mass. Thus, on a seasonal basis, the water levels may actually be slightly lower during the winter and spring seasons, and slightly higher during the summer and fall seasons, than computed here.

Present Conditions Scenario - Hydrologic Lake and River Levels

For comparison with the changed climate scenario, we used a 38-year series (1952-1989) of monthly lake levels and outflows, also developed for Phase II of the Levels Reference Study, that represents the present conditions of the Great Lakes-St. Lawrence River System (Lee, 1993). Water levels for the four locations along the Detroit River were computed in the same manner as described for the changed climate scenario.

Computation of Storm Fluctuation Values

Storm fluctuation values were calculated for maximum and minimum instantaneous water levels recorded at American and Canadian gauges located in the study area. Recorded water level data were obtained from 12 U.S. National Ocean Service and 5 Canadian Marine Environmental Data Service gauges. Table 1 lists the gauge locations, and the periods of record used here. Maximum monthly storm surge was obtained by subtracting the maximum instantaneous level occurring for a month from the corresponding monthly mean level. Likewise, maximum monthly storm set down was obtained by subtracting the minimum instantaneous level occurring for a month from the corresponding monthly mean level.

Table 1. Gauges and their Period of Record Used to Compute Storm Fluctuations		
U.S. National Oceanic Service Gauges		
Gauge No.	Gauge Location	Period of Record (month/year)
3053	Fairport, Ohio	6/1975 - 9/1994
3063	Cleveland, Ohio	1/1904 - 9/1994
3079	Marblehead, Ohio	5/1959 - 8/1994
3085	Toledo, Ohio	7/1904 - 9/1994
3090	Stony Point, Michigan	9/1963 - 9/1994
4020	Gibraltar, Michigan	1/1950 - 9/1994
4030	Wyandotte, Michigan	4/1957 - 9/1994
4035 4036	Fort Wayne, Michigan[1] Fort Wayne, Michigan	7/1901 - 12/1969 1/1970 - 9/1994
4049	Windmill Point, Michigan	1/1952 - 9/1994
4051 4052	Grosse Point Yacht Club, Michigan[1] St. Clair Shores, Michigan	7/1952 - 2/1968 3/1968 - 9/1994
Marine Environmental Data Service Gauges		
Gauge No.	Gauge Location	Period of Record (month/year)
12250	Erieau, Ontario	7/1957 - 6/1994
12065	Kingsville, Ontario	4/1962 - 12/1992
12005	Bar Point, Ontario	6/1966 - 12/1992
11965	Belle River, Ontario	1/1965 - 6/1994
11975	Tecumseh, Ontario	12/1926 - 6/1994

[1]Because of their close spatial proximity, the records of these stations have been joined to create one continuous record.

Because the effect of climate change on Great Lakes storms and their resulting short-term water level fluctuations is not known, no correction was applied to the observed storm surges. Storm fluctuations under a changed climate may be of the same magnitude as those now experienced because over-water wind speeds and fetch lengths are not greatly affected. As shown in Figures 2 and 3, only a slight decrease in steady-state windspeed averages (about 2-3%) for Lake St. Clair and Lake Erie are expected under a changed climate. And, although lake levels drop dramatically, because of their vast surface area, the fetch lengths along predominant wind directions are only reduced by a few percentages as well. However, the projected change in ice cover extent and duration may increase the magnitude and seasonal occurrence of winter and spring storm surges, particularly for the months of February, March, and April. Figures 2 and 3 compare the steady-state water temperatures for Lake St. Clair and Lake Erie for the present climate with a changed climate.

Application of CFP

The CFP was used to compute seasonal frequency curves of maximum and minimum instantaneous water levels for both a changed climate and the present climate. Seasonal curves were produced as opposed to annual curves because of the importance of seasonal variation in lake levels and storm fluctuations. The seasons were defined as follows: Spring (February-April); Summer (May-July); Autumn (August-October); and Winter (November-January). For each season and year of record, the maximum storm surges and the maximum hydrologic lake levels were selected for input to the CFP. Likewise, the maximum storm set downs (the largest negative fluctuation) and the minimum hydrologic levels were selected. Because the set down values were negative, they had to be transformed for input to the CFP. The transformation applied was to take the absolute values of the set down, and to subtract the hydrologic lake levels from a constant of 200. The CFP results for the minimum instantaneous levels were then untransformed by subtracting the results from 200.

Results

With a changed climate, St. Clair River and Detroit River flows decrease by 35% and 36%, respectively (Croley, 1991). Net basin supplies to Lake St. Clair and Lake Erie decrease by 65% and 101%, respectively (Croley, 1991). The decrease in total water supplies (river inflows plus net basin supplies) result in a drop in long-term average annual levels of 1.6 m for Lake St. Clair (from 175.2 m to 173.6 m) and 1.5 m for Lake Erie (from 174.3 m to 172.8 m). The changes in long-term monthly mean levels for Lake St. Clair and Lake Erie are illustrated in Figures 2 and 3, respectively, and tabulated in Table 2. Correspondingly, Detroit River levels decrease by 1.6 m at the head of the river and by 1.5 m at the mouth of the river.

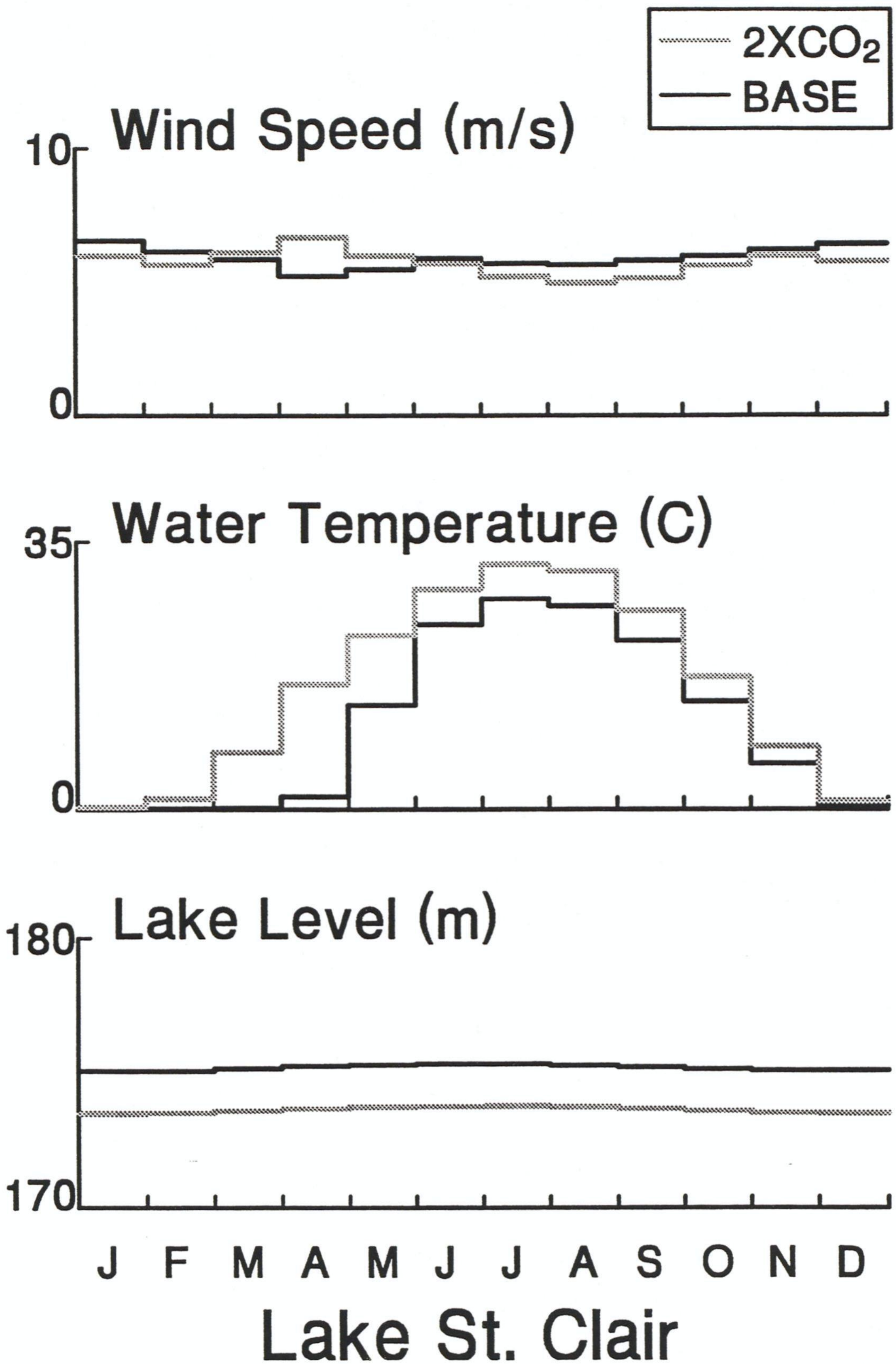

2XCO2
BASE
Wind Speed (m/s)
10
0
Water Temperature (C)
35
0
Lake Level (m)
180
170
J F M A M J J A S O N D
Lake St. Clair

Figure 2.

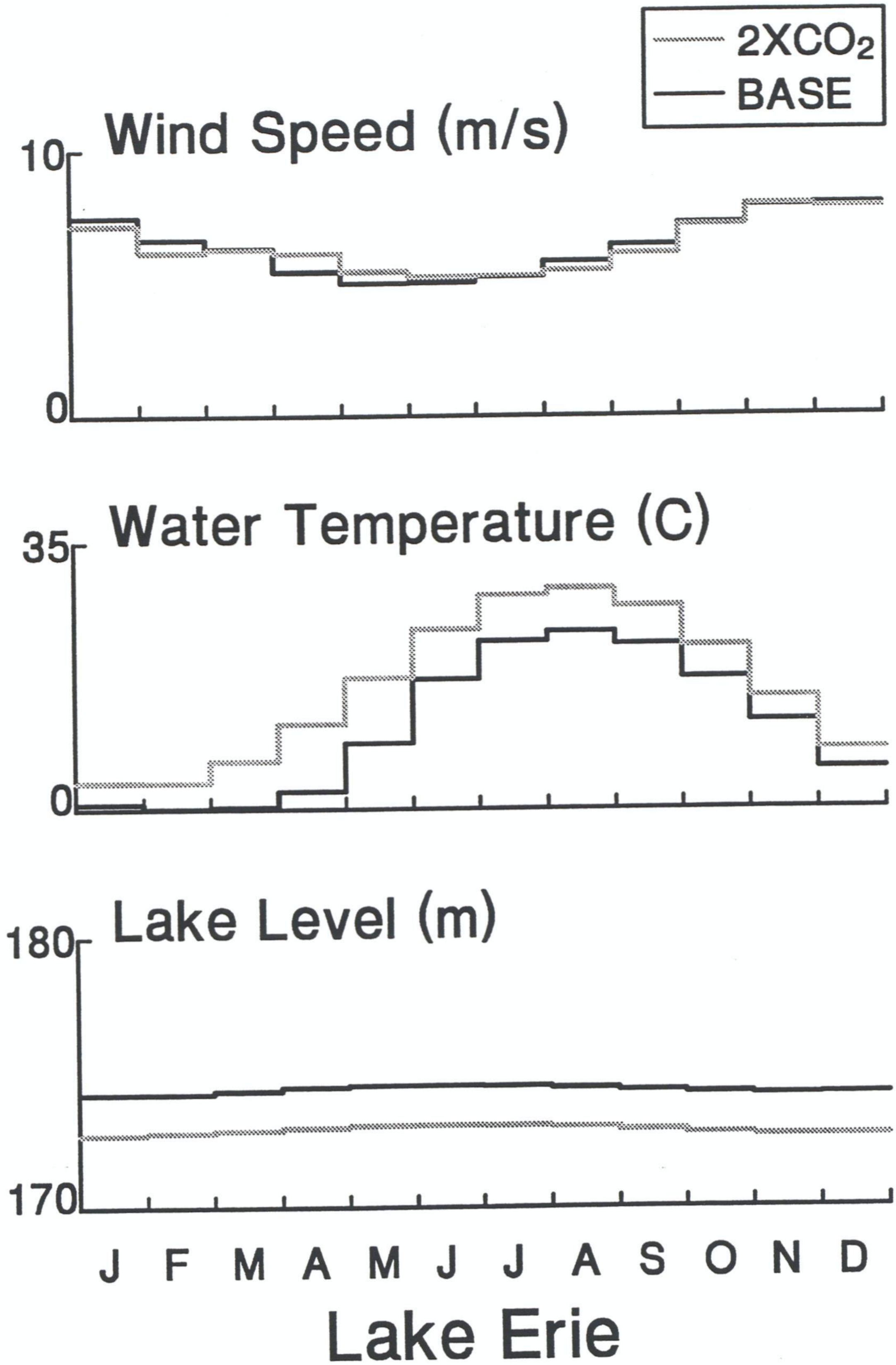

2XCO2
BASE
Wind Speed (m/s)
10
0
Water Temperature (C)
35
0
Lake Level (m)
180
170
J F M A M J J A S O N D
Lake Erie

Figure 3.

