NWRI CONTRIBUTION 87-18

This report has been prepared for the Marine Directorate,
Public Works Canada, Ottawa.

GREAT LAKES WATER LEVELS:
A REVIEW FOR COASTAL ENGINEERING DESIGN

by

Craig T. Bishop

Research and Applications Branch

National Water Research Institute
Environment Canada
867 Lakeshore Road, P.O. Box 5050
Burlington, Ontario L7R 4A6

August, 1987

MANAGEMENT PERSPECTIVE

Water levels on the Great Lakes are a major factor in the planning and management of the resource itself, and in the management of the shoreline. This latter fact was brought home by the recent high water levels. It is necessary for planning purposes to have pre-assigned design water levels. This report reviews the available literature on subjects related to Great Lakes water levels and provides information on anticipated water levels. It was prepared for Public Works Canada and provides them with the necessary background information to establish design levels.

Dr. J. Lawrence
Director
Research and Applications Branch

PERSPECTIVE DE GESTION

Les niveaux d'eau dans les Grands Lacs constituent un facteur important dans la planification et la gestion de la ressource elle-même et la gestion du rivage. On a pu se rendre compte de ce fait à la suite des récents niveaux élevés de l'eau. Pour la planification, il est nécessaire de disposer de niveaux d'eau nominaux fixés à l'avance. Ce rapport recense la documentation disponible sur les sujets reliés aux niveaux d'eau des Grands Lacs et fournit des renseignements sur les niveaux anticipés. Il a été rédigé à l'intention de Travaux Publics Canada et fournit aux fonctionnaires de ce Ministère les données de base nécessaires pour établir des niveaux nominaux.

ABSTRACT

Available Great Lakes water level data, some as early as 1815, are reviewed. Estimates of earlier (up to 350 years ago) water level ranges are deduced from historical, archeological and geologic sources. The latter water levels did not exceed those on record since 1815. Literature on climate change, both past and future, is reviewed from the Great Lakes Basin. Results from numerical hydrologic response models are summarized to determine possible ranges for future Great Lakes water levels. Over the next 50 years, water levels are unlikely to exceed appreciably the modern records.

RÉSUMÉ

On examine les données disponibles sur le niveau de l'eau des Grands Lacs, dont certaines datent de 1815. A partir de sources historiques, archéologiques et géologiques, on évalue par déduction les intervalles de variation du niveau de l'eau à des époques anciennes (jusqu'à il y a 350 ans). Ces niveaux plus anciens ne dépassent pas ceux enregistrés depuis 1815. On examine, à partir du bassin des Grands Lacs, la documentation publiée sur le changement du climat dans le passé et dans le futur. On résume les résultats obtenus de modèles numériques de réponse hydrologique pour déterminer les gammes de variation possibles des niveaux d'eau des Grands Lacs pour l'avenir. Au cours des 50 prochaines années il n'est guère probable que ces niveaux dépassent de façon appréciable les valeurs qui sont relevées dans les registres de notre temps.

TABLE OF CONTENTS

1.0 INTRODUCTION

High water levels occurred on all the Great Lakes, except Lake Ontario, during 1985-1986, setting new records for the 20th century. Many harbour structures and small craft facilities on the Great Lakes were submerged or overtopped during some storms in this period. Consequently, many cases of structural damage and unacceptably high wave transmission were reported.

Most of the federal harbour structures were constructed in the 1900-1930 period. Later reconstructions and additions between 1930-1960 continued to use the initial design water levels with some updating. As a result, most of the harbour structures are built to elevations representative of water levels from the 1900-1960 period, often referred to as the "normal" water levels. This has defined what is accepted as a "normal" elevation for structures and the subsequent freeboard.

Public Works Canada is in the process of developing guidelines for evaluating the need for remedial measures at federal harbour structures and for establishing guidelines for design elevations for new structures. This report addresses historical Great Lakes water level information and looks at possible future levels for the purpose of planning coastal facilities over the next 50 years. In particular, the potential impacts of predicted climate change on Great Lakes levels are reviewed.

2.0 RECORDED WATER LEVEL MEASUREMENTS

Recorded water level measurements on the Great Lakes date to 1815 (U.S. Deep Waterways Commission 1897). Man-made changes in the basin have had some effects on the levels. These actions of man include water diversions, construction of control structures, landfilling and construction in connecting channels, land use alteration (urbanization, deforestation, improved drainage) and increased consumptive uses. However, for the most part, the effects of man are small in comparison to the seasonal water level variations and to those related to climatic variability.

Prior to 1860 most water level measurements on the Great Lakes were made intermittently or, at best, somewhat irregularly. Starting in 1860 a regular program of recording daily water level readings from staff gauges was instituted. From the turn of the century to around the time of World War I, automatic water level gauges began to be used. The quality and quantity of water level data is best for the measurements made with the automatic gauges, somewhat poorer for the daily staff gauge measurements back to 1860, and poorer still prior to 1860. However, to ignore the data prior to 1860, as has been done in many Great Lakes water level studies, is to discard much valuable information. Due to numerous datum changes and the irregular nature of the data collection, the accuracy of the water level data prior to 1860 is not known. Monthly water level estimates since 1860 are probably accurate to within a few centimetres. Except when specifically noted, all elevations in this report are referenced to the International Great Lakes Datum (1955), or simply IGLD (1955).

2.1 Diversions

The Great Lakes Basin and existing diversions are shown in Figure 1. There are two existing diversions of water into Lake Superior - the Long Lac diversion completed in 1941 and the Ogoki diversion completed in 1943. Their combined average flow is 159 m^3/s (5600 cfs). Water has been diverted from the Great Lakes basin via the Chicago diversion since 1848. Until 1900 the diverted flow averaged 14 m^3/s (500 cfs). After 1900, and until 1938, the diverted flow was increased, and at times exceeded 118 m^3/s (4167 cfs). From 1938, the diverted flow has averaged 91 m^3/s (3200 cfs). The Welland Canal takes water from Lake Erie, bypassing the Niagara River, and diverts it across the Niagara Peninsula to Lake Ontario. The original canal was built in 1829 but has been reconstructed, lengthened and realigned several times. Canal flow rates have been increased with time to the present value (since 1973) averaging 260 m^3/s (9200 cfs). A relatively small diversion takes water from the Niagara River (downstream from the natural hydraulic control of Lake Erie) into the New York State Barge Canal. The average flow is estimated at 20 m^3/s (700 cfs) and, since it is all returned to Lake Ontario, has no hydraulic effect on the Great Lakes levels.

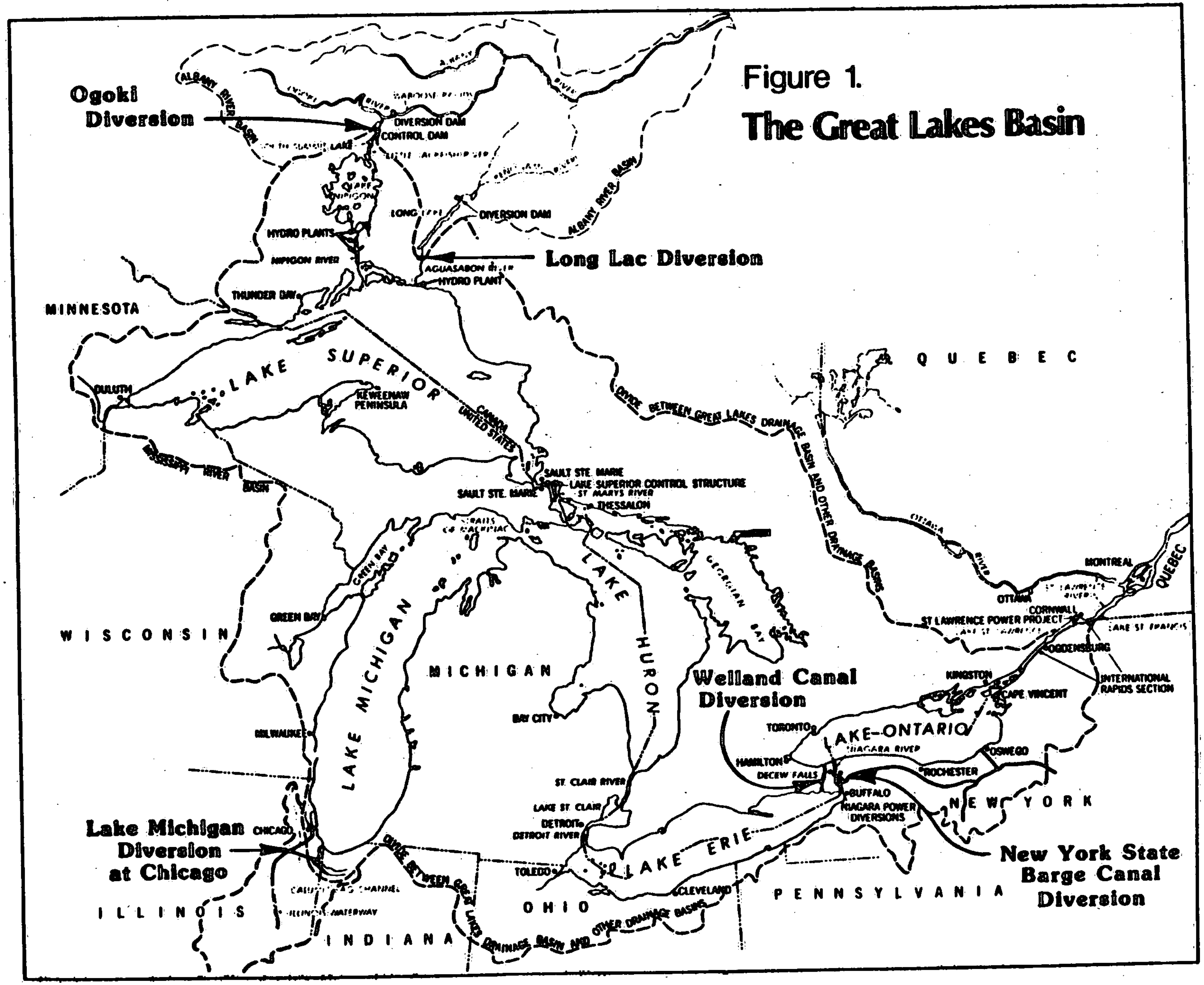

Figure 1.
The Great Lakes Basin

The theoretical effect of existing diversions on Great Lakes water levels is given in Table 1. The combined effect is to raise the mean levels of Lakes Superior and Ontario by 2.1 cm and 2.4 cm, respectively, while the mean levels of Lakes Michigan-Huron and Erie have been reduced by 0.6 cm and 10.1 cm, respectively (IJC 1985).

2.2 Lake Superior

Prior to 1887, a natural flow regime controlled Lake Superior outflows through the St. Mary's River. Construction of the International Bridge in 1887 effectively decreased the river's flow. By 1914, several more changes in the river channel had been completed, including control structures for hydropower companies. The levels of Lake Superior have been controlled to varying extents since 1903, and have been considered fully regulated since 1922. IJC Orders in 1979 require that Lake Superior be maintained so as not to exceed 183.49 m (602.0 ft) nor fall below 182.39 m (598.4 ft)

The longest record of water level measurements on Lake Superior is at Marquette, Michigan (Coordinating Committee 1978). The National Ocean Survey (NOS) report gives continuous data beginning in 1860, but Hartmann (1986) points out that the gauge at Marquette was not operational between December 1868 and October 1871. Accordingly, the missing levels must have been derived from other gauges. Also, lack of common benchmarks for the data prior to 1868 means these levels should be used with caution. The Marquette gauge was closed in

TABLE 1: Theoretical effect of existing diversion rates on Great Lakes water levels (IJC 1985) (centimetres).

Diversion	Rates m^3/s	Superior				Michigan-Huron			
		Mean	Max	Min	Range	Mean	Max	Min	Range
Long Lac/Ogoki	159	+6.4	+3.7	+25.9	-22.3	+11.3	+11.0	+13.1	-2.1
Lake Michigan at Chicago	91	-2.1	0	-1.8	+1.8	-6.4	-6.1	-7.3	+1.2
Welland Canal[2]	266	-1.8	0	-1.8	+1.8	-5.5	-5.5	-5.5	0
Combined	159 91 266	+2.1	+3.4	+22.3	-18.9	-0.6	-1.8	+1.2	-3.0

Diversion	Rates m^3/s	Erie				Ontario[1]			
		Mean	Max	Min	Range	Mean	Max	Min	Range
Long Lac/Ogoki	159	+7.6	+7.9	+8.5	-0.6	+6.7	+38.4	+44.8	-6.4
Lake Michigan at Chicago	91	-4.3	-4.6	-4.6	0	-3.0	-55.5	-14.6	-40.8
Welland Canal[2]	266	-13.4	-12.8	-14.6	+1.8	0	-2.1	+0.3	-2.4
Combined	159 91 266	-10.1	-9.8	-11.0	+1.2	+2.4	+19.5	+18.0	+1.5

Notes:
1. Lake Ontario levels were computed under the current regulation Plan 1958-D without application of the International St. Lawrence River Board of Control discretionary deviations.
2. The Study Board evaluated a rate of 266 cms for the Welland Canal, a rate that could likely occur in the future. The evaluation of the current rate of 260 m^3/s would give very similar results.
3. The (-) sign signifies a reduction in level while a (+) signifies an increase.

October 1980. The time series of annual maximum monthly mean water levels for Lake Superior at Marguette is given in Figure 2, with data from Michipicoten, Ontario from 1981 to 1986.

The highest recorded monthly mean level since 1860 is 183.51 m (602.07 ft) in 1876 (Table 2). The lowest recorded monthly mean level since 1860 is 182.34 m (598.23 ft) in 1926. By 1912, Lake Superior levels had been permanently raised by 0.18 m (0.6 ft) due to the reduced discharge capacity of the St. Mary's River (Hartmann 1986). The report of the Select Committee of the Ontario Legislature (1953) gives a maximum level of 183.94 m (603.46 ft) for Lake Superior in 1838. However, no gauges were in operation on Lake Superior in 1838. Therefore, the level reported for 1838 was inferred from other information (U.S. Army Corps of Engineers 1861); its accuracy is not known. Prior to 1860, a few lake level estimates for Lake Superior in 1847, 1851 to 1856, and 1859 can be found in the report of the U.S. Deep Waterways Commission (1897). Lack of reference to permanent benchmarks prevents accurate updating of these levels to other datums.

In 1985, daily mean water levels at some gauging stations on Lake Superior exceeded 183.49 m on three occasions. Public pressure to reduce water levels on the lower Great Lakes by storing water on Lake Superior called into question the sanctity of the 183.49 m limit specified by the IJC. In reviewing this upper limit, Hartmann (1986) concluded that the 183.49 m (602.0 ft) level should only be considered

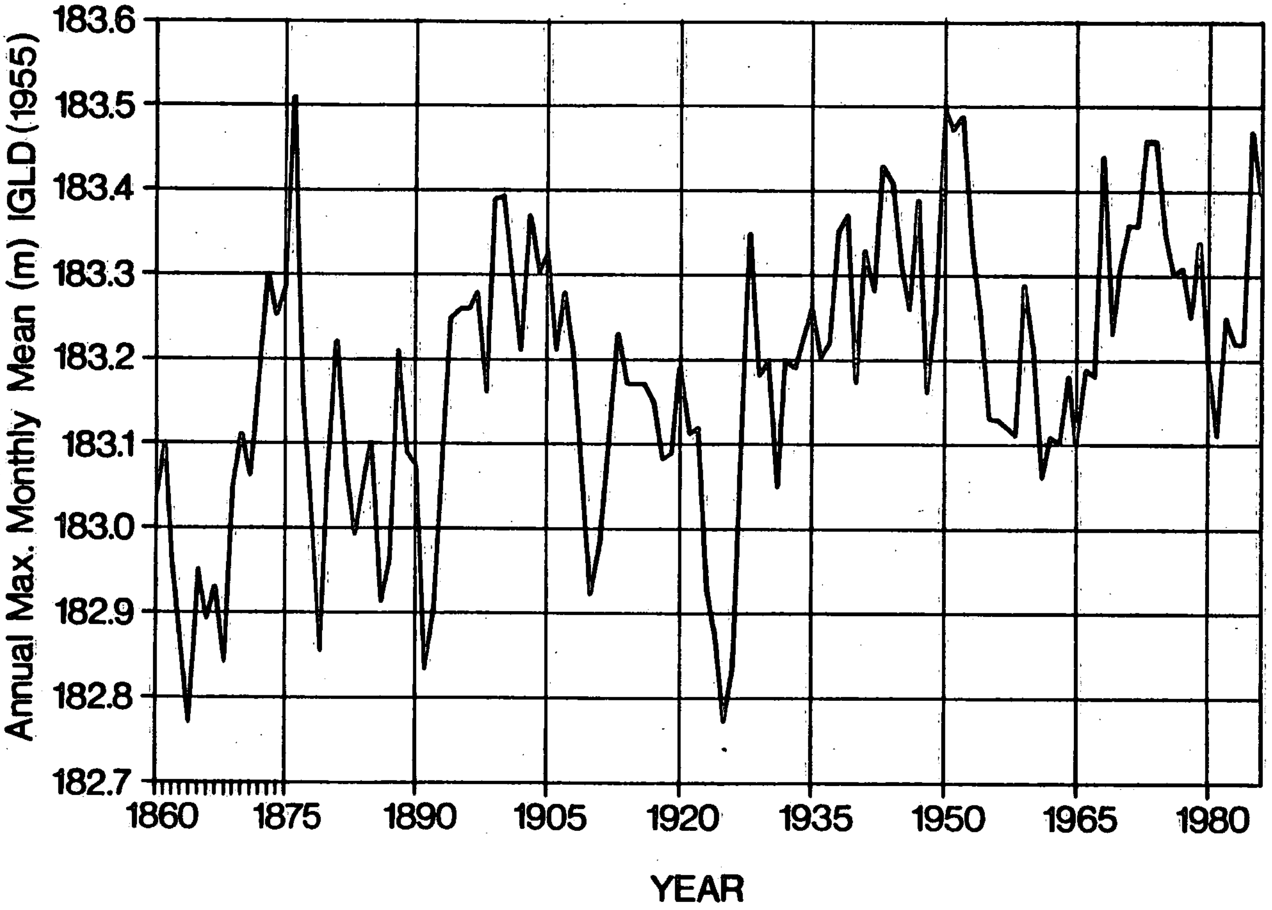

Figure 2. Lake Superior Water Levels (Marquette)

(1981–86 at Michipicoten)

a goal for regulation under ordinary water supply conditions; in times of high water supplies such as in 1876 and 1985, Lake Superior should be expected to exceed this upper limit by up to 0.15 m (0.5 ft) giving an upper limit of 183.64 m (602.5 ft). The estimated high water level of 1838 is 0.3 m (1 ft) above this upper limit.

TABLE 2: Highest annual maximum monthly mean water levels for Lake Superior, 1860 to 1986.

Rank	Year	Water Level m IGLD (1955)
1	1876	183.51*
2	1950	183.50
3	1952	183.49
4	1951	183.47
	1985	
6	1973	183.46
	1974	
8	1968	183.44
9	1943	183.43
10	1944	183.41
11	1899	183.39
	1900	
	1986	
14	1903	183.37
	1939	
16	1971	183.36
	1972	
18	1928	183.35
	1938	
	1975	

* The mean monthly level for October 1985 at Thunder Bay, Ontario was 183.53 m IGLD.

2.3 Lake Michigan-Huron

Lakes Michigan and Huron are connected by the broad, deep Straits of Mackinac; hydraulically, they behave as one lake. The earliest reliable water levels recorded for Lake Michigan-Huron are from Milwaukee in 1819 (U.S. Deep Waterways Commission 1897, Coordinating Committee 1978). These early records for the period 1819 to 1859 have been converted to IGLD (1955) and are presented in Table 3. The accuracy of this data is unknown. The U.S. Deep Waterways Commission (1897) also indicates that the levels in 1800 to 1802 were "very high", and in 1814-1815 "unusually high".

Water levels of Lake Michigan-Huron have been affected by the actions of man at the outlet of Lake Huron and in the St. Clair River. Artificial changes for navigation improvements began in 1856 when a channel was cut across sand bars in the lower St. Clair River to provide a 2.7 m draft. Additional dredging in the period 1893 to 1899 was estimated to be responsible for a 0.2 m permanent lowering of the lake level (Quinn and Croley 1981). Other estimates for the pre-1900 drop in lake level due to dredging include 0.43 m by Brunk (1968) and 0.09 m by Lawhead (1961).

Post-1900 changes consist of dredging for commercial gravel removal in the upper St. Clair River from 1908 to 1925 and uncompensated navigation improvements for the 25 ft (7.6 m) and 27 ft (8.2 m) projects completed in 1933 and 1962, respectively. Using dynamic flow models, Derecki (1982) estimated the ultimate effect of post-1900

TABLE 3: Lake Michigan-Huron water levels pre-1860 (source: U.S. Deep Waterways Commission 1897) m IGLD (1955)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1819		175.66				176.27						
1820												
1821												
1822												
1823												
1824												
1825												
1826												
1827												
1828						177.14	177.15	177.14				
1829						177.14						
1830												
1831												
1832												
1833												
1834												
1835												
1836			176.48			177.39						
1837					176.72	177.52						
1838						177.70	177.70					
1839							177.29					176.58
1840	176.33			176.76	176.80	176.82	176.90	176.82	176.71	176.67	176.61	176.54
1841	176.57											176.35
1842												
1843												
1844												
1845						176.67						
1846	176.36	176.35	176.40	176.54	176.65	176.65	176.67	176.58	176.44	176.36	176.28	176.16
1847	176.06	176.02	176.09	176.12	176.18	176.30	176.32	176.30	176.34	176.24	176.21	176.15
1848	176.09	176.07	176.07	176.17	176.08	176.16	176.34	176.34	176.28	176.26	176.23	176.24
1849	176.23	176.26	176.20	176.26	176.30	176.46	176.55	176.55				
1850												
1851							176.91	177.00			176.96	
1852								177.24	177.08	177.06	177.10	
1853												
1854				176.57	176.77	176.85	176.95	176.94	176.90	176.73	176.65	176.61
1855	176.54	176.53	176.55	176.58	176.75	176.85	176.88	176.91	176.94	176.90	176.84	176.87
1856	176.89	176.74	176.75	176.79	176.92	176.90	176.92	176.86	176.82	176.76	176.75	176.68
1857	176.62	176.70	176.74	176.88	176.99	177.08	177.21	177.27	177.22	177.24	177.00	177.01
1858	176.99	176.90	176.87	177.03	177.18	177.31	177.43	177.41	177.29	177.25	177.15	177.15
1859	177.00	177.04	177.06	177.26	177.30	177.30	177.50	177.41	177.33	177.23	177.08	177.10

dredging to be a permanent lowering of the lake levels by 0.27 m. Therefore, the total lowering of Lake Michigan-Huron due to pre- and post-1900 dredging and other navigation improvements is approximately 0.5 m.