Results of the CFP computations are tabulated in Appendix A for the climate change scenario and in Appendix B for the present conditions scenario. Plates 1 through 7 illustrate the change in shoreline for the decrease in long-term average lake levels due to climate change. The water level frequencies from Appendix A are shown graphically on these plates. Figure 4 shows the region of the study area covered by each plate.

The maps presented in Plates 1 through 7 were created from National Ocean Service Coast and Geodetic Survey Charts:

14850 Lake St. Clair (10/17/1992)
14830 West End of Lake Erie (8/27/1994)
14848 Detroit River (12/11/1993)

and Canadian Hydrographic Service charts:

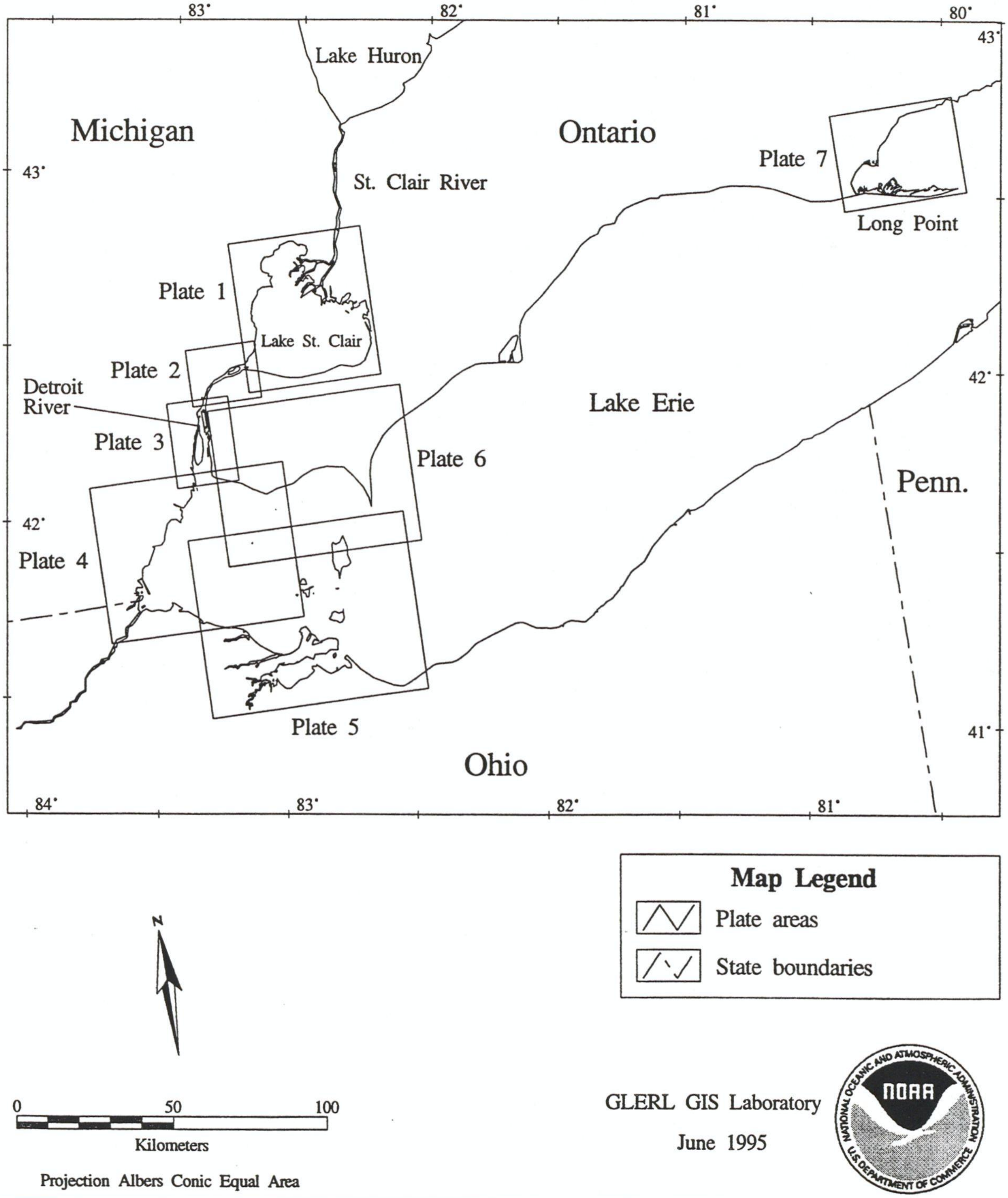
2110 Long Point Bay (5/15/1987)
2122 Pointe Aux Pins to Point Pelee (7/5/1991).

From each chart, four features were digitized: the shoreline, major navigation channels, the 2 m depth contour, and soundings less than 2 m. The depth, relative to chart datum, related to each sounding was added to a feature attribute table. Using the digitized information, a three-dimensional model of the nearshore was generated using a triangulated irregular network. The contour representing the shoreline with a changed climate was then obtained from the three-dimensional model. Note that the bathymetry on the charts are relative to chart datum (IGLD 1985) - 173.5 m and 174.4 m for Lake Erie and Lake St. Clair, respectively. Thus, the climate change levels will be 0.7 m (173.5 m - 172.8 m) below chart datum for Lake Erie and 0.8 m (174.4 m - 173.6 m) below chart datum for Lake St. Clair. The maps exist as Arc/Info v. 7.0 coverages and can be obtained from the Great Lakes Environmental Research Laboratory.

Table 2. Monthly and Annual Mean and Lake Levels with the Present Climate and With a Changed Climate

Month	Lake Erie			Lake St. Clair		
	Present Climate (m, IGLD 85)	Changed Climate (m, IGLD 85)	Difference (m)	Present Climate (m, IGLD 85)	Changed Climate (m, IGLD 85)	Difference (m)
January	174.17	172.67	1.50	175.06	173.48	1.58
February	174.18	172.74	1.44	175.06	173.51	1.55
March	174.28	172.82	1.46	175.15	173.58	1.57
April	174.41	172.92	1.49	175.25	173.66	1.59
May	174.46	172.99	1.47	175.30	173.72	1.58
June	174.47	173.01	1.46	175.33	173.74	1.59
July	174.44	173.00	1.44	175.33	173.75	1.58
August	174.38	172.95	1.43	175.28	173.73	1.55
September	174.29	172.84	1.45	175.22	173.66	1.56
October	174.20	172.72	1.48	175.14	173.58	1.56
November	174.13	172.63	1.50	175.08	173.51	1.57
December	174.15	172.62	1.53	175.08	173.49	1.59
Annual Mean	174.30	172.82	1.48	175.19	173.62	1.57

Figure 4 - Index of Plates



Impacts

Surface Area and Volume

Because Lake St. Clair is small relative to the other Great Lakes, its surface area and volume would be greatly affected by the projected decline in water levels. A decline in long-term average lake levels of 0.8 m relative to chart datum would reduce the surface area from 1,144 km^2 (this includes the surface area of the delta river channels) to 969 km^2, a 15% reduction. The volume of the lake below chart datum is 4 km^3 (Great Lakes Basin Commission Study, 1976) and would be reduced by 0.8 km^3, or about 20%. The total change in volume from the long-term average level of 175.2 m (present climate) to 173.6 m (changed climate) would be about 37%.

The change in surface area of the lake predominantly occurs along the north and east shores, with the most dramatic changes occurring in the St. Clair Delta (Plate 1). Much of the nearshore area would emerge as lake levels decline. At the long-term average level of 173.6 m, many of the delta river channels would no longer connect to the main body of the lake. The water of the St. Clair River would flow to Lake St. Clair mainly through the Middle Channel, South Channel, St. Clair Cutoff, and Chenal Ecarté. The North Channel, Chenal Bout Rond, and Johnston Channel would contain water, but because they terminate in bathymetry less than .8 m relative to chart datum, they would be separated from the main body of the lake by emergent land. Flow of water through these channels to Lake St. Clair may occur intermittently during periods of above average levels (relative to the climate change long-term average, not the present climate) and new channels to the lake may develop, allowing flow to the lake during periods of lower levels. The Chematogan Channel would have no flow, as the depths at the head and terminus of the channel are less than .8 m. Local inflow and groundwater may pool in some of the deeper sections of the channel, creating local ponding of water within the channel. There is insufficient information on the bathymetric chart for the Pottowatamie dredged cut, Goose Lake, and Johnston Bay to determine their condition under climate change.

Some small, shallow lakes and ponds would potentially form in the delta as areas of deeper bathymetry remain filled with water, as the surrounding, shallower bathymetry emerges with decreasing lake levels. The largest of these, located between the Chenal Bout Rond and Middle Channel in Goose Bay would be 2.5 km^2, and about 0.4 m deep. These lakes or ponds may not exist if intermittent channel flow, local surface runoff, and groundwater could not provide sufficient water supply to the shallow lake.

And conversely, some new islands would emerge in the delta's nearshore area. The largest of these, located south of the present Grassy Bend Islands, would be about 2.0 km^2 with a relief of about .5 m. It is conceivable that these islands would be intermittently submerged at times of above average levels (again, relative to climate change long-term averages) or during storm surge events.

The Lake St. Clair shoreline would be considerably removed from that of the present shoreline. Along the northern edge of the lake, the new shoreline is displaced by more than 6 km as the water recedes from Goose Bay and Big Muscamoot Bay. For the majority of the northern edge of the lake, shoreline displacements vary from about 1 km to 3 km. Displacements on the eastern shore are as great as 2 km, and along the western and southern shores, displacements average about 1 km or less.

Because of the steep-sided channel of the Upper Detroit River (Plate 2), the change in surface area predominantly occurs at the head of the river. The area of Peche Island would nearly double, increasing from 0.5 km^2 to 0.9 km^2, Belle Isle increases slightly, from 3.6 km^2 to 4.1 km^2, and a small island emerges in the north channel around Belle Isle. These and other changes result in about a 2 km^2 decrease in surface area.

Changes in the surface area of the Lower Detroit River (Plate 3) are more substantial, totaling 14 km^2, or a decrease of 19%. All of the islands increase in area, and several small islands emerge. Fighting Island increases from 5.1 km^2 to 7.7 km^2. Grassy Island increases from 0.4 km^2 to 0.7 km^2. Grosse Ile increases from 22.5 km^2 to 26.5 km^2. The increase in Grosse Ile's area occurs mainly because a small isthmus emerges, connecting the island to Stony Island. Sugar Island quadruples in area, increasing from 0.1 km^2 to 0.4 km^2. Celeron Island almost doubles in area, increasing from 0.6 km^2 to 1.1 km^2. The shoreline recedes primarily in the vicinity of the Canard River estuary on the eastern river shore, and on both shores where the river enters Lake Erie. In these locations the shoreline would be displaced up to 1 km.