The water level record for Harbor Beach, Michigan is the longest continuous record for Lake Huron, starting in 1860. Earlier partial data from Milwaukee are used to supplement the Harbor Beach data in Figure 3. The highest annual maximum monthly means are given in Table 4. The recent high levels of 1986, 1974 and 1973 would have been comparable to the record highs of the 1800's if the lowering of the lake by about 0.5 m due to dredging had not occurred.

Extreme high water levels on Lake Michigan-Huron were experienced in 1814, 1815, 1836 to 1838, 1858 to 1861, 1876, 1883 to 1887 and 1986. Extreme low water levels occurred in 1925, 1926, 1932 to 1937 and 1963 to 1965.

2.4 Lake Erie

The earliest reliable water levels recorded for Lake Erie are from Buffalo in 1819 (U.S. Deep Waterways Commission 1897, Coordinating Committee 1969, 1987). Tait (1983) has converted measurements from various sources for the period 1819 to 1859 to IGLD (1955) and the results are given in Table 5.

The outlet of Lake Erie is controlled naturally by a rock sill at the Peace Bridge between Buffalo and Fort Erie. The level of Lake Erie is also affected, to a small degree, by the operation of the

TABLE 4: Highest annual maximum monthly mean water levels for Lake Michigan-Huron, 1836 to 1986*.

Rank	Year	Water Level m IGLD (1955)
1	1838	177.70
2	1837	177.52
3	1859	177.50
4	1858	177.43
5	1886	177.42
6	1876	177.40
7	1836	177.39
8	1861	177.37
9	1883	177.32
10	1885	177.31
11	1860	177.30
12	1986	177.29
	1839	
14	1857	177.27
	1862	
16	1852	177.24
17	1884	177.23
18	1887	177.19
19	1871	177.16
20	1974	177.15
	1828	
22	1830	177.14
23	1973	177.09

* No data for 1841 to 1844, 1850, 1853.

Chippawa-Grass Island Pool (CGIP) at the Robert Moses Power Plant. The present International Joint Commission (IJC) Directive requires that the CGIP control structure be operated to ensure maintenance of the present long term mean level of the Pool at an elevation of 561.0 ft (170.99 m). When the level of Lake Erie is above average, maintenance of the Pool level at 561.0 ft (which is below the natural level) has the tendency to slightly lower the level of Lake Erie. Any further lowering of the Pool level has progressively less effect on

TABLE 5: Lake Erie water levels pre-1860 (source: Tait 1983) m IGLD (1955)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1819						173.10		173.19				
1820								173.19				
1821												
1822						173.18						
1823												
1824												
1825						173.48						
1826						173.84						
1827												
1828						173.47		173.67				
1829												
1830								173.67				
1831												
1832						173.84						
1833						173.74						
1834						173.93						
1835						173.86			173.70			
1836								173.97				
1837	173.80					173.96		174.34	173.63			
1838					174.41	174.72	174.64	174.49	174.32	174.26		174.13
1839	173.63				174.17	174.27	174.34	174.36	174.12	174.41		
1840					174.42	174.59	174.42	174.44	174.11	174.05		
1841			173.91		174.17	174.09	174.95	173.80	173.63	173.37		
1842	174.01				174.17							
1843					174.00							
1844					174.08							
1845					174.08			173.90	173.81	173.77	173.63	173.56
1846	173.48	173.37	173.35	173.47	173.76	173.86	173.86	173.79				
1847					173.93					173.84		
1848					173.85					174.00		
1849					174.11	174.14	174.10	174.10	174.05	173.99	174.07	174.15
1850		173.99	174.05	174.10	174.10	174.03	174.07	174.02	173.97	173.95	173.86	173.93
1851	174.06	173.98	174.11	174.11	174.30	174.38	174.40	174.33	174.23	174.24	174.21	174.26
1852	174.08	173.96	174.05	174.27	174.52	174.58	174.49	174.43	174.37	174.27	174.30	174.39
1853	174.43	174.41	174.37	174.34	174.61	174.67	174.55	174.47	174.40	174.33	174.16	174.23
1854	174.30	174.02	174.14	174.19	174.41	174.37	174.40	174.21	174.11	174.07	174.16	173.99
1855	173.97	173.87	173.89	173.98	174.14	174.22	174.38	174.44	174.24	174.32	174.34	174.42
1856	174.23	174.11	174.01	174.16	174.14	174.26	174.27	174.22	174.15	173.95	173.91	174.00
1857	173.77	173.78	173.73*	173.92*	174.31	174.42	174.45	174.44	174.36	174.22	174.38	174.38
1858	174.41	174.29	174.30	174.33	174.41	174.83	174.81	174.78	174.61	174.58	174.45	174.48
1859	174.48	174.41	174.54	174.71	174.68	174.67	174.69	174.59	174.41	174.48	174.42	174.36

* Data for Cleveland.

the level of Lake Erie because there is an increase in the hydraulic control of the sill at the Peace Bridge. Calculations show that lowering the Pool to 560.3 ft (170.78 m), the lowest possible while still meeting the requirements of the Niagara Treaty, would lower the level of Lake Erie by only 0.04 to 0.06 ft (0.01 to 0.02 m). Accordingly, the International Niagara Board of Control recommends not using the CGIP Control Structure to attempt to lower the level of Lake Erie (International Niagara Board of Control 1986).

Unlike Lake Michigan-Huron, changes at the outlet of Lake Erie since 1819 are usually considered to have had a negligible effect on water levels. Numerical calculations using the HEC-2 backwater model with a steady flow of 231,800 cfs (the monthly mean flow with a 10% probability of exceedance) show that landfilling on both sides of the Niagara River since 1918, as well as the construction of the Peace Bridge in 1925, have raised the level of Lake Erie by about 0.18 ft (0.055 m) relative to pre-1918 conditions (Water Planning and Management Branch 1983).

The longest continuous record of Lake Erie levels is for Port Colborne, Ontario, beginning in May 1849. Prior to 1849, partial data are available from Buffalo and Cleveland. These early data are used to supplement the Port Colborne data in Figure 4. The highest annual maximum monthly means are listed in Table 6. Prior to the "modern" period of record using automatic gauges (starting August 1911 at Port Colborne), extreme high water levels were experienced in 1838 and again during the decade of the 1850's. Extreme low water levels occurred in 1819 to 1825, 1925, 1934 to 1936 and 1963 to 1965. A downward trend in the annual maxima can be seen from the 1850's to the mid 1930's, and a rising trend from then to now. This has been discussed by Fleming (1983).

TABLE 6: Highest annual maximum monthly mean water levels for Lake Erie, 1832 to 1986.

Rank	Year	Water Level m IGLD (1955)
1	1986	174.85
2	1858	174.83
3	1985	174.82
4	1973	174.79
5	1974	174.73
6	1838	174.72
7	1859	174.71
8	1862	174.70
9	1853	174.67
10	1860	174.66
11	1876	174.63
12	1861	174.62
13	1976	174.60
14	1840	174.59
15	1952	174.58
	1852	
17	1975	174.56
18	1883	174.54
19	1882	174.52
	1980	
	1983	

Additional early information for Lake Erie is given in the report of the U.S. Deep Waterways Commission (1897):

- 1790, 5.50 ft above 1819, which gives 174.87 m (this is comparable to the record high level of 1986).
- 1795-96, described as low.
- 1800-02, high.
- 1806, low.
- 1809, unusually low.
- 1810-11, 6 ft below 1838, which gives 172.9 m (this is comparable to the record low level of 1819).

The report also states "At Buffalo the year 1810 is remembered as one of low water, nearly or quite as low as 1819. ... [at] Cleveland ... the level during the summer of 1819 is regarded as the lowest". Further on, the report states "The old French inhabitants of Detroit have no tradition of a water level below that of the year 1819, although Detroit has been occupied since 1702. ... It is now a matter of record that in 1814 to 1815 the St. Clair and Detroit rivers were unusually high".

2.5 Lake Ontario

The earliest reliable water levels recorded for Lake Ontario are from Fort Niagara, New York in 1815 (U.S. Deep Waterways

Commission 1897, Coordinating Committee 1987). These partial records continue until 1827. From 1837 to the present, water levels have been recorded at Oswego, New York. The early records from 1815 to 1859 have been converted to IGLD (1955) and are presented in Table 7.

Water levels of Lake Ontario have been controlled by dams at Cornwall, Ontario - Massena, New York as part of the St. Lawrence Seaway since 1958. Changes in the natural hydraulic control of Lake Ontario prior to 1958 are documented in two reports of the International Lake Ontario Board of Engineers (1958a, b).

The natural control of Lake Ontario outflows was at the Galop Rapids, located approximately 113 km (70 miles) downstream from Kingston. Man-made changes to the natural control began in 1881 with dredging in the Canadian Galop Rapids channel (completed 1888) and continued with realignment of the Galop channel from 1897 to 1901, improvements to the North Channel and construction of the Gut Dam from 1903 to 1908. From water level gauge relationships, the combined effect of the works from 1881 to 1908 was to raise Lake Ontario levels by 10 cm at flows of 6800 to 8360 m^3/s (240,000 to 295,000 cfs); the average flow is approximately 6800 m^3/s.

During the period 1909 to 1952, there are no known construction activities in the Galop Rapids reach. The Gut Dam was removed between 30 October, 1952 and 6 January, 1953. From gauge relationships the effect of this dam removal was to lower Lake Ontario levels by 11, 12 and 13 cm at flows of 6800, 7570, and 8360 m^3/s (240,000;

TABLE 7: Lake Ontario water levels pre-1860 (source: U.S. Deep Waterways Commission 1897) m IGLD (1955)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1815			74.11				74.92					
1816			74.06				74.57					
1817			74.26			74.84						
1818				74.11		74.67						
1819			73.83			74.57						
1820			73.68				74.26					
1821				73.81			74.77					
1822			73.88			74.57						
1823			73.91			74.67						
1824			73.96				74.72					
1825			73.50			74.19						
1826			73.50				74.26					
1827						74.77				74.57		
•												
•												
•												
•												
1837	75.05	74.78	74.83	74.94	75.12	75.25	75.00	75.14	74.99	74.85	74.82	74.79
1838	74.93	74.91	74.96	75.07	75.25	75.39	75.49	75.15	75.19	74.97	74.95	74.92
1839	74.80	74.68	74.73	74.84	75.02	75.16	75.05	75.08	74.93	74.77	74.65	74.69
1840	74.68	74.50	74.67	74.83	75.04	75.18	75.13	75.05	74.92	74.80	74.73	74.67
1841	74.67	74.64	74.57	74.65	75.02	75.05	74.97	74.84	74.70	74.50	74.28	74.24
1842	74.34	74.43	74.55	74.61	74.72	74.65	74.80	74.70	74.65	74.54	74.47	74.37
1843	74.44	74.40	74.54	74.40	74.73	74.90	74.85	74.71	74.56	74.54	74.51	74.40
1844	74.40	74.40	74.46	74.55	74.80	74.80	74.81	74.83	74.42	74.43	74.41	74.29
1845	74.39	74.46	74.55	74.85	74.85	74.85	74.75	74.61	74.55	74.45	74.33	74.41
1846	74.27	74.19	74.34	74.42	74.50	74.57	74.57	74.50	74.42	74.42	74.34	74.42
1847	74.34	74.50	74.65	74.65	74.83	74.93	74.93	74.93	74.83	74.57	74.47	74.40
1848	74.83	74.70	74.47	74.60	74.60	74.63	74.60	74.57	74.45	74.32	74.19	74.22
1849	74.54	74.53	74.59	74.70	74.89	74.90	74.58	74.45	74.36	74.25	74.24	74.21
1850	74.28	74.31	74.41	74.51	74.66	74.72	74.62	74.48	74.43	74.32	74.20	74.21
1851	74.22	74.27	74.42	74.59	74.69	74.72	74.69	74.62	74.59	74.43	74.39	74.37
1852	74.37	74.38	74.48	74.65	74.92	75.07	75.04	74.92	74.80	74.73	74.72	74.72
1853	74.75	74.80	74.77	74.84	75.04	75.34	75.18	74.90	74.82	74.72	74.70	74.69
1854	74.65	74.58	74.60	74.72	74.93	75.03	75.05	74.99	74.86	74.65	74.44	74.23
1855	74.23	74.18	74.23	74.17	74.36	74.72	74.76	74.72	74.80	74.63	74.42	74.41
1856	74.29	74.14	74.29	74.51	74.74	75.01	75.06	74.92	74.37	74.47	74.31	74.12
1857	74.11	74.20	74.35	74.51	74.78	75.07	75.11	75.23	75.14	75.03	75.02	75.11
1858	75.12	75.08	75.05	75.13	75.40	75.49	75.45	75.45	75.32	75.24	75.21	75.20
1859	75.20	75.16	75.06	75.26	75.39	75.48	75.50	75.45	75.31	75.13	74.95	74.82

267,000; 295,000 cfs). The combined effect of all works from 1881 to 1953 is estimated to be a lowering of Lake Ontario levels by 1, 2 and 3 cm at flows of 6800, 7570 and 8360 m^3/s.

Other artificial factors which have affected the levels of Lake Ontario are diversions into Lake Superior, diversions from Lake Michigan and the regulation of outflows from Lake Superior. Diversion from Lake Michigan via the Chicago Sanitary and Ship Canal reached a maximum of 283 m^3/s (10,000 cfs) in 1928 and then decreased to about 91 m^3/s (3,200 cfs) in 1938, the limit decreed by the U.S. Supreme Court in 1930. The maximum lowering of Lake Ontario levels due to the Lake Michigan diversion was about 13 cm (0.43 ft) and occurred during 1930 to 1935.

The effects on Lake Ontario levels of regulation of Lake Superior since 1922 have varied from a raising of about 7 cm (0.23 ft) to a lowering of about 6 cm (0.19 ft). The effects are not related to Lake Ontario stages due to the storage effect of the large intervening lakes and the resulting time lag.

Prior to 1947 the net effect of diversions was a lowering of Lake Ontario levels. During 1947 the increase in Lake Ontario levels due to diversions into Lake Superior was about the same as the decrease due to diversions out of Lake Michigan. In June 1952, when the maximum monthly mean level of record was reached on Lake Ontario, the net effect of diversions was that the lake level was about 2 cm (0.06 ft) higher than it would have been without diversions. In the same month, the net effect of the Gut Dam and channel changes in the Galop Rapids reach was to raise levels 10 cm (0.33 ft) and the effect of Lake Superior regulations was to raise levels about 4 cm (0.13 ft). Therefore, man-made changes caused the level in June 1952 to be about 16 cm (0.52 ft) higher than it would have been under natural conditions.

In November 1934, when the lowest monthly mean level record was reached on Lake Ontario, the effect on Lake Ontario of diversions out of Lake Michigan was to lower levels 13 cm (0.42 ft), the net effect of the Gut Dam and channel changes was to raise levels by 8 cm (0.25 ft) and the effect of Lake Superior regulations was to lower levels by 3 cm (0.11 ft). Therefore, man-made changes caused the level in November 1934 to be about 8 cm (0.28 ft) lower than it would have been under natural conditions.

From July 1958 onwards, the level of Lake Ontario has been regulated by the Moses-Saunders and Long Sault Dams. Plan 1958-D states that the regulated monthly mean level of Lake Ontario shall not exceed 75.22 m IGLD (1955). Under abnormally high water supply conditions, the level of Lake Ontario can be expected to exceed this limit as it did in 1973, 1974 and 1976. In fact, the peak monthly mean level in 1973 was 75.57 m which is only 0.04 m less than the record level of 75.61 m set in 1952. The six-month water level forecast for Lake Ontario issued in November 1986 by the Governments of Canada and the United States predicted a mean monthly level of 75.85 m for May

1987. A subsequent moderation in water supplies, combined with continued high outflows through the St. Lawrence River made possible by benign ice conditions, led to much lower forecasts in the ensuing months. However, this episode points to the possibility that regulated Lake Ontario levels could exceed the maximum recorded level of 75.61 m.

Regulation Plan 1958-D also states that the regulated mean monthly level of Lake Ontario should be at or above 74.0 m. In general, the effect of regulation on Lake Ontario has been to moderate the extremes in levels.

Figure 5 shows the record of annual maximum monthly mean water levels for Lake Ontario using data from Fort Niagara from 1815 to 1827 and from Oswego from 1837 to the present. High levels were experienced in 1838, 1858, 1859, 1862, 1870, 1947, 1951, 1952, 1973 and 1974. Table 8 gives the 20 highest annual maximum monthly mean levels of record. Low levels were experienced in 1820, 1825, 1826, 1934 and 1935.

The Report of the U.S. Deep Waterways Commission (1897) gives the following additional information for Lake Ontario:

- 1795, the lake reported to be higher than for the past thirty years.
- Low in 1803, 1804, 1808 to 1811, 1822 to 1828.
- High in 1798, 1805 to 1807, 1812 to 1819, 1829 to 1831.

TABLE 8: Highest annual maximum monthly mean water levels for Lake Ontario, 1815 to 1986*.

Rank	Year	Water Level m IGLD (1955)
1	1952	75.61
2	1973	75.57
3	1870	75.51
	1947	
5	1859	75.50
6	1838	75.49
	1858	
8	1862	75.47
	1951	
10	1943	75.44
11	1886	75.42
	1974	
13	1908	75.40
14	1976	75.38
15	1861	75.37
	1867	
17	1929	75.36
18	1853	75.34
	1876	
	1955	

* No data for 1828 to 1836.

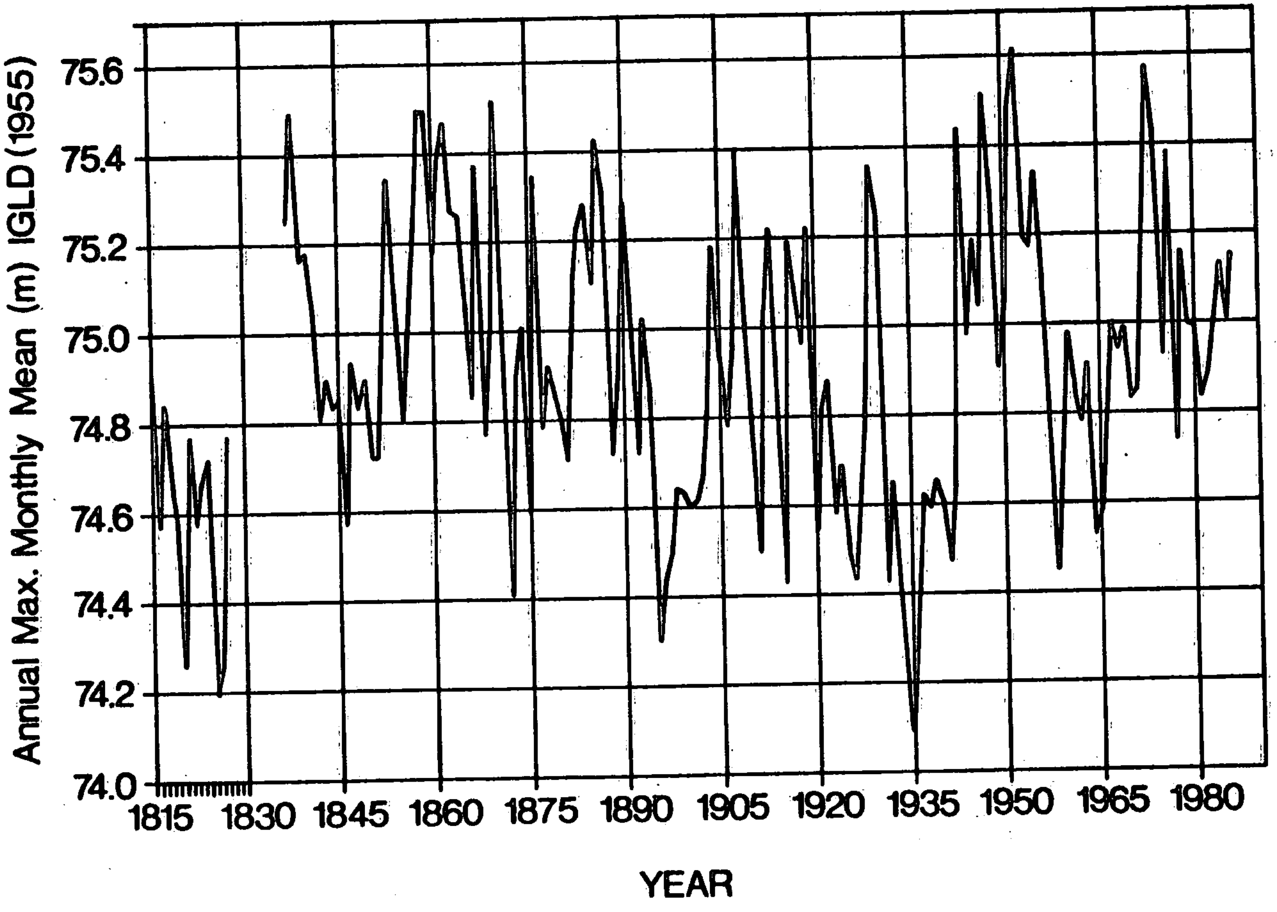

Figure 5. Lake Ontario Water Levels (Oswego)

(1815 – 1827 at Fort Niagara)

3.0 WATER LEVEL INFORMATION FROM HISTORICAL, ARCHEOLOGICAL AND GEOLOGIC SOURCES

Information concerning Great Lakes water levels can be obtained from early European settlements on the Great Lakes and, to some extent, pre-European settlements. Information from four sites is presented here. Due to time limitations of this study, this is not purported to be a complete review of such information. For instance, early water level information for Lake Ontario may be available from records of Fort Frontenac at Kingston.