Lake Erie has a greater average depth and steeper nearshore slopes than Lake St. Clair, but the surface area and volume of water in the lake would still be significantly impacted. The surface area of the western basin would decrease by 4%. The volume of the lake's western basin, below chart datum, is 25 km^3 (Bolsenga and Herdendorf, 1993) and would be reduced by 2.4 km^3, or about 10%. The total change in volume from the long-term average level of 174.3 m (present climate) to 172.8 m (changed climate) would be about 20%. The surface area of Sandusky Bay would decrease by 22%. The western shoreline of the basin, between Pointe Mouillee and Maumee Bay, would undergo the most dramatic change. The shoreline would generally be displaced between 1 km and 3 km. The southern shore of the basin would be displaced by up to 1 km. The northern shore of the basin would have the least displacement, with differences less than 0.5 km, and generally of 0.1 - 0.2 km. The islands (Pelee, Kelleys, Bass, Middle, Chicken, and East Sister), do not substantially change in area because a significant portion of their shores are steep cliffs. Two new small islands near Maumee Bay emerge.

Significant changes in the shoreline of Long Point and Inner Bay (Plate 7) on Lake Erie would also occur. The shoreline moves from a minimum of 0.2 km to greater than 2 km off shore. A formerly submerged reef at the mouth of Inner Bay would emerge, and along with the extended shoreline, significantly decrease the interchange of water between Inner and Long Point Bay, with the mouth of the Bay decreasing from 5 km to less than 2.5 km. Other reefs would emerge in the interior of Inner Bay, ranging in area from 0.03 km^2 to 0.56 km^2. The surface area of Inner Bay is reduced from 75.4 km^2 to 51.2 km^2.

It is important to note that the losses in surface area were derived by comparing surface areas at chart datum levels to surface areas at average levels under a changed climate. If average levels under both the present climate and changed climate were used for comparison, losses in surface area would be even larger. The average levels of the present climate are 0.8 m higher than chart datum. Unfortunately, maps of the shoreline at existing average levels are not available to permit such a comparison.

Wetlands

As mentioned earlier, there are extensive wetlands along the shores of Lake St. Clair, Lake Erie, and the Detroit River. In the case of Lake St. Clair, it is estimated that there are about 17,000 ha of wetland along its shore (International Lake Erie Regulation Study Board, 1981). Much of the north and east shoreline from Fair Haven, Michigan to Stoney Point, Ontario is wetland. The St. Clair Flats wetland complex, located on the north shore, is the most significant, with approximately 3,400 ha within Michigan, and 8,100 ha within Ontario (Bolsenga and Herdendorf, 1993). The wetland type is delta marsh, with 5 major and 3 minor plant zones. The major zones are (driest to wettest) 1) oak-ash hardwood forest, 2) dogwood-grass zone, 3) sedge marsh, 4) cattail marsh, and 5) bulrush marsh. The minor zones are 1) canal-pond-abandoned channel aquatic plant zones, 2) lake and bay bottom communities, and 3) reed grass zones (Jaworski and Raphael, 1978). The wetlands would most likely undergo substantial transition as lake levels declined. The zone of oak-ash hardwood forest could be expected to increase significantly as the other four zones migrated with the declining lake levels. The lake and bay bottom communities that occur along low wave energy lake bottoms and nearshore environments of bays may substantially decrease with the loss of water in Little Muscamoot, Fisher, and Johnston Bays. Some new types of wetland may evolve, such as bogs, that could form in shallow lakes left as water recedes from the bays (such as described previously for Goose Bay).

Most of the islands in the lower Detroit River are fringed by coastal wetlands (primarily cattails). The most noteworthy marshes, listed by Bolsenga and Herdendorf (1993), are on Gibraltar Island, Cherry Isle, Celeron Island, Horse Island, Round Island, Elba Island, Calf Island, Stony Island, Grassy Island, and Grosse Ile. Some of the wetlands would migrate as water levels declined, particularly for Celeron Island, Round Island, Elba Island, Calf Island, Stony Island, Grassy Island, and Grosse Ile. Additional wetlands may form along the perimeters of the new emergent islands. However, significant wetland loss could be expected in the freshwater estuaries along the river. These estuaries include the Canard River on the east shore, Brownstown Creek, including Cherry Isle and Gibraltar and Horse Islands, and an un-named estuary in the vicinity of Sturgeon Bar on the west shore. At long-term average climate change levels, a backwater effect due to the Detroit River would no longer exist in these estuaries. The estuaries could expect periods of inundation during storm events and above- average levels (relative to the climate change average), but with less frequency and with lower levels than are now experienced. The estuaries would also experience lower levels than have occurred with the present climate. The majority of the existing wetlands would most likely transform to upland habitat, and those remaining along the margins of the river and creek channels would be more representative of riverine wetlands than estuarial wetlands.

Along the shoreline of the western basin Lake Erie there are about 16,200 hectares of wetlands, many of which are owned by private clubs or are state, federal, or provincial wildlife refuges (Bolsenga and Herdendorf, 1993). Many are managed for waterfowl habitat and consist of natural lowlands separated from Lake Erie by a stable beach ridge. The managed marshes are also often surrounded and transected by earthen dikes to control their water levels and to protect them from the 1980's high water levels (Bolsenga and Herdendorf, 1993). The most significant of the wetlands are Mouille Marsh, Maumee Bay, Locust Point, Sandusky Bay, and Point Pelee.

Mouille Marsh is formed by the estuarine mouths of the Huron River and Mouillee Creek, and is located about 5 miles south of the Detroit River mouth. It is the most extensive wetland on the Michigan shore of Lake Erie, covering about 570 ha (Bolsenga and Herdendorf, 1993). Most of the wetland is protected and separated from Lake Erie by dikes and a confined disposal facility, used by the U.S. Army Corps of Engineers for disposal of dredged materials. With long-term average climate change lake levels, Lake Erie would no longer consistently supply water to the wetlands. The main supply of water for the diked area of the wetland would be Mouille Creek, which would have significantly diminished flows. Water from Lake Erie could be pumped over distances of up to 1 km, or captured during storm events (events with sufficient levels would occur about once every 2 years). Because of the confined disposal facility and dikes, it would be unlikely for the wetlands to migrate. The portion of the marsh in the Huron River estuary is not diked, and considerable loss of the wetland habitat would most likely occur. Some of the wetland may migrate with the declining lake levels, adapting from an estuary wetland to a coastal wetland.

Between Mouille Marsh and Maumee Bay, several other freshwater estuary and coastal wetlands exist. These include Swan Creek, Sandy Creek, and Plum Creek and La Plaisance Bay. They would suffer a similar fate as that of the Huron River estuary wetland.

Maumee Bay is protected by two sandy spits, little Cedar Point on the east, and Woodtick Peninsula on the west. In addition to the protected bay, additional wetlands are found in the Maumee River and Ottawa River estuaries along the bay's shore. Estuarine wetlands also occur along the Maumee River valley as far upstream as Perrysburg, Ohio (Bolsenga and Herdendorf, 1993). The Cedar Point National Wildlife Refuge, the Erie State Game Area, and Maumee Bay State Park are located in this region. With the decline in lake levels under climate change, considerable loss of wetlands would occur, as is the case for all of Lake Erie's freshwater estuaries. The Ottawa River estuary would be particularly affected due to its shallow bathymetry and reliance on the backwater from Lake Erie. However, the Bay experiences a wider range of storm induced water levels than those at Mouille Marsh. Thus, water levels needed to inundate the estuaries will occur with more frequency (more than once every 2 years). The wetland habitat in the estuaries and along the present shoreline would be expected to change from those depending on standing water to those typical of sites with periodic inundation. The types dependent on more consistent water depths may migrate with the receding shoreline and be more representative of a coastal wetland.

Locust Point is the region located between Maumee Bay and Sandusky Bay, on the southern shore of the western Lake Erie basin. Within this region, are approximately 3,500 ha of prime coastal marshes, mostly in federal or state ownership. The wetlands are the Cedar Point Marsh, Ottawa Marsh, Navarre Marsh, and Derby Marsh (managed by the U.S. Fish and Wildlife Service); and the Metzger Marsh, Magee Marsh, and Crane Creek State Park (managed by the Ohio Department of Natural Resources). All of these marshes are protected from Lake Erie flooding by extensive earthen and rip-rap dikes. The federal marshes are predominantly managed as waterfowl refuges (Bolsenga and Herdendorf, 1993). Similar to the Mouille Marsh, under climate change, water may need to be pumped from Lake Erie to maintain these diked marshes. This may be more feasible than at Mouille Marsh because the new shoreline under climate change is closer (less than 0.5 km). Because the marshes are diked, a migration of the wetland with the receding coastline is unlikely. New coastal marshes may form along the climate change shoreline, supplementing the managed marshes and perhaps increasing plant diversity.

Several wetlands occur along the rivers and creeks that empty into the lake in this region. These include Turtle Creek in the Magee Marsh, the Toussaint River, and the Portage River. The water levels in these rivers would also decline with the decline in Lake Erie levels due to a diminished or non-existent (in the case of the Toussaint River) backwater effect and reduced stream flows. The wetlands would be diminished and change from estuary wetlands to riverine wetlands.

The larger islands (Pelee, Kelleys, South Bass, Middle Bass, North Bass, and East Sister) of the western Lake Erie basin have several small wetlands. According to Bolsenga and Herdendorf (1993), these wetlands occupy depressions behind sand spits or barrier bars that have been built by alongshore currents. These wetlands would undergo change with the declining lake levels. It is unlikely that they would be able to migrate beyond the sand spits or barrier bars.

Sandusky Bay (including the Catawba Island peninsula) contains a wide variety of wetlands. The wetlands (about 1,700 ha) at the western end of the bay and in the vicinity of the bay bridges are diked, and although privately owned, are managed for waterfowl hunting and furbearer trapping. Because of the declining lake levels and shallowness of the Bay, the backwater from Lake Erie would no longer reach into Muddy Creek Bay. The diked marshes in this location would have to depend on pumped water or cease to exist. Because of the dikes, the wetlands could not migrate. The marshes that aren't diked would most likely transition to wetland types typical of intermittent inundation. The marshes at the eastern end of the bay depend upon the sand spits of Cedar Point and Bay Point for their protection. They are generally wetlands and ponds occupying depressions between sand ridges on the spits (Bolsenga and Herdendorf, 1993). These wetlands would probably begin to disappear with the decline in lake levels. Other wetlands have formed in the low lands between Marblehead Peninsula and Catawba Island. The West and East Harbors have been greatly modified by development, but Middle Harbor still contains a marsh community (Bolsenga and Herdendorf, 1993). Because of the shallowness of these harbors, they would be significantly impacted by the decline in lake levels.

Point Pelee contains about 1,000 ha of high quality cattail marsh, enclosed by barrier beaches (Bolsenga and Herdendorf, 1993). The entire point lies within the Point Pelee National Park. The marsh contains six open-water ponds. The Point Pelee wetland is likely to undergo fundamental changes in response to declining levels. The area of the wetlands and ponds would most likely decrease, with changes in the wetland type reflecting the drier conditions.

The largest wetland on Lake Erie is located at Long Point, with about 4,000 ha, including Big Creek and Turkey Point marshes (Nelson et al., 1980). There are several different types of wetlands at Long Point: Big Creek marsh is separated from Lake Erie by a barrier beach, extensive areas along the north shore of Long Point are partially separated from Long Point Bay and the Inner Bay by islands, while other wetland areas are fully exposed to these two bays. While some portions of the wetland would likely undergo significant changes, other portions may migrate into areas that are currently open water.

In summary, the loss of wetlands due to a changed climate will be significant and severe. The fresh water estuaries of the lower Detroit River and Lake Erie will only be inundated during storm events or when lake levels are above the long-term average climate change levels. Some migration of coastal wetlands may be expected, particularly for Lake St. Clair and the lower Detroit River. Most of Lake Erie's coastal wetlands will not be able to migrate due to man-made dikes or natural beach barriers.