Water level information for Lake Michigan-Huron over the past few thousands of years has been deduced from geologic interpretation of stratigraphic studies of a beach-ridge complex by Larsen (1985a,b; 1987). His work is also reviewed here.

Differential crustal movement over periods of centuries can significantly alter water levels relative to land elevations. Therefore, to begin, isostatic rebound is reviewed.

3.1 Isostatic Rebound

Apparent vertical crustal movement in the Great Lakes Basin is a well recognized phenomenon believed to be due to ongoing rebound following the last period of glaciation (approximately 10,000 years ago). Rates of vertical movement have been determined from long period water level records measured at numerous gauging stations on the Great Lakes. The method employed has been to average mean monthly water levels for the four months June to September recorded at each station in order to provide a yearly time series for each station. Then, differences between the yearly values are determined for selected pairs of stations and the rates of apparent vertical movement computed by linear regression of the differences. A contour map of relative crustal movement rates over the Great Lakes Basin is shown in Figure 6 from Clark and Persoage (1970) based on results of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1957). These results are based on data from 1860 to 1956, except for Lake Ontario, in which case data from 1916 to 1956 was used.

Tait and Bolduc (1985) provide the most recent analysis of rates of apparent vertical movement using data from 1916 to 1983. They included a couple of water level adjustments to the Lake Erie data which were not included in the study of 1957. Results from Tait and Bolduc (1985) show some significant differences from those of 1957 (Table 9), especially for Lake Erie, and to a lesser extent Lake Superior, but in general, the trends shown in Figure 6 are the same.

Changes in relative land-water levels resulting from crustal movement should be recognized in the design of all major marine facilities in the Great Lakes. Coastal structures having a useful life of 50 years could experience significant changes. For example, after 50 years a structure located at the western end of Lake Ontario, between Hamilton and Niagara Falls, can be expected to experience

TABLE 9: **Apparent vertical movement around the Great Lakes.**

Gauging Station Pair	Coordinating Committee (1957) mm/century*	Coordinating Committee (1957) ft/century	Tait and Bolduc (1985) mm/century	Tait and Bolduc (1985) ft/century
Lake Ontario	1916 - 1956		1916 - 1983	
Toronto Kingston	+177	+0.58	+164	+0.54
Oswego Kingston	+73	+0.24	+76	+0.25
Oswego Toronto	-104	-0.34	-88	-0.29
Lake Erie	1860 - 1956		1916 - 1983	
Cleveland Port Colborne	+131	+0.43	+3	+0.01
Port Stanley Port Colborne	+21	+0.069	-46	-0.15
Port Stanley Cleveland	+34	+0.11	-49	-0.16
Lake Michigan-Huron	1860 - 1956		1916 - 1983	
Thessalon Goderich	-213	-0.70	-215	-0.71
Goderich Milwaukee	-140	-0.46	-131	-0.43
Goderich Collingwood	+162	+0.53	+206	+0.68
Goderich Harbor Beach	-3	-0.01	+37	+0.12
Goderich Mackinaw City	+113	+0.37	+117	+0.38
Lake Superior	1860 - 1956		1916 - 1983	
Michipicoten Thunder Bay	-85	-0.28	-210	-0.69
Michipicoten Marquette	-308	-1.01	-394	-1.29
Michipicoten Duluth	-408	-1.34	-509	-1.67
Thunder Bay Marquette	-183	-0.60	-175	-0.57
Thunder Bay Duluth	-280	-0.92	-299	-0.98

* Positive values indicate that second station is rising with respect to first station.

relative water levels approximately 0.15 m (0.5 ft) higher than when built (using Figure 6). Similarly, after 50 years a structure built on the north shore of Lake Huron's North Channel can be expected to experience relative water levels approximately 0.13 m (0.4 ft) lower than when built. In general, when designing a coastal structure at any given location in the Great Lakes, Figure 6 and Table 9 should be consulted to establish the rate of differential isostatic rebound. The rate so determined, multiplied by the design life of the structure, should be considered in the design process. In fact, rates of isostatic rebound are nonlinear and are decreasing with time. However, for engineering purposes over design lives up to 100 years the nonlinearity can be assumed to be negligible.

3.2 Sainte Marie Among the Hurons

Ste. Marie was established by Jesuits in 1639 as a central base for missions to the Huron Indians. It was located on the banks of the Wye River near Georgian Bay, close to present day Midland, Ontario (Figure 7). Being the earliest European settlement on the Great Lakes, and because the water level of the river estuary there is the same as that of Lake Huron, it offers potential information on the level of Lake Huron over 300 years ago. Ste. Marie was abandoned and burned by the Jesuits on May 15, 1649. Ste. Marie II was then established on Christian Island in Georgian Bay, about 30 km to the northwest. It was abandoned in 1650 and the surviving Jesuits returned to Quebec.

HUNTER AND KIDD

Ste. Marie had a trench or canal system which ran into the Wye River (Figure 8). Based on the bottom elevation of these trenches relative to the water level in the river, two archeologists - Hunter (1911) and Kidd (1949) - estimated that the water level in the Wye River must have been considerably higher in the 1640's than now in order to allow canoes to use the trenches to enter the pallisaded walls. Using the measured mean annual level of Lake Huron for 1911, the year of his investigation, Hunter's estimate of the "necessary" water level can be brought to 179.8 m IGLD (1955). Kidd's estimate is 177.8 to 178.7 m. They did not account for differential isostatic rebound between the outlet of Lake Huron and Ste. Marie (approximately 0.55 m from Figure 6) or the permanent lowering of Lake Huron due to dredging and channel improvements in the nineteenth and twentieth centuries (approximately 0.5 m from Derecki (1982)). The combined effect of differential isostatic rebound and dredging is that the water level at Ste. Marie is approximately 1 m lower relative to the land now than it was in 1649. In other words, the land has emerged 1 m relative to the water level.

Hunter (1911) also points to the fact that Ste. Marie II was located in 1911 on a 1.2 m high abandoned beach, about 23 m from the 1911 shoreline of Georgian Bay and 3 to 3.7 m above the water level. Hunter reasoned that because Ste. Marie I was at the water's edge so was Ste. Marie II. He assumed that the level of Georgian Bay once stood at that 1.2 m high beach line and, therefore, that the water level in the 1640's was 3 to 3.7 m above the 1911 level. However, this assumption is questionable because the high abandoned beach can be explained by isostatic rebound over thousands of years.

JURY

Jury and Jury (1954) discovered an aqueduct in 1949 that carried spring water from the base of the hill northeast of Ste. Marie I into the trench system. This did away with the need for a higher lake level to flood the trenches. Based on their excavations the Jurys claim to have discovered a series of three lift locks in the trench system (Figure 8). They believe the lift lock system was used to raise building materials and other supplies from the level of the Wye River to the level of Ste. Marie I. From Kidd's contour map (Kidd 1949), the elevation of the top of the river bank and the settlement is 588 to 590 ft above mean sea level (GSC datum), or the equivalent of 179.0 to 179.6 m IGLD (1955). This gives a difference in elevation between water and land at present of only 2 to 3 m, so, accounting for differential isostatic rebound and dredging effects, the 1649 difference would have been only 1 to 2 m. This theory suggests that the Lake Huron water levels in the 1640's were not significantly higher than today's or else there would have been no need for a lift.

RUSSELL

Subsequently, Russell (1965) put forward the theory that the aqueduct and trench system were used to drive a small mill. Russell provides a good review of the lift lock controversy; it is also summarized in Heidenreich (1970). An hydraulic head is needed to drive a mill; 1 to 2 m would be adequate. Therefore, the mill theory also suggests that lake levels in the 1640's were not significantly higher than today's.

WOOD REMAINS

Jury and Jury (1954) discovered and excavated burned timber pilings near the mouth of the trench system. Their Plate XVI shows the outlet of the canal after excavation had been completed. The photograph shows charred posts neatly lined up and leaning on the banks of the canal. Russell (1965, p. 14) seems to have assumed that these posts were found in these vertical positions, because he says

> "... the pilings leading into the first lock are burnt off but a foot or so above the water level, which seems to indicate a relatively low surface to the water during Sainte Marie's existence."

Unfortunately, the posts were not found in such an ordered fashion, but rather they were placed there for the photograph and the general interest of the public (E. Jury 1987, personal communication).

Jury and Jury (1954) reported finding heavy timbers, partly charred, at the outlet of the canal, 1 foot (0.3 m) below the water level and 8 ft (2.4 m) below the level of the site. Heidenreich (1970, p. 65) interprets this as

> "The charred tops of the timbers of the retaining wall as well as the burned remains of the feature described by Jury as 'the first lock', were found eight feet below the top of the river bank."

Assuming that the timbers burned to the water level of May 15, 1649, and that the excavated timbers were found in their original vertical position, Heidenreich goes on to estimate the 1649 level at the equivalent of 176.6 m IGLD (1955) (neglecting effects of isostatic rebound and dredging). However, close examination of the writings of Jury and Jury (1954) reveals that the timbers were not found in their original positions, but rather were found lying in the mud. Therefore, the hoped for find of a vertical post in its original position, with a horizontal char line indicating the prevailing water level when Ste. Marie was burned, does not seem to exist.

At the outlet of the canal, Jury and Jury (1954, p. 72) describe finding "two well-preserved 9-foot troughs". The outer trough was 9 ft 4 in long, 24 inches wide on the inside, with walls 3 to 4 inches thick and 14 to 16 inches high. The inner trough was 8 ft 8 in long, 2 ft 5 in tapering to 18 inches in width, with walls 3 to 4 in thick and 15 inches high. Unfortunately, details of the bottom elevation are not given but it can be deduced that they were at least 1 foot below the water level during the summer of 1949 (the time of their discovery). However, we cannot be sure that they were found in their original positions. In fact, Jury makes the same comment in his field notes (E. Jury 1987, personal communication). Perhaps they were used to channel the water away from the downstream end of the 2 ft 6 in (0.76 m) drop spillway found just below the "second lock" about 34 ft (10.4 m) away; this would imply that the troughs had slid downstream about 34 ft.

In his field notes, Jury remarks that the wood comprising the troughs was the only wood found that was not charred to some extent (E. Jury 1987, personal communication). If these troughs were used to carry water in the positions in which they were found, one would expect their bottom elevation to be close to and somewhat lower than the prevailing water level during their time of use. However, if the bottom elevation of the troughs had been the same as the 1649 water level, one would expect to have found the troughs about 1 m above this same water level in 1949 due to effects of differential isostatic rebound and dredging. Of course, ice and general weathering would have destroyed the troughs, if they had been so exposed, over the intervening 300 years.

The measured mean water level for Lake Huron in the summer of 1949 averaged 176.13 m IGLD (1955) which is slightly below the twentieth century mean for May of 176.25 m. Heidenreich (1970) refers to the Jesuit Relations which mention drought at Ste. Marie in 1643 and 1649. Since Great Lakes levels generally lag precipitation by about a year, and since 1648 is not mentioned as a year of drought, the level of Lake Huron in May 1649 was probably not significantly lower than usual for that time period. However, finding the wooden troughs about 0.3 m below the water level in 1949, assuming them to have been found in their original positions, and accounting for effects of isostatic rebound and dredging, implies that the water level on May 15, 1649 was approximately 1.3 m lower than that in the summmer of 1949, i.e., 176.13 m - 1.3 m = 174.83 m. Such a level is lower than any recorded for Lake Michigan - Huron since 1819 (see Figure 3). Consequently, it seems probable that the wood troughs were not found in their original positions.

This conclusion is supported by deductions from the temperature reconstruction for the Eastern United States of Fritts and Lough (1985) based on tree-ring analysis. Their study found temperatures in 1645 to 1650 to be 1.5 to 1.9°C cooler than those in the 1930's (which are roughly 0.8°C warmer than those in the 1980's). In general, cooler temperatures tend to reduce evaporation, which, in turn, leads to higher water levels. Therefore, it is very unlikely that the level of Lake Huron was unusually low in 1649.

In summary, the upper range of Lake Huron levels for the period 1639 to 1649 was probably not significantly higher than that from modern day measurements. This is supported by the following logical reasoning. The Jesuit record in Huronia extends back to 1628 and, of course, the Huron Indians had lived there for generations. Remembering that the main mode of transportation was by canoe, one can deduce that extreme variations in the level of Lake Huron would have been observed first hand and accounts passed on to future generations. Hence, if Lake Huron had been 2 m higher than now, and the site at Ste. Marie had been flooded, it seems likely that the French would have known about it; consequently, they would have avoided the site for settlement.

3.3 Fort Michilimackinac

French settlement at the Straits of Mackinac in northern Michigan began in 1671 at modern day St. Ignace (Fitting 1976). Later, the French moved to the south shore where, in about 1715 French traders established a small trading post/mission, which they named Fort Michilimackinac, in what today is Mackinaw City (Figure 9). This small settlement existed until sometime in the 1730s when it was demolished by burning and rebuilt on the same site as a much larger and important palisaded trading town (Heldman and Grange 1981). It was expanded somewhat in 1744 by the French and once more in 1765 as a major British military post. For reasons of defense, the British abandoned the Fort in 1781. Thus, the site of Michilimackinac was occupied continuously from 1715 to 1781, and the French had lived in the general area as early as 1671.

Excavation of a French house ruin in the Fort dating from the 1730s to 1775 showed no sign whatsoever of flooding (Heldman 1977, 1978). This ruin is located about 245 ft (75 m) south of the present shoreline (D. Heldman 1987, personal communication). Moreover, the evolution of the settlement shows the most recent (1760s) expansion to be closest to the shore (Figure 10). If flooding of the site due to high lake levels had been a problem, expansion or relocation of the Fort would have been to the south away from the lake to higher ground. However, the archeological record shows that flooding was not a problem, at least not between 1715 and 1781.

A topographic map of Fort Michilimackinac done in 1967 (Heldman and Minnerly 1976) shows the northeast corner of the Fort on ground elevation below 586 ft (USGS datum). This USGS elevation converts to 178.3 m IGLD. The maximum monthly mean of Lake Michigan-Huron in 1986 was 177.3 m. Therefore, it is not surprising that wave spray is reported (D. Heldman 1987, personal communication) to have reached parts of the nearest reconstructed Fort walls in 1986 (aided by storm surge further increasing the lake level, and wave runup).

The differential rate of isostatic rebound between Mackinaw City and Sarnia is about 0.15 m/century. Therefore, in the period around 1671 to 1715 the land at Fort Michilimackinac would have been about 0.45 m lower relative to the lake level than at present. Furthermore, dredging and other channel improvements at the outlet of Lake Huron since the 1890s have permanently lowered the level of Lake Michigan-Huron by about 0.5 m. Accordingly, if the high water supplies of the past few years had occurred around 1715, the level of Lake Michigan-Huron may have risen to about 178.25 m, with consequent flooding of part of the Fort. But, the only evidence of flooding or wave-induced damaged to the Fort is at the extreme northwest corner, occurring sometime after 1781, when the site was abandoned by the British (D. Heldman 1987, personal communication). This may have occurred during the high water period of 1837-38, when the monthly mean reached a maximum of 177.7 m.

Based on this evidence, it seems unlikely that the level of Lake Michigan-Huron, relative to the land, could have been substantially higher in the period 1671 to 1781 than in 1986.

3.4 Campau House, Detroit

Historical and archeological evidence shows that a site adjacent to the Detroit River in modern day Detroit (Figure 11) was occupied continuously from c. 1757 to 1848 A.D. (Demeter and Weir 1983). Known as the Jacques Campau house, it offers valuable information on water levels in the Detroit River just below Belle Isle during this time period. According to Demeter and Weir, the difference in elevation between the original ground surface and the level of the river, less than 100 ft (30 m) to the south, would have been no more than 4 ft (1.2 m). In fact, during the archeological excavation, groundwater flooding of excavated trench lines was a common problem.

Demeter and Weir found that the original ground surface could still be distinguished from later fill throughout much of the site. They report finding the original surface elevation as low as

579.87 ft, or 176.3 m IGLD (1955). The maximum monthly mean elevation of the Detroit River water surface at this location in 1986 was approximately 175.6 m IGLD (F. Quinn 1987, personal communication), about 0.1 m lower than the corresponding level of Lake St. Clair. From Figure 6 differential isostatic rebound for this site is causing water levels to rise relative to the land at approximately 0.03 m/century (0.1 ft/century). Combined, the preceding information suggests that the river level during 1757 to 1848 could not have been significantly higher than the modern levels.

Furthermore, based on the tentative identification of prehistoric ceramics recovered from the excavation, the site is believed to have been inhabited by Indians of the Younge tradition (600 to 1300 A.D.) of the Late Woodland period (Demeter and Weir 1983). This offers preliminary evidence that the local river level was not significantly higher than now, possibly as far back as 600 A.D.

3.5 Springstead, Michigan

Another site, known as Springstead, near modern day Gibraltar, Michigan at the western end of Lake Erie has been under excavation by crews from Wayne State University of Detroit (Figure 11). The site was occupied continuously from about 1798 until at least 1829 (A. Pilling 1987, personal communication) which suggests that flooding due to high lake levels during this period was not a problem. The U.S. Geological Survey topographic map for Rockwood shows the 575 foot contour crossing the site; this elevation converts to 174.83 m IGLD (1955), which is below the maximum monthly mean Lake Erie level of 174.85 m recorded in 1986. Furthermore, archeological evidence shows a builder's trench, probably dating from about 1800, going at least 18 inches (0.46 m) below the ground surface of this site to what may be 573.5 ft USGS or 174.37 m IGLD (1955) (A. Pilling 1987, personal communication). This latter elevation must have been higher than the prevailing water table around 1800.

From Figure 6 isostatic rebound is causing water levels to rise relative to the land at Springstead at about 0.06 m/century (0.2 ft/century). This combined evidence suggests that the level of Lake Erie was not significantly higher than the modern levels during 1798 to 1829. This agrees with limited information in Section 2.4 which suggests that this period did not include any exceptional high lake level episodes.

3.6 Historical Accounts of Lake Erie Levels

Prior to the earliest recorded Lake Erie water levels in 1819, some information on the relative water levels can be gained from the accounts of early explorers. Stewart (1981) conducted a thorough search of the accounts of early French and English explorers and traders, and the Jesuit misssionaries, who documented their trips along the north shore of Lake Erie. Most of the early travel on Lake Erie was done in canoes which were portaged at Long Point

(Figure 11). Consequently, many accounts mention and describe the Long Point portage. These accounts are summarized in Table 10, giving deduced relative lake levels assuming that higher levels would tend to reduce the width of the portage. The lake levels in Table 10 compare favourably (except in 1806) with observations cited in Section 2.4.

The correlation between lake levels and the width of the portage is complicated by variations in littoral drift and patterns of sand erosion and deposition, by man's interference (e.g., the channelization in 1761 by Maj. Gladwin), variations in estimating the width and differences in defining the width of the portage, e.g., water's edge to water's edge or something else. In spite of these qualifications, Table 10 shows that the width of the portage varied from 0 ft (in 1749, 1806 and 1815) to 825 ft (in 1766). Unfortunately, the present day width of the portage cannot be estimated because of changes at Long Point due to man, e.g., roads, shore stabilization. Breaches at the neck of Long Point, in the general vicinity of the old portage, were experienced during recent high water episodes in 1973 and 1985.

3.7 Larsen

Larsen (1985a, b; 1987) has put forward a controversial theory for Lake Michigan-Huron levels that occurred over the past 2000 years. This theory suggests a long-term fluctuating cycle in mean annual levels, lasting for periods of centuries, with variations

TABLE 10: Widths of portage at Long Point from accounts of travellers

Year	Source from Stewart (1981)	Width of Portage at Long Point (ft)	Deduced Relative Lake Level	Comments
1721	Charlevoix	150	High	A most charming climate.
1749	Chaussegros de Léry	50	High	Almost an island; on return trip, portaged without unloading canoes; no beaches, can only disembark at river.
1761	Johnson	120	High	Carrying place cut open a little by Maj. Gladwin.
1765	Porteous	600	Low	
1766	Carver	825	Low	
1789	Ford			Lake level estimated to be 4 ft higher than in 1785.
1792	Letter to Simcoe		High	Lake level rising for past 7 years
1806	Heriot	18	High	Mentions breaching.
1812	Askin		Low?	Great difficulty to get boat over.
1815	Vidal		High	Lake level much higher than known for many years; marshes at Turkey Point flooded 2 to 3 ft.
1815	Aldersley	0	High	Breached.
1819	Thompson	432	Low*	Difficulty finding brook to portage.
1821	Cockburn		Low*	Very difficult to find brook.

* The measured lake level in August 1819 and 1820 was 173.19 m IGLD (1955) from Tait (1983).

as large as two metres above and below an approximate modern mean level of 177 m IGLD (1955). According to Hough (1958, 1963), modern Lakes Michigan and Huron were formed about 2,500 B.P. (Before Present, i.e., 550 B.C.). Since that time, the classical view is that lake levels have been relatively stable and that the regional climate has been similar to that of recent history.

Larsen's data is from radiocarbon-dated stratigraphic studies of a beach ridge complex along the southwestern shore of Lake Michigan. The theoretical framework for his studies is from Fraser et al. (1975) and is described in Larsen (1987) as:

> "increased precipitation contributed greater run-off resulting in higher lake level. This caused a rise in the base levels of tributary streams and aggradation of the stream channels, leaving prominent terraces on the alluvial deposits graded to the contemporaneous base level. High levels caused flooding of lakeshore marshes resulting in fine sediment deposition and submergence of earlier cattail-marsh vegetation. Finally, a rise in adjacent groundwater levels increased soil moisture in nearshore sand and dune deposits. Together with increased precipitation, this allowed vegetation and organic soils to develop on these permeable sediments."

Detailed stratigraphic studies of the alluvial deposits of four streams entering Lake Michigan north of Waukegan, Illinois, provided information on the subaerial deposits, while buried peat deposits provided subaqueous information. Larsen concluded that the base levels of the steams had been as much as 2 m higher than those at present. Peat deposits from 1 to 2 m below the present level of the adjacent lake provided information on lower lake levels. The upward growth of the floodplains during aggradation furnishes an upper limit to the base level controlling contemporaneous deposition. This relative thickness is taken as proxy evidence for the relative elevation of the adjacent lake levels. Similarly, the elevations of submerged cattail-marsh peats provide the lower range of lake level transgressions. The composite data set is shown in Figure 12 and reveals the following:

(a) The most recent data point is from 1450 A.D.; this means that the postulated rise in lake levels c. 1500 to 1800 A.D. is not really based on stratigraphic evidence.