Marinas/Recreational Boating

Lake St. Clair, the Detroit River, western Lake Erie, and the Long Point area are all heavily used for recreational boating. All of these locations would be severely affected by low water levels.

On the U.S. side of Lake St. Clair and the St. Clair River there are about 14,500 wet slips (Levels Reference Study Board, 1993). Impacts of the climate change scenario on recreational boating were evaluated as a part of the International Joint Commission's Levels Reference Study (International Joint Commission, 1993), and annual losses at these locations were estimated to be $17.8 million (U.S. currency), based on a total willingness to pay analysis of marina users.

As part of the same study, 15 marinas were identified on the Canadian side of Lake St. Clair, and interviews were conducted with operators of 8 of them. Seven of the eight indicated that critical minimum depth for their operations is between 174.0 m and 175.2 m. These seven also indicated that they experienced low water level problems in 1988-1991, when the lowest May-July level was 175.14 m and the lowest August-October level was 175.00 m. Problems ranged from insufficient depth at the slips to insufficient depths in access channels. Under the climate change scenario, there is a 50 percent probability that the May- July level would be below 173.6 m for at least 1 month, and the August-October level would be below 173.5 m for at least 1 month. Based on this information, it is evident that these marinas will experience serious problems on a regular basis under the climate change scenario.

The major difficulty for recreational boaters that use Lake St. Clair will be access to the lake. Most marinas will have insufficient depths within their basins to accommodate boats at long-term average climate change lake levels. The recession of the shoreline from less than 1 km to 6 km will make it impossible for boaters that use trailers to launch at existing ramps. New ramps could be put in place fairly easily, but at many locations it would be difficult to navigate to deep water in the lake due to very shallow conditions in the nearshore.

Some sites that would still have direct access to the lake, but with reduced drafts, would be the Clinton River, Thames River, Ruscom River, Pike Creek, Jefferson Beach Marina (St. Clair Shores, MI), Grosse Pointe Yacht Club, and the Grosse Pointe Club (Grosse Pointe, MI). Access could also be obtained by launching from sites on the St. Clair and Detroit Rivers.

The problem of access to and from the lake may be accentuated by temporary set down conditions due to winds and barometric pressure. This could be a safety concern, since there may be times when boats could be launched, but declining water levels as storms advanced could make it impossible for boats to return to the launch site. The end result of the climate change impacts may be fewer and smaller craft on the lake. Personal water craft such as "SeaDoos" may be the popular choice.

In the Upper Detroit River, public and private marinas predominate from Peche Island to the cities of Detroit, Michigan and Windsor, Ontario. A few slips serve industry and the U.S. Coast Guard. On the Canadian shore, across from Belle Isle and Peche Island, many private docks extend from the shore. Below the cities of Detroit and Windsor (downstream from the Ambassador Bridge) to the head of Fighting Island, the area is heavily industrialized with many commercial slips and few marinas. Because of the steep-sided river channel and adequate dredged or natural depths, most of the marinas and all of the commercial slips in the Upper Detroit River would be able to operate under climate change water levels, but with reduced draft. Additional dredging to deepen the marinas and commercial slips would improve the available draft. Some notable exceptions are the Detroit Yacht Club and the Detroit Boat Club on Belle Isle. However, the private docks primarily on the Canadian shore, would lose access to the river as levels decline. These docks are located in shallow depths, and the new shoreline would be about 100 m or more from the present shoreline at long-term average climate change levels.

In the Lower Detroit River, from the head of Fighting Island to Lake Erie, public and private marinas, and private docks predominate. Some of the marinas would have access to the lake with reduced drafts, but nearly all of the private docks are located in shallow depths and would no longer have direct access to the river under climate change levels.

As mentioned in the preceding section, the freshwater estuaries of Lake Erie's western basin would no longer be inundated at long-term average climate change water levels, and the shoreline would recede from the present shoreline by up to 3 km. The majority of marinas and private docks located in the estuaries and along the shore would no longer have adequate water depths (if any) or access to the lakes. Exceptions occur where dredged channels are maintained such as at the River Raisin, La Plaisance Creek, Toledo Beach Marina, the mouth of the Maumee River, the mouth of the Portage River, West Harbor on Catawba Island, Sandusky Bay between Sandusky, Ohio and Cedar Point, Put-In-Bay (South Bass Island), Lonz Marine Harbor (Middle

Bass Island), Kelleys Island Seaway Marina (Kelleys Island), and Scudder (Pelee Island). The marinas in these locations would have to dredge to maintain the present depths.

Recreational boating is a very popular activity at Long Point. The hydrographic chart for the area identifies 14 marinas on the Inner Bay. Access to these marinas will become increasingly difficult with a decline in lake levels. The 1 m depth contour is at least 500 m offshore around the entire bay, and it is over 1 km offshore in most areas. Under the climate change scenario, there is a 10 percent probability in any year that the water level will be at least 1 m below chart datum for 1 month during the May-July period. The probability increases to 20 percent for the August-October period. The probabilities increase to 20 percent and 50 percent, respectively, for levels at least 0.75 m below chart datum. This depth is not reached until at least 500 m offshore of eight of these marinas.

In summary, impacts of the climate change scenario on marinas and recreational boating will be widespread and significant. The most significant problems will be lake access and adequate water depths. Some marinas and boating areas will not be as severely affected as most. In some locations, dredging may provide at least partial relief, while this may not be economically viable at other locations, particularly those that would have long distances to navigable water. It is likely that there will be increased demand for berths at marinas that are able to adapt. It is also likely that there will be a trend to smaller boats at locations that cannot fully adapt.

Commercial Navigation

Lake St. Clair, the Detroit River, and the western basin of Lake Erie form an important link in the Great Lakes - St. Lawrence commercial navigation route. Since these areas tend to be shallow, much of the navigation channel has been dredged to permit passage of vessels drawing 7.9 m (26 feet) of water at chart datum. Since 1966, monthly mean levels on both Lakes St. Clair and Erie have continuously been at least 20 cm above chart datum, which has permitted navigation through this area of vessels drawing more than 7.9 m. Within this time period, levels in western Lake Erie have occasionally dropped below chart datum for periods of a few hours in response to strong southwesterly winds, which cause a set down in lake level at this location. Warnings have been issued to mariners in advance of these events.

Under the climate change scenario, the levels of both lakes will almost always be below chart datum. As discussed earlier, the mean level for Lake St. Clair over the 38 years of model results is about 0.8 m below chart datum, and the mean for Lake Erie is about 0.7 m below chart datum. Set down due to storm conditions will cause further short-term declines in levels from time to time.

The impacts of this decline in water levels on commercial navigation will be tremendous. The load capacity of ships will be greatly reduced, which will raise the cost per tonne of shipping products. A possible adaptive step would be dredging of channels and harbours to accommodate lower levels, but there would be very high costs and environmental considerations associated with this. Navigation locks would also have to be modified to allow full use of increased dredged depths in navigation channels.

The reduction of load capacity due to lower levels will be partially offset by a longer navigation season due to a reduction in duration and extent of ice cover. However, the additional ice-free period will occur during the period of lowest lake levels in the annual cycle.

In summary, commercial navigation will suffer from reduced loading capacity that may be partially offset by a longer navigation season. Maintaining current navigation depths through additional dredging and modification of locks will be expensive.

Water Intakes

Water intakes for municipal and industrial purposes exist at many locations along the shore of the study areas. These intakes were typically constructed to accommodate the historical range of lake level fluctuations, but most were designed prior to knowledge of potential climate change effects.

Along the Canadian side of Lake St. Clair there are five intakes (Griffiths, 1990), of which four are located in about 2 m of water, at chart datum. The fifth intake is located in Mitchell Bay at a depth of less than 1 m. An additional four intakes were identified along the American side of the lake from a hydrographic chart. Three of these intakes are located in over 2 m of water, while one is between 1 and 2 m of depth. It is not known what the minimum operable water depths are for each of the intakes, but the indicated depths over cribs at the ends of four of the intakes varies from less than 1 to 2 m.

A monthly mean level of 1 m below chart datum would occur about once in three winters on Lake St. Clair under the climate change scenario. It is likely that at least some of the water intakes would experience problems at this lake level. A monthly mean level of 2 m below chart datum would occur about once in 50 years, and this would likely create problems for almost all intakes.

Temporary difficulties in obtaining water from intakes during storm conditions would occur more frequently. Minimum instantaneous levels of 1.5 m below chart datum would occur about once in five winters at St. Clair Shores and Belle River. It is likely that similar or lower levels would occur in Anchor Bay, where two intakes are located.

There are seven active Canadian water intakes along the Detroit River (Griffiths, 1990) and two American intakes are indicated on the hydrographic chart. These intakes are generally at greater depths than those on Lake St. Clair, and are likely to be less affected by declining water levels.

Within the Lake Erie portion of the study area there are about 14 water intakes shown on the hydrographic chart along the American shore. Two are located in less than 2 m of water, three are in over 5 m, and the remainder are in between. Depth above the intakes would be less than these values.

Under the climate change scenario, a winter monthly mean level 1 m below chart datum would occur about once in three years, and 2 m below chart datum would occur about once in 100 years. The shallower intakes would occasionally experience extended periods during which they could not operate.

Many of these intakes could experience temporary interruptions during set down in the western basin. An instantaneous level of 2 m below chart datum in this area during winter months has a return period of about 2 years, and a level of 3 m below chart datum has a return period of between 10 and 50 years.

Along the Canadian shoreline of this area there are three water intakes, all in between 2 and 5 m of water. These intakes would experience problems similar to those of the American intakes. There is also one intake within the Inner Bay at Long Point. It is likely that this intake would frequently experience interruptions in supply under the climate change scenario.

At most locations it may be possible for water intake facilities to be modified by extension of intakes to deeper waters in order to adapt to declining levels. However, this may not be a feasible alternative for water intakes on Mitchell Bay and Inner Bay.

In addition to impacts on availability of supply, the decline in levels will likely affect the properties of water. Water temperatures will be higher due to both an increase in air temperature and shallower depths at the intakes. These two factors may also lead to an increase in levels of undesirable contaminants such as bacteria and algae, and a decrease in dissolved oxygen. Furthermore, the reduction in volume and surface area may reduce the lakes' ability to assimilate and dilute contaminants in the water.

In summary, many of the water intakes will experience periods when they cannot operate due to reduced water depths, especially during storm events. The loss of normal depths will reduce their demand capacity. In addition, they may experience increased problems due to poor water quality - increased temperatures and contaminants, and decreased dissolved oxygen.

Summary

In this study, the means and frequencies of water levels in Lake St. Clair, the Detroit River, and western Lake Erie were determined for a changed climate resulting from a doubling of atmospheric carbon dioxide. Under this scenario, mean water levels of Lake St. Clair would decline by 1.6 m, and the mean level of Lake Erie would decline by 1.5 m.

This study has shown that a decline in water levels of this magnitude would result in very significant decreases in water volume and surface area within the study areas. Water volumes would decrease by as much as 37% in Lake St. Clair and 20% in Erie, and surface areas would decrease significantly resulting in significant losses of wetlands, freshwater estuaries and embayments. For example, the surface of Inner Bay at Long Point would decrease by 32%.

Wetlands, marinas/recreational boating, commercial navigation, and public water supply intakes would be adversely impacted by the decline in lake levels. While adaptation may be possible at some locations, the cumulative impacts would be negative for each of these sectors.

There is a need for researchers to conduct more detailed analyses of impacts to these sectors and to develop adaptive strategies that could assist people in planning for and minimizing impacts.

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Appendix A
Climate Change Scenario

Maximum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Spring

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	173.24	173.54	173.67	173.88	173.97
Cleveland, OH	173.32	173.62	173.76	173.98	174.09
Marblehead, OH	173.46	173.76	173.90	174.12	174.21
Toledo, OH	173.81	174.16	174.33	174.67	174.84
Stony Point, MI	173.60	173.92	174.08	174.37	174.51
Gibraltar, MI	173.61	173.92	174.07	174.32	174.44
Wyandotte, MI	173.77	174.07	174.21	174.42	174.51
Fort Wayne, MI	173.82	174.13	174.26	174.46	174.54
Windmill Point, MI	173.87	174.20	174.34	174.55	174.63
St. Clair Shores, MI	173.77	174.08	174.21	174.40	174.47
Erieau, ONT	173.21	173.51	173.64	173.87	174.00
Kingsville, ONT	173.43	173.73	173.87	174.10	174.21
Bar Point, ONT	173.42	173.74	173.88	174.12	174.22
Tecumseh, ONT	173.95	174.28	174.43	174.64	174.73
Belle River, ONT	173.97	174.30	174.45	174.67	174.77

Maximum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Summer

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	173.28	173.55	173.66	173.81	173.87
Cleveland, OH	173.37	173.65	173.78	174.05	174.23
Marblehead, OH	173.38	173.66	173.78	173.96	174.05
Toledo, OH	173.81	174.16	174.33	174.67	174.84
Stony Point, MI	173.47	173.77	173.90	174.16	174.30
Gibraltar, MI	173.57	173.86	173.99	174.22	174.34
Wyandotte, MI	173.74	174.02	174.14	174.30	174.36
Fort Wayne, MI	173.81	174.09	174.21	174.37	174.43
Windmill Point, MI	173.90	174.20	174.33	174.50	174.56
St. Clair Shores, MI	173.93	174.24	174.37	174.54	174.59
Erieau, ONT	173.24	173.51	173.62	173.77	173.83
Kingsville, ONT	173.40	173.67	173.79	173.97	174.06
Bar Point, ONT	173.43	173.73	173.88	174.17	174.32
Tecumseh, ONT	173.97	174.28	174.40	174.58	174.63
Belle River, ONT	174.02	174.33	174.46	174.64	174.71

Maximum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Autumn

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	173.24	173.51	173.62	173.78	173.85
Cleveland, OH	173.32	173.59	173.71	173.90	173.99
Marblehead, OH	173.37	173.65	173.77	173.98	174.09
Toledo, OH	173.58	173.88	174.03	174.32	174.47
Stony Point, MI	173.44	173.72	173.84	174.03	174.12
Gibraltar, MI	173.49	173.77	173.88	174.07	174.15
Wyandotte, MI	173.71	173.98	174.09	174.25	174.31
Fort Wayne, MI	173.78	174.06	174.18	174.34	174.40
Windmill Point, MI	173.87	174.16	174.29	174.45	174.50
St. Clair Shores, MI	173.90	174.20	174.32	174.49	174.53
Erieau, ONT	173.19	173.46	173.57	173.73	173.80
Kingsville, ONT	173.37	173.65	173.78	174.00	174.10
Bar Point, ONT	173.35	173.63	173.76	173.95	174.03
Tecumseh, ONT	173.94	174.25	174.38	174.54	174.59
Belle River, ONT	173.99	174.29	174.42	174.59	174.65

Maximum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Winter

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	173.00	173.28	173.41	173.58	173.64
Cleveland, OH	173.08	173.38	173.50	173.71	173.80
Marblehead, OH	173.27	173.59	173.74	174.03	174.18
Toledo, OH	173.55	173.88	174.06	174.43	174.61
Stony Point, MI	173.39	173.71	173.86	174.17	174.33
Gibraltar, MI	173.40	173.71	173.85	174.10	174.22
Wyandotte, MI	173.67	173.97	174.11	174.34	174.45
Fort Wayne, MI	173.72	174.02	174.15	174.35	174.44
Windmill Point, MI	173.74	174.05	174.18	174.38	174.46
St. Clair Shores, MI	173.77	174.08	174.21	174.40	174.47
Erieau, ONT	172.97	173.27	173.39	173.57	173.64
Kingsville, ONT	173.26	173.57	173.71	173.97	174.09
Bar Point, ONT	173.28	173.62	173.78	174.06	174.17
Tecumseh, ONT	173.83	174.15	174.29	174.48	174.55
Belle River, ONT	173.83	174.15	174.29	174.51	174.60

Minimum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Spring

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	172.58	172.26	172.05	171.59	171.40
Cleveland, OH	172.43	172.09	171.87	171.40	171.20
Marblehead, OH	172.14	171.77	171.54	171.07	170.85
Toledo, OH	171.64	171.13	170.82	170.14	169.81
Stony Point, MI	171.85	171.34	171.02	170.28	169.92
Gibraltar, MI	172.04	171.63	171.38	170.87	170.61
Wyandotte, MI	172.91	172.55	172.33	171.85	171.65
Fort Wayne, MI	173.04	172.69	172.46	171.99	171.78
Windmill Point, MI	173.19	172.83	172.59	172.09	171.87
St. Clair Shores, MI	173.32	172.96	172.73	172.22	172.00
Erieau, ONT	172.46	172.13	171.92	171.46	171.26
Kingsville, ONT	172.07	171.66	171.41	170.91	170.65
Bar Point, ONT	172.01	171.61	171.38	170.90	170.67
Tecumseh, ONT	173.21	172.84	172.61	172.09	171.88
Belle River, ONT	173.34	172.99	172.76	172.25	172.03

Minimum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Summer

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	172.85	172.55	172.35	171.92	171.74
Cleveland, OH	172.78	172.47	172.47	171.84	171.66
Marblehead, OH	172.68	172.37	172.17	171.73	171.54
Toledo, OH	172.39	172.04	171.83	171.38	171.18
Stony Point, MI	172.54	172.21	172.01	171.56	171.37
Gibraltar, MI	172.63	172.30	172.10	171.66	171.47
Wyandotte, MI	173.20	172.89	172.68	172.24	172.05
Fort Wayne, MI	173.34	173.02	172.81	172.36	172.17
Windmill Point, MI	173.48	173.14	172.91	172.43	172.22
St. Clair Shores, MI	173.62	173.27	173.05	172.55	172.34
Erieau, ONT	172.82	172.51	172.32	171.88	171.70
Kingsville, ONT	172.62	172.30	172.10	171.66	171.48
Bar Point, ONT	172.60	172.27	172.06	171.61	171.42
Tecumseh, ONT	173.55	173.21	172.98	172.49	172.28
Belle River, ONT	173.60	173.25	173.02	172.53	172.32

Minimum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Autumn

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	172.55	172.25	172.05	171.61	171.42
Cleveland, OH	172.44	172.13	171.93	171.48	171.30
Marblehead, OH	172.22	171.88	171.66	171.21	171.02
Toledo, OH	171.90	171.49	171.24	170.74	170.48
Stony Point, MI	172.01	171.62	171.38	170.90	170.66
Gibraltar, MI	172.18	171.84	171.62	171.17	170.97
Wyandotte, MI	172.91	172.59	172.38	171.94	171.75
Fort Wayne, MI	173.12	172.81	172.61	172.16	171.97
Windmill Point, MI	173.32	172.99	172.76	172.28	172.07
St. Clair Shores, MI	173.46	173.12	172.90	172.40	172.19
Erieau, ONT	172.45	172.13	171.93	171.49	171.30
Kingsville, ONT	172.18	171.83	171.61	171.16	170.96
Bar Point, ONT	172.20	171.82	171.60	171.13	170.90
Tecumseh, ONT	173.39	173.04	172.81	172.31	172.10
Belle River, ONT	173.44	173.10	172.87	172.37	172.16

Minimum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Winter

Location	Return Period (years) 2	5	10	50	100
Fairport, OH	172.41	172.08	171.87	171.42	171.22
Cleveland, OH	172.21	171.87	171.65	171.19	170.99
Marblehead, OH	171.77	171.34	171.09	170.56	170.30
Toledo, OH	171.24	170.76	170.47	169.88	169.59
Stony Point, MI	171.40	171.00	170.77	170.28	170.05
Gibraltar, MI	171.75	171.40	171.18	170.71	170.50
Wyandotte, MI	172.71	172.38	172.17	171.71	171.52
Fort Wayne, MI	172.90	172.56	172.35	171.88	171.69
Windmill Point, MI	173.11	172.75	172.52	172.01	171.80
St. Clair Shores, MI	173.27	172.91	172.68	172.17	171.95
Erieau, ONT	172.21	171.87	171.65	171.19	170.99
Kingsville, ONT	171.72	171.37	171.15	170.68	170.47
Bar Point, ONT	171.77	171.36	171.12	170.63	170.40
Tecumseh, ONT	173.13	172.76	172.52	172.00	171.78
Belle River, ONT	173.28	172.92	172.69	172.17	171.96

Appendix B
Present Conditions Scenario

Maximum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Spring

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	174.71	175.01	175.16	175.44	175.55
Cleveland, OH	174.78	175.09	175.25	175.53	175.65
Marblehead, OH	174.93	175.23	175.39	175.67	175.76
Toledo, OH	175.29	175.64	175.83	176.19	176.37
Stony Point, MI	175.07	175.40	175.57	175.9	176.05
Gibraltar, MI	175.08	175.4	175.56	175.86	176
Wyandotte, MI	175.22	175.52	175.67	175.95	176.06
Fort Wayne, MI	175.29	175.58	175.72	175.93	176.01
Windmill Point, MI	175.45	175.76	175.9	176.11	176.19
St. Clair Shores, MI	175.48	175.79	175.93	176.13	176.2
Erieau, ONT	174.70	175.00	175.14	175.36	175.50
Kingsville, ONT					
Bar Point, ONT					
Tecumseh, ONT					
Belle River, ONT	175.55	175.85	176.00	176.21	176.31

Maximum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Summer

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	174.76	175.01	175.12	175.26	175.31
Cleveland, OH	174.84	175.11	175.23	175.5	175.68
Marblehead, OH	174.85	175.12	175.23	175.41	175.5
Toledo, OH	175.08	175.37	175.52	175.82	175.97
Stony Point, MI	174.95	175.23	175.36	175.62	175.75
Gibraltar, MI	175.04	175.32	175.44	175.67	175.78
Wyandotte, MI	175.20	175.45	175.56	175.71	175.77
Fort Wayne, MI	175.27	175.53	175.64	175.79	175.84
Windmill Point, MI	175.47	175.75	175.87	176.03	176.09
St. Clair Shores, MI	175.52	175.8	175.92	176.07	176.13
Erieau, ONT	174.72	174.97	175.08	175.22	175.27
Kingsville, ONT					
Bar Point, ONT					
Tecumseh, ONT					
Belle River, ONT	175.59	175.87	175.99	176.16	176.22

Maximum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Autumn

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	174.67	174.92	175.03	175.18	175.24
Cleveland, OH	174.75	175.01	175.12	175.30	175.39
Marblehead, OH	174.80	175.06	175.18	175.39	175.49
Toledo, OH	175.02	175.30	175.44	175.73	175.88
Stony Point, MI	174.88	175.14	175.25	175.43	175.52
Gibraltar, MI	174.93	175.19	175.29	175.47	175.55
Wyandotte, MI	175.12	175.37	175.47	175.61	175.66
Fort Wayne, MI	175.2	175.46	175.56	175.71	175.77
Windmill Point, MI	175.41	175.69	175.81	175.96	176.01
St. Clair Shores, MI	175.45	175.73	175.85	176.01	176.05
Erieau, ONT	174.63	174.88	174.98	175.13	175.19
Kingsville, ONT					
Bar Point, ONT					
Tecumseh, ONT					
Belle River, ONT	175.53	175.81	175.93	176.09	176.14