(b) Of 16 data points used in Figure 12, 7 are for wood or peat deposits and 9 are for paleosols. Paleosol data is notoriously weak (Hoeller 1982; Ruellan 1971).

(c) Of the 7 data points for wood and peat, only 2 are outside the range of recorded water levels since 1819 A.D. Of these, point 6 (Figure 12), from a peat deposit, is less than 0.5 m below the lowest recorded monthly mean water level; this difference is within the expected error due to compaction of a peat deposit.

(d) There is a large amount of scatter in the data. Data points 5, 7, 11 and 13 do not agree with the interpreted water level curve.

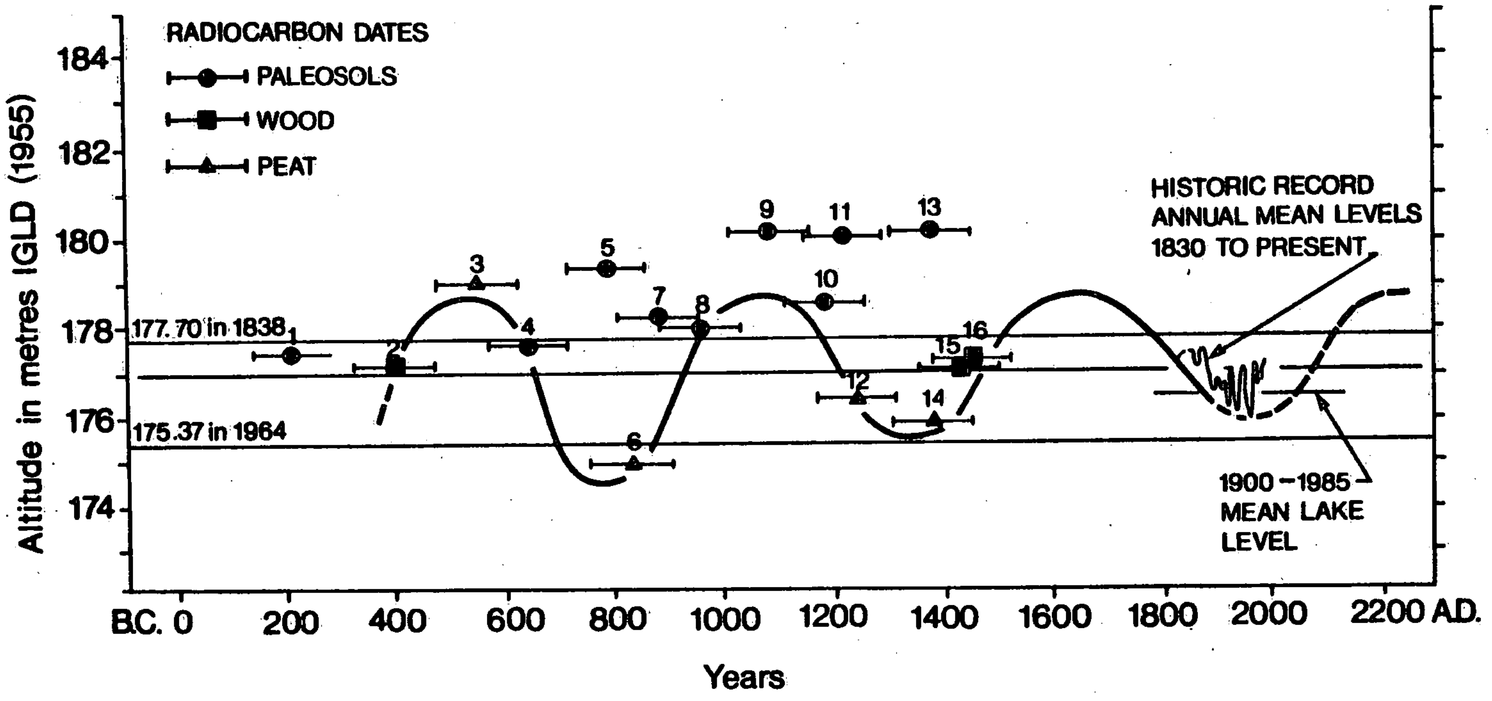

Figure 12. Long term trends in Lake Michigan annual levels derived from radiocarbon – dated stratigraphic sections (Larsen 1987), with maximum and minimum monthly means indicated.

Historical-archeological information from Ste. Marie, Fort Michilimackinac and the Campau House indicates that Lake Michigan-Huron water levels in the 17th and 18th centuries were not significantly higher than those recorded since 1819. Furthermore, geobotanical studies conducted by Olson (1958a, b) also conflict with the trends postulated by Larsen. Based on observations of dune formation and lake level fluctuations, with dating estimated from plant succession, Olson proposed an extended period of high Lake Michigan levels about 1350 A.D. followed by an extended low about 1550 A.D. These postulated transgressions are opposite to those of Larsen shown in Figure 12.

From apparent vertical crustal movement rates between Milwaukee and Calumet Harbor and Goderich (Coordinating Committee 1977), and the approximate rate between Goderich and Sarnia from Figure 6, it can be concluded that the lake level at Kenosha-Waukegan is rising about 0.09 m/century (0.3 ft/century) relative to the land. Over two thousand years, this rate of isostatic rebound would account for lake levels being 1.8 m (6 ft) lower relative to the land than at present. However, Larsen (1985a) neglected the effects of isostatic rebound stating "Because this region has undergone only slight isostatic uplift, the effect of isostatic rebound on lake level change is minimal here." This helps to explain why Larsen's data point 6 (Figure 12) from 820 A.D. at elevation 174.7 m is slightly lower than the modern range of recorded water level fluctuations.

In summary, Larson's theory of Lake Michigan-Huron water level fluctuations over the past 2000 years disagrees with limited historical-archeological information over the past 350 years. Furthermore, his own data, under different interpretation, does not support his theory.

4.0 CLIMATE CHANGE

4.1 Historical Climatic Change

Statistical analysis of recorded water level variations makes the implicit assumption that the measurements are from the same statistical population. This implies that variations in climate, the main driving force behind water level variations, are random and have no trends. However, a perusal of climate change literature shows that variations in our climate have shown pronounced trends in the past and are likely to do so in the future. Climatic change refers to those differences between successive averaging periods (typically 30 years) that cannot be accounted for by short term weather changes or climatic noise (Parry and Carter 1986). Seemingly small climatic changes, such as a change in mean annual temperature of 2°C, can have large impacts on human civilization (Bryson 1974). It is estimated that the mean global surface temperature difference from full glaciation to the present is about 4° to 6°C (Bryson 1974). During the past two thousand years two significant changes have occurred: the Little Optimum or medieval warm epoch (c.800 to 1200 A.D.), and the Little Ice Age (c. 1500 to 1800 A.D.)

Lamb (1977) presents a plethora of proxy data to document historical climatic change. For example, there is evidence of successful English vineyards, where now there are none, from about 1100 to 1310 A.D. (Lamb 1977, p. 276-279). The shortfall of summer temperatures prevailing in 1921-1950 A.D. below those representing the modern northern limit of commercial vineyards in Europe, in what were the best English wine districts, is in the range 0.5 to 1.5°C.

Another example is the rise and fall of Viking settlements in Iceland and Greenland which have been attributed to climatic change (Lamb 1977, p. 6).

> "In the first centuries after the Viking settlement of Iceland in 870-930 A.D., and of southwest Greenland from 987 onwards, sea ice was practically never mentioned in the accounts of the voyages. ... From that time until 1200 A.D. there were only one or two years each century when ice is reported to have caused any difficulty in sailing about Iceland and southern Greenland. Yet about 1250 the King's Mirror tells us that the East Greenland ice was formidable and Ivar Bardarson in his Description of Greenland reports that by about 1342 the old sailing route along the 65°N parallel to the Greenland coast - and thence following the coast round to the colonies on the western side - had been abandoned because of the increase of the ice. ... The situation worsened further after that, as is recorded in a letter of Pope Alexander VI in 1492 ... shipping to that country [East Greenland] is very infrequent because of the extensive freezing of the waters - no ship having put in to shore, it is believed, for eighty years".

An expedition from Iceland to Greenland in 1540 A.D. established that the old Norse colony had died out. Variations in the incidence of sea ice at the coast of Iceland since 860 A.D. are shown in Figure 13. Figure 14 shows the length of glaciers in Iceland and Norway since 10,000 B.C.

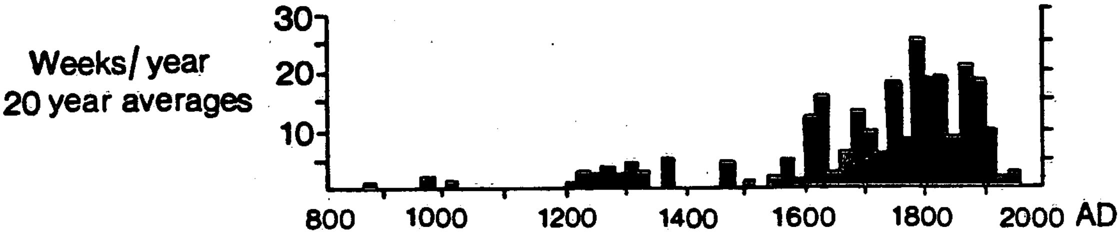

Figure 13. Variation in the incidence of sea ice at the coast of Iceland since 860 A.D. (Lamb 1977)

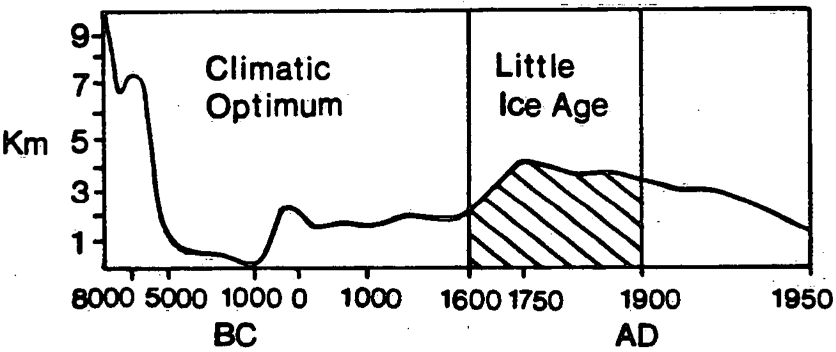

Figure 14. Variations in the length in km of the glaciers in Iceland and Norway since 10 000 B.C. (Lamb 1977)

4.2 Measurement of Climate Variation

Early climatological data for the eastern United States (Wahl 1968, Wahl and Lawson 1970) established that, for the Great Lakes Basin, the period 1830-1869 was 1 to 2°F (0.55 to 1.1°C) cooler and about 10% wetter than climate "normals" based on data from 1931-1960. From an analysis of precipitation data over the Great Lakes Basin from 1854 to 1979, Quinn (1981) showed a relatively wet regime prior to the mid-1880's, followed by a relatively dry regime until the late 1930's, and a resumption of relatively wet conditions from about 1940 to the present. Figure 15 and Table 11 show Quinn's estimates of Great Lakes annual precipitation from 1854 to 1979; Table 11 is supplemented by data from the Great Lakes Environmental Research Laboratory for 1980 to 1986. Figure 16 shows the variation in the five-year running mean of precipitation from 1855 to 1979 for the Great Lakes Basin. Figures 17 and 18 show the annual precipitation and three-year running mean from 1890 to 1986. A wetter regime is evident from 1940 and, in particular, since 1967 the precipitation in all but one year has been above the twentieth century mean of 812 mm.