Maximum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Winter

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	174.48	174.77	174.92	175.19	175.28
Cleveland, OH	174.57	174.86	175.02	175.30	175.41
Marblehead, OH	174.76	175.08	175.26	175.58	175.74
Toledo, OH	175.04	175.39	175.58	175.96	176.15
Stony Point, MI	174.88	175.21	175.38	175.72	175.88
Gibraltar, MI	174.88	175.2	175.37	175.66	175.8
Wyandotte, MI	175.12	175.41	175.55	175.78	175.89
Fort Wayne, MI	175.18	175.47	175.60	175.80	175.89
Windmill Point, MI	175.28	175.59	175.76	176.04	176.15
St. Clair Shores, MI	175.32	175.63	175.79	176.07	176.17
Erieau, ONT	174.47	174.76	174.91	175.18	175.28
Kingsville, ONT					
Bar Point, ONT					
Tecumseh, ONT					
Belle River, ONT	175.37	175.69	175.86	176.15	176.26

Minimum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Spring

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	173.96	173.66	173.50	173.22	173.12
Cleveland, OH	173.82	173.50	173.32	173.00	172.85
Marblehead, OH	173.53	173.18	172.99	172.63	172.46
Toledo, OH	173.04	172.56	172.27	171.59	171.27
Stony Point, MI	173.26	172.78	172.47	171.74	171.37
Gibraltar, MI	173.43	173.05	172.83	172.38	
Wyandotte, MI	174.28	173.96	173.78	173.46	172.15
Fort Wayne, MI	174.42	174.10	173.94	173.63	173.30
Windmill Point, MI	174.67	174.34	174.16	173.85	173.73
St. Clair Shores, MI	174.81	174.49	174.32	174.01	173.90
Erieau, ONT	173.85	173.54	173.37	173.08	172.96
Kingsville, ONT					
Bar Point, ONT					
Tecumseh, ONT					
Belle River, ONT	174.82	174.50	174.33	174.03	173.92

Minimum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Summer

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	174.30	174.01	173.82	173.41	173.24
Cleveland, OH	174.23	173.93	173.74	173.33	173.15
Marblehead, OH	174.13	173.83	173.64	173.22	173.04
Toledo, OH	173.84	173.50	173.30	172.87	172.67
Stony Point, MI	173.99	173.67	173.47	173.05	172.87
Gibraltar, MI	174.08	173.77	173.57	173.15	172.97
Wyandotte, MI	174.64	174.35	174.16	173.75	173.58
Fort Wayne, MI	174.78	174.49	174.30	173.89	173.71
Windmill Point, MI	175.04	174.72	174.52	174.06	173.87
St. Clair Shores, MI	175.18	174.87	174.66	174.21	174.02
Erieau, ONT	174.27	173.98	173.79	173.38	173.20
Kingsville, ONT					
Bar Point, ONT					
Tecumseh, ONT					
Belle River, ONT	175.15	174.83	174.63	174.17	173.98

Minimum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Autumn

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	174.03	173.74	173.56	173.14	172.97
Cleveland, OH	173.92	173.62	173.43	173.02	172.84
Marblehead, OH	173.70	173.37	173.17	172.74	172.55
Toledo, OH	173.38	172.98	172.74	172.25	172.00
Stony Point, MI	173.48	173.11	172.88	172.42	172.18
Gibraltar, MI	173.66	173.33	173.12	172.70	172.51
Wyandotte, MI	174.34	174.04	173.85	173.45	173.28
Fort Wayne, MI	174.55	174.27	174.08	173.68	173.51
Windmill Point, MI	174.87	174.56	174.36	173.91	173.72
St. Clair Shores, MI	175.01	174.70	174.50	174.05	173.86
Erieau, ONT	173.92	173.63	173.44	173.03	172.15
Kingsville, ONT					
Bar Point, ONT					
Tecumseh, ONT					
Belle River, ONT	174.98	174.67	174.46	174.01	173.82

Minimum Instantaneous Levels (m, IGLD 85): Frequency of Occurrence

Winter

Location	Return Period (years)				
	2	5	10	50	100
Fairport, OH	173.86	173.56	173.40	173.12	173.01
Cleveland, OH	173.67	173.35	173.18	172.87	172.74
Marblehead, OH	173.24	172.84	172.61	172.13	171.89
Toledo, OH	172.72	172.26	171.99	171.42	171.16
Stony Point, MI	172.88	172.49	172.28	171.91	171.73
Gibraltar, MI	173.22	172.88	172.71	172.39	172.25
Wyandotte, MI	174.13	173.83	173.67	173.38	173.26
Fort Wayne, MI	174.31	174.00	173.84	173.56	173.43
Windmill Point, MI	174.62	174.30	174.13	173.82	173.71
St. Clair Shores, MI	174.78	174.46	174.29	174.00	173.89
Erieau, ONT	173.67	173.35	173.18	172.88	172.75
Kingsville, ONT					
Bar Point, ONT					
Tecumseh, ONT					
Belle River, ONT	174.78	174.46	174.29	173.98	173.88

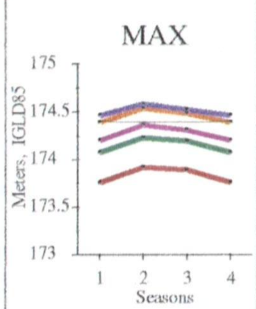
PLATE 1

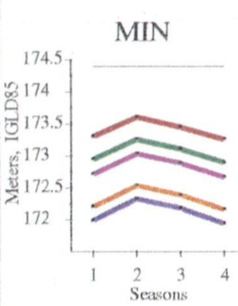
Great Lakes – St. Lawrence River Basin Project

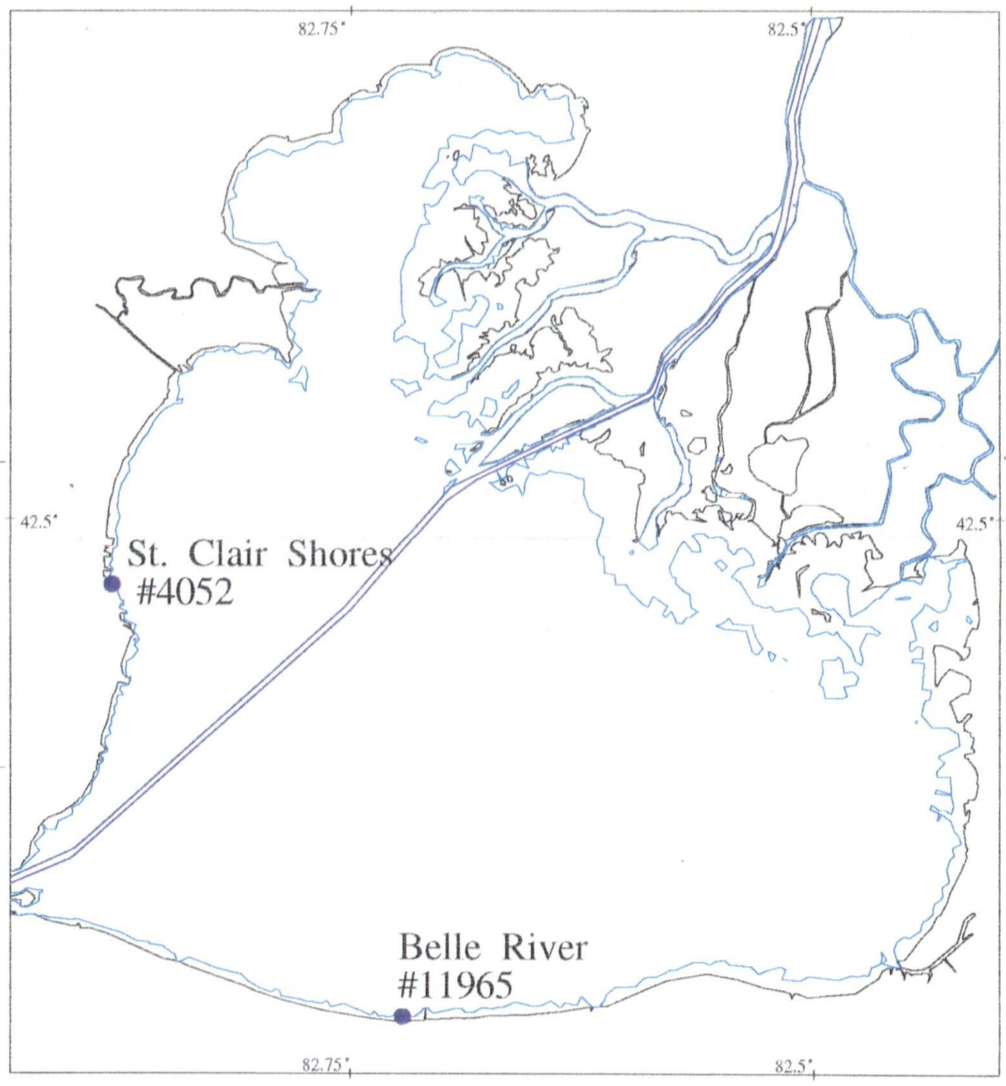
Lake St. Clair

Map Legend

- Current Lake St. Clair Shoreline
- Altered Climate Lake St. Clair Shoreline
- Navigation Channels
- ● Water Level Gauge Location and Number







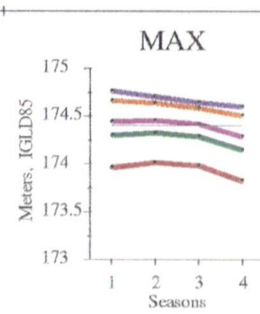
Graph Key

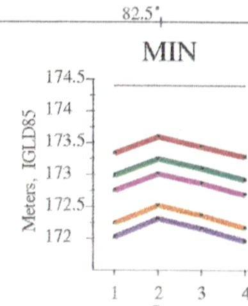
Water Level

- 2 year return period
- 5 year return period
- 10 year return period
- 50 year return period
- 100 year return period
- chart datum

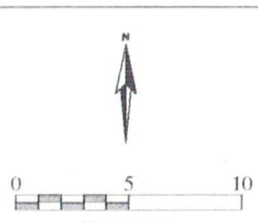
Seasons

1 = Feb – Apr
2 = May – Jul
3 = Aug – Oct
4 = Nov – Jan





Climate Change Impacts on Western Lake Erie, Detroit River, and Lake St. Clair Water Levels



Polyconic Projection

GLERL GIS Laboratory

June 1995

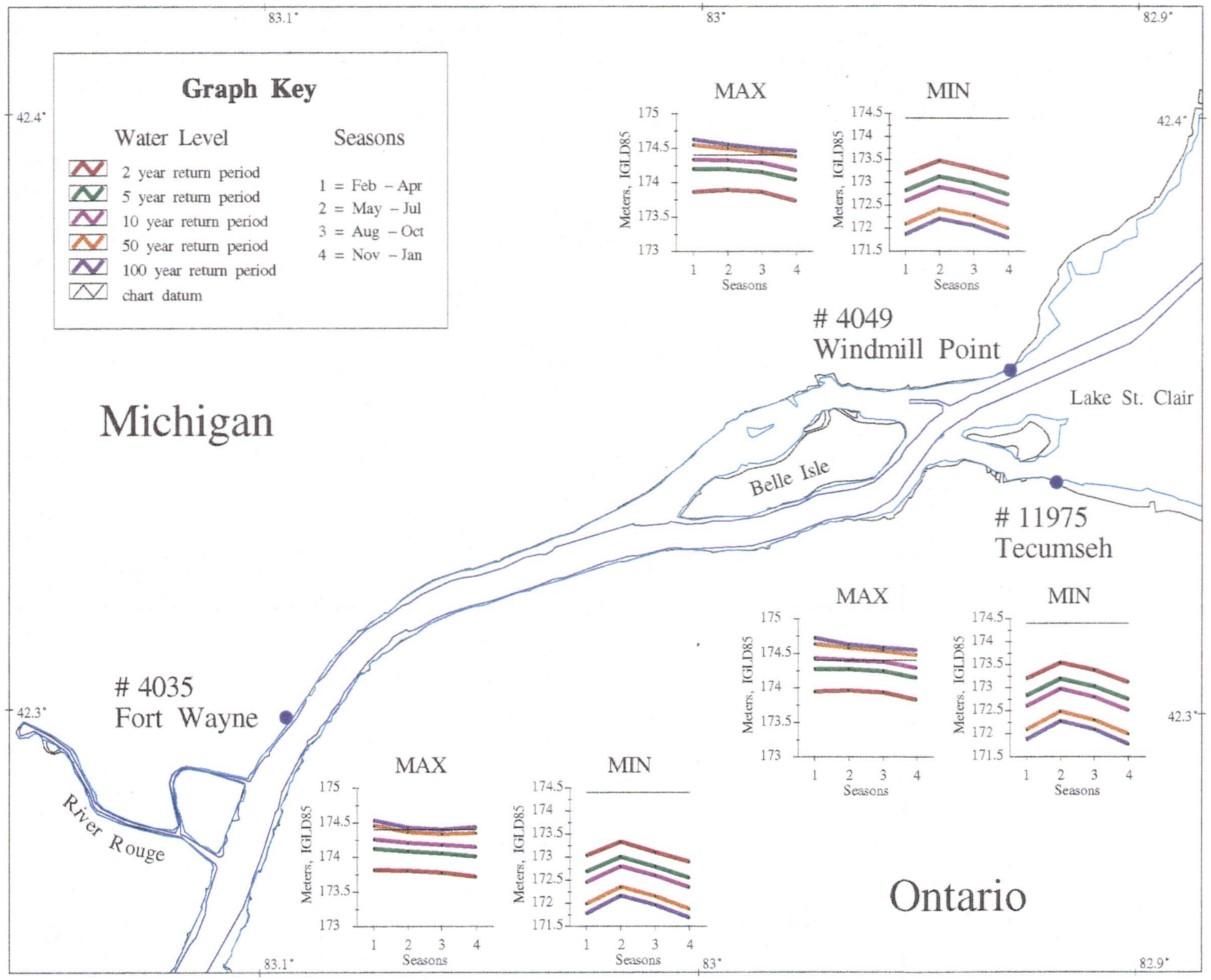


PLATE 2

Upper Detroit River

Great Lakes – St. Lawrence River Basin Project

Climate Change Impacts on Western Lake Erie, Detroit River, and Lake St. Clair Water Levels

Map Legend

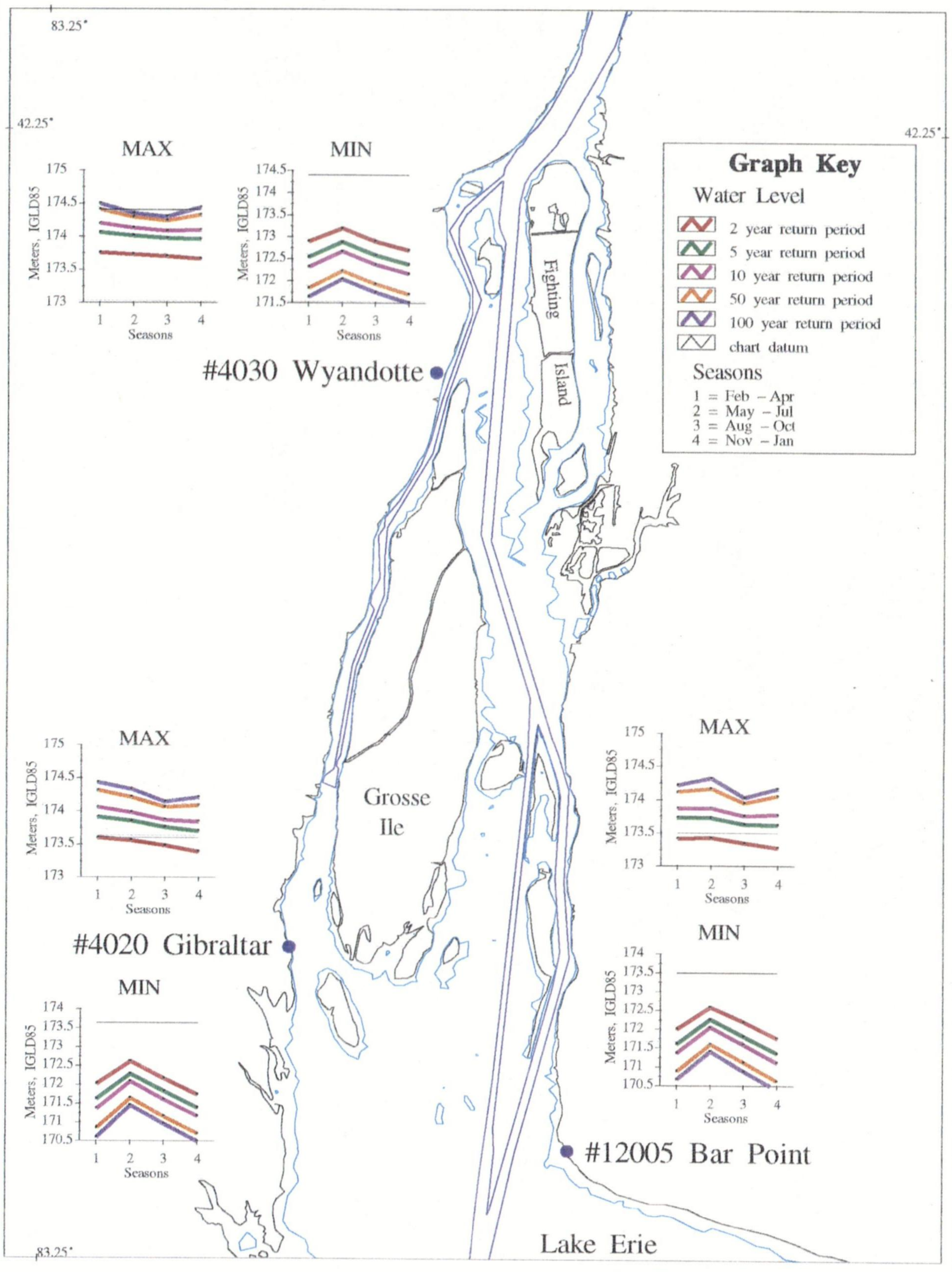
- Current Detroit River Shoreline
- Altered Climate Detroit River Shoreline
- Navigation Channels
- Water Level Gauge Location and Number

GLERL GIS Laboratory, June 1995

0 2.5 5
Kilometers

Polyconic Projection

PLATE 3 **Lower Detroit River**



Great Lakes– St. Lawrence River Basin Project

Climate Change Impacts on Western Lake Erie Detroit River, and Lake St. Clair Water Levels

N

0 2.5 5

Kilometers

Polyconic Projection

Map Legend

- Current Detroit River Shoreline
- Altered Climate Detroit River Shoreline
- Navigation Channels
- Water Level Gauge Location and Number

GLERL GIS Laboratory

June 1995

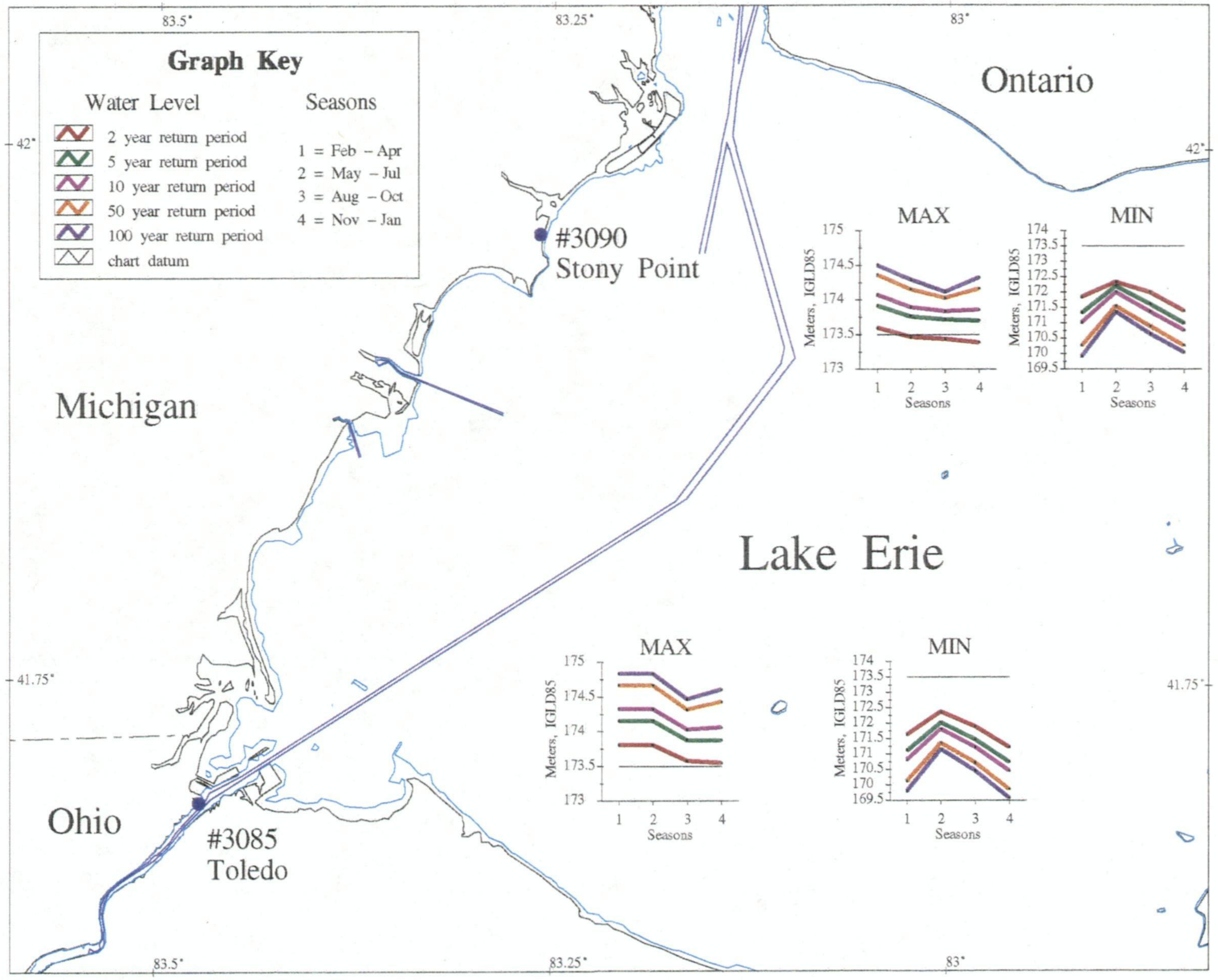


PLATE 4

Western Lake Erie

Great Lakes – St. Lawrence River Basin Project

Climate Change Impacts on Western Lake Erie, Detroit River, and Lake St. Clair Water Levels

Map Legend

- Current Lake Erie Shoreline
- Altered Climate Lake Erie Shoreline
- Navigation Channels
- State Boundary
- Water Level Gauge Location and Number

GLERL GIS Laboratory, June 1995

N

0 5 10

Kilometers

Polyconic Projection

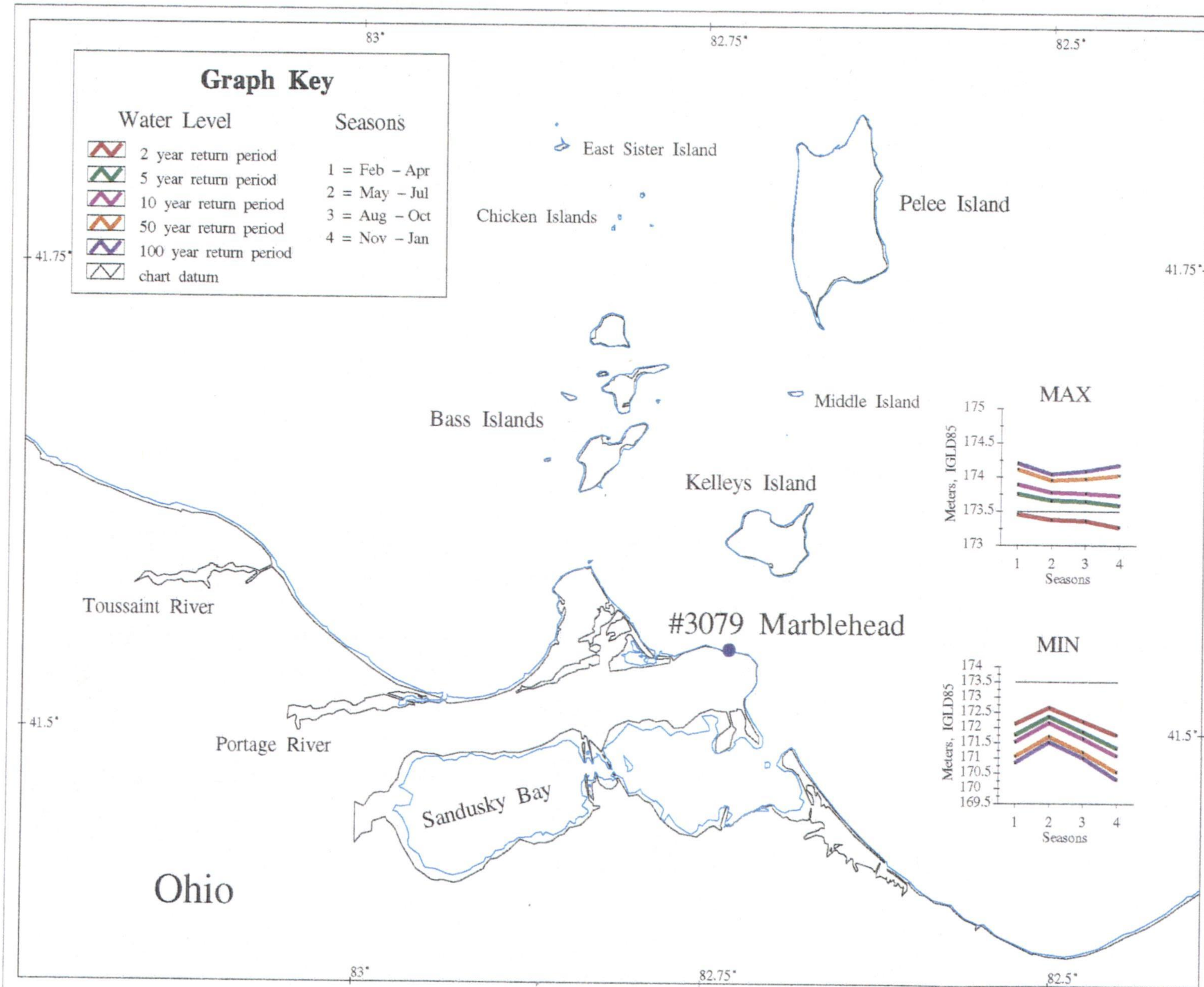


PLATE 5

Western Lake Erie

Great Lakes – St. Lawrence River Basin Project

Climate Change Impacts on Western Lake Erie, Detroit River, and Lake St. Clair Water Levels

Map Legend

Current Lake Erie Shoreline

Altered Climate Lake Erie Shoreline

Water Level Gauge Location and Number

GLERL GIS Laboratory, June 1995

N

0 5 10

Kilometers

Polyconic Projection

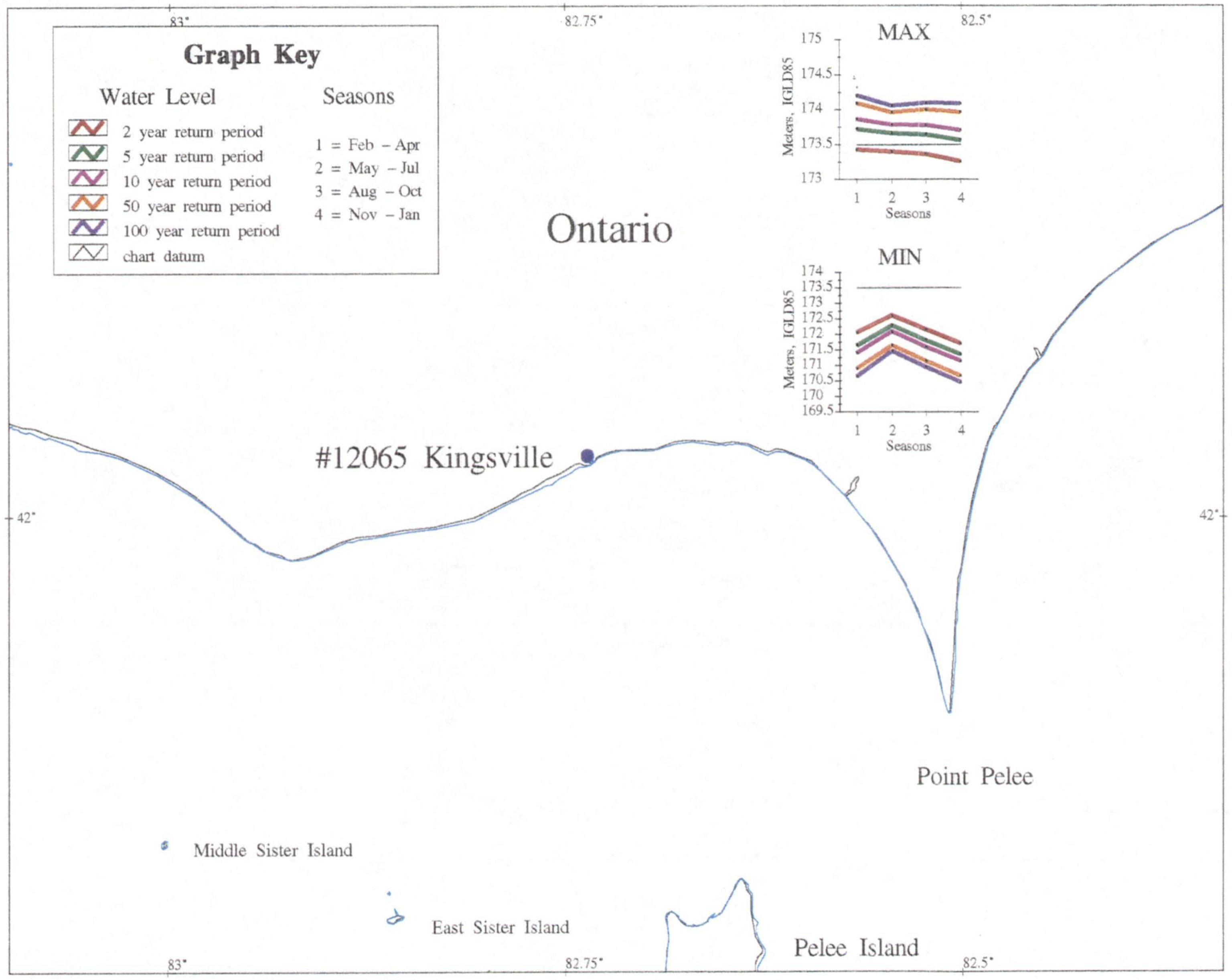


PLATE 6

Western Lake Erie

Great Lakes – St. Lawrence River Basin Project

Climate Change Impacts on Western Lake Erie, Detroit River, and Lake St. Clair Water Levels

Map Legend

- Current Lake Erie Shoreline
- Altered Climate Lake Erie Shoreline
- Water Level Gauge Location and Number

GLERL GIS Laboratory, June 1995

N

0 5 10
Kilometers

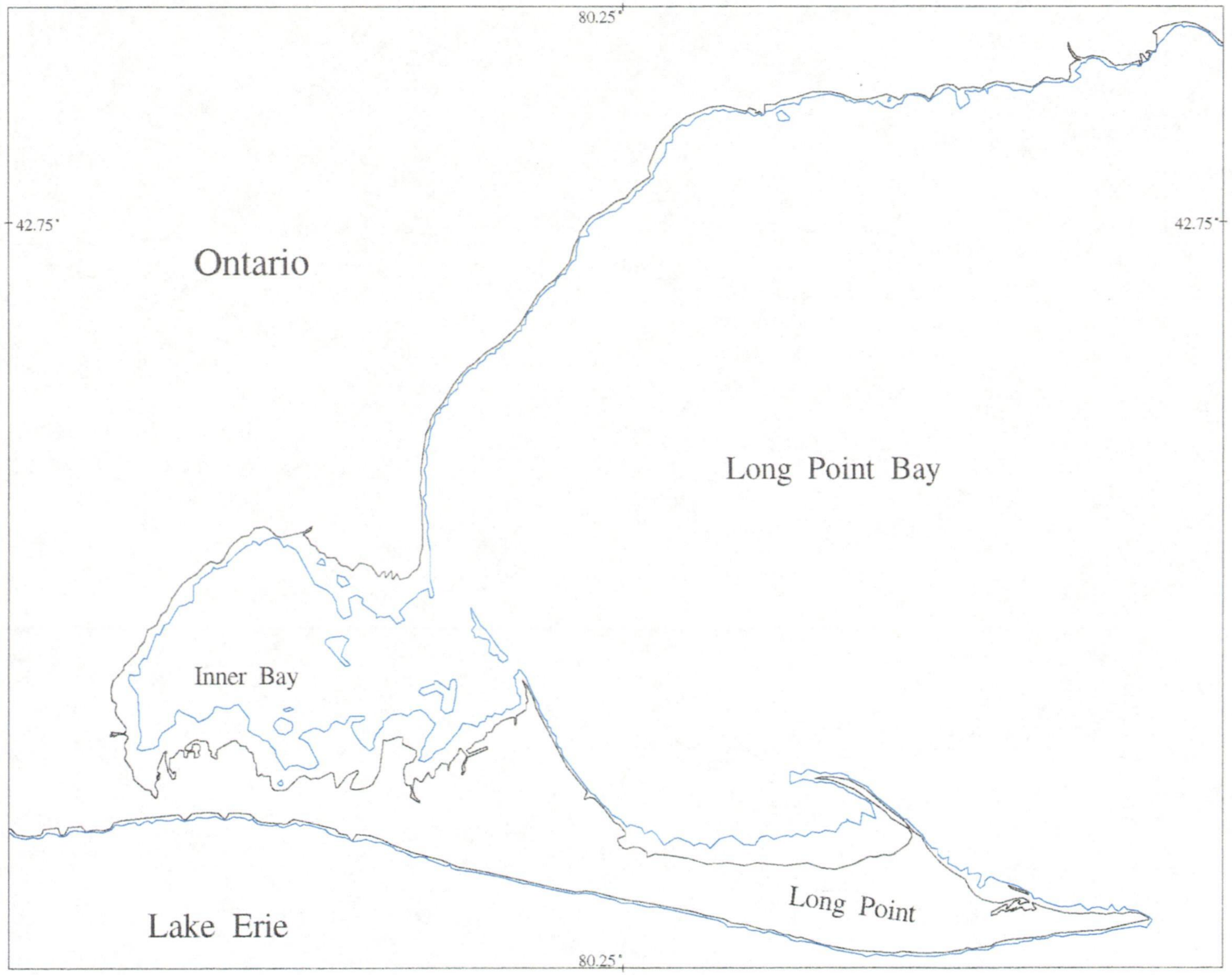
Polyconic Projection

PLATE 7

Long Point

Great Lakes – St. Lawrence River Basin Project

Climate Change Impacts on Western Lake Erie, Detroit River, and Lake St. Clair Water Levels



Map Legend

- Current Lake Erie Shoreline
- Altered Climate Lake Erie Shoreline

GLERL GIS Laboratory, June 1995

N

0 5 10

Kilometers

Polyconic Projection