Quinn (1981) concluded that a significant change in the Great Lakes precipitation regime occurred around 1940, primarily due to increased precipitation in spring and summer. The mean precipitation increased from 781 mm for 1900-1939 to 831 mm for 1940-1979 coupled with an increase in variance of approximately 100%. The

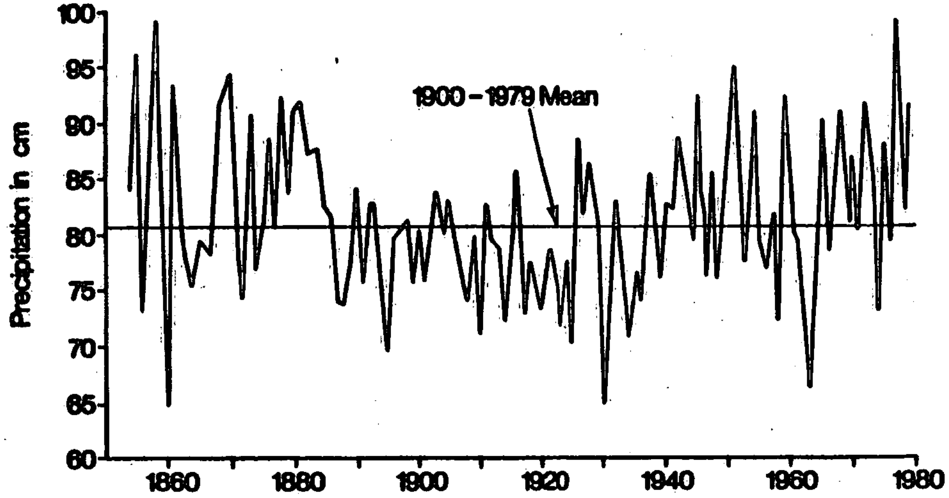

Figure 15 Great Lakes Annual Precipitation (Quinn 1981)

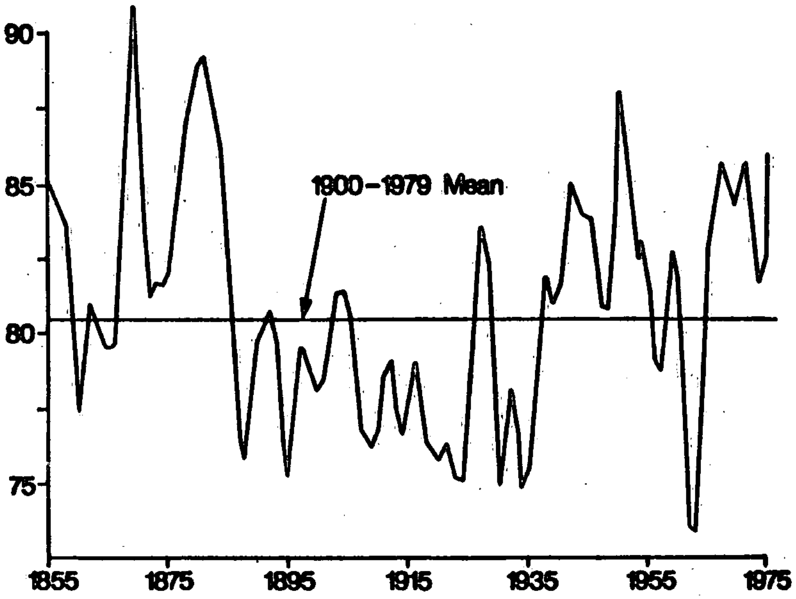

Figure 16 Five Year Weighted Average Precipitation (Quinn 1981)

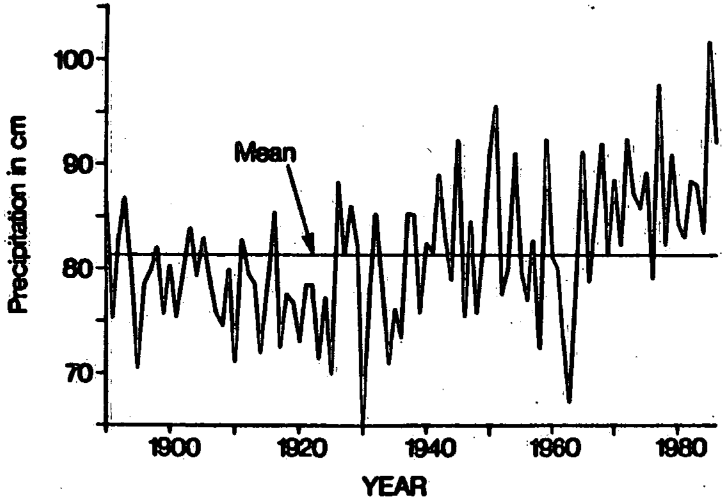

Figure 17 Great Lakes Annual Precipitation (Moulton and Cuthbert 1987)

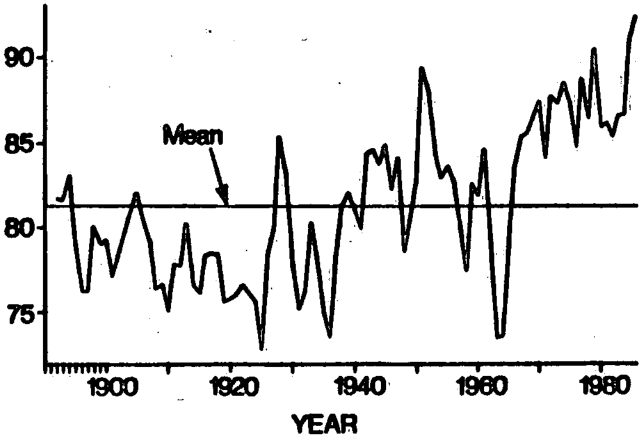

Figure 18 Three Year Moving Average Precipitation (Moulton and Cuthbert 1987)

TABLE 11: **Annual Great Lakes precipitation (Quinn 1981).**

Decade Beginning	Precipitation (mm)									
	0	1	2	3	4	5	6	7	8	9
1850					835	964	732	857	990	837
1860	646	933	824	775	749	794	793	780	905	929
1870	945	804	739	909	768	802	887	809	922	835
1880	907	921	874	874	878	822	815	739	735	772
1890	843	755	830	828	751	697	797	800	814	753
1900	804	756	806	840	796	830	792	759	741	800
1910	713	827	796	787	722	779	855	727	777	767
1920	730	783	783	715	777	703	883	816	859	821
1930	652	775	834	769	706	771	740	849	852	759
1940	831	822	890	840	790	923	759	856	758	822
1950	912	952	772	790	908	791	764	824	721	924
1960	807	795	724	660	795	902	784	847	910	808
1970	869	799	915	860	735	879	790	988	819	911
1980	844	831	885	881	835	1017	915			

relatively dry regime that ended around 1940 began around 1885. Prior to 1885, the limited available data indicates a precipitation regime similar to that from 1940 to the present.

Comparison of Figures 2 to 5 with Figures 15 to 18 shows that, in general, the levels of the Great Lakes follow the fluctuations in precipitation. Agreement is best for Lakes Michigan-Huron and Erie, whose central locations in the Basin would mean their individual basin precipitation amounts are quite well represented by those of the entire Great Lakes Basin.

The annual mean temperature around the perimeter of the Great Lakes since 1900 has been summarized by Croley (1986) and is shown in Figure 19. It indicates a cooler regime from 1900 to 1929, a warmer regime from 1930 to 1959 and a return to the cooler regime from

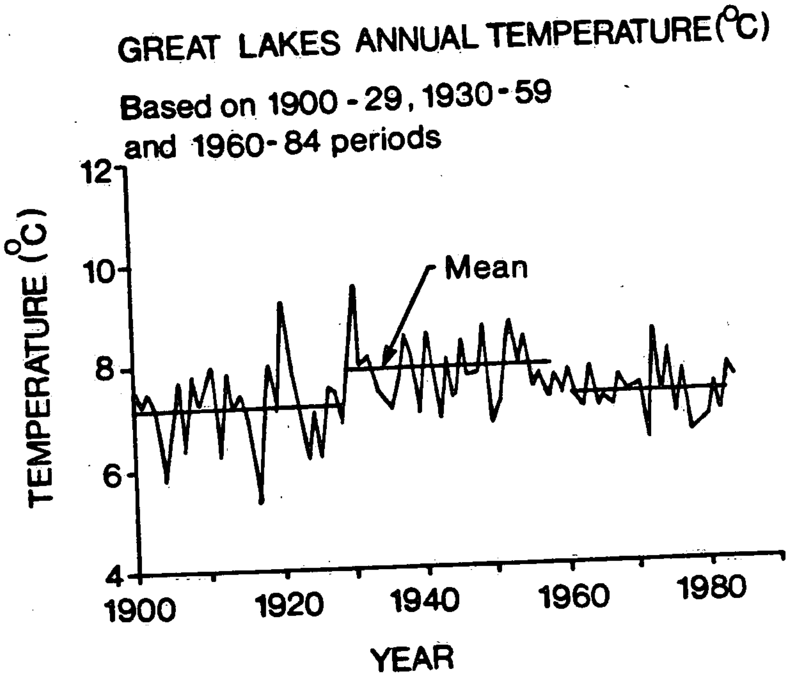

Figure 19. Historic air temperatures.

1960 to the present. The difference in mean annual temperatures between the regimes is about 0.8°C.

An earlier study by Thomas (1957) showed a cold period in southwestern Ontario in the decade of the 1880's, followed by a 10-year warming trend of about 2°F (1.1°C) to 1900, a stable temperature regime until around 1930, then a warming trend of another 2°F (1.1°C) through to 1955.

The temperature reconstruction of Fritts and Lough (1985) for the eastern United States, based on tree-ring chronologies from 65 arid-sites in western North America, shows a pronounced warming trend of about 1.8°C from the mid 1880's to the mid 1930's, followed by a cooling trend of 0.8°C from the mid 1930's to 1962.

For further information on climate change in Canada, the interested reader can refer to the annotated bibliography of Harrington and Rice (1984).

Predicted global temperatures from the global climate model of Hansen et al. (1981) show a pronounced warming trend of approximately 0.5°C from around 1905 to 1940 (Figure 20). Similar to Croley, a warm regime can be seen for the period 1930 to 1959. Simulated global temperatures peaked around 1940, declined to a low in the mid 1960's and have been rising ever since. Hansen et al. belong to the so-called "Greenhouse Effect" school of climatologists. This school of thought predicts inevitably increasing global temperatures as a result of increasing atmospheric concentrations of carbon dioxide and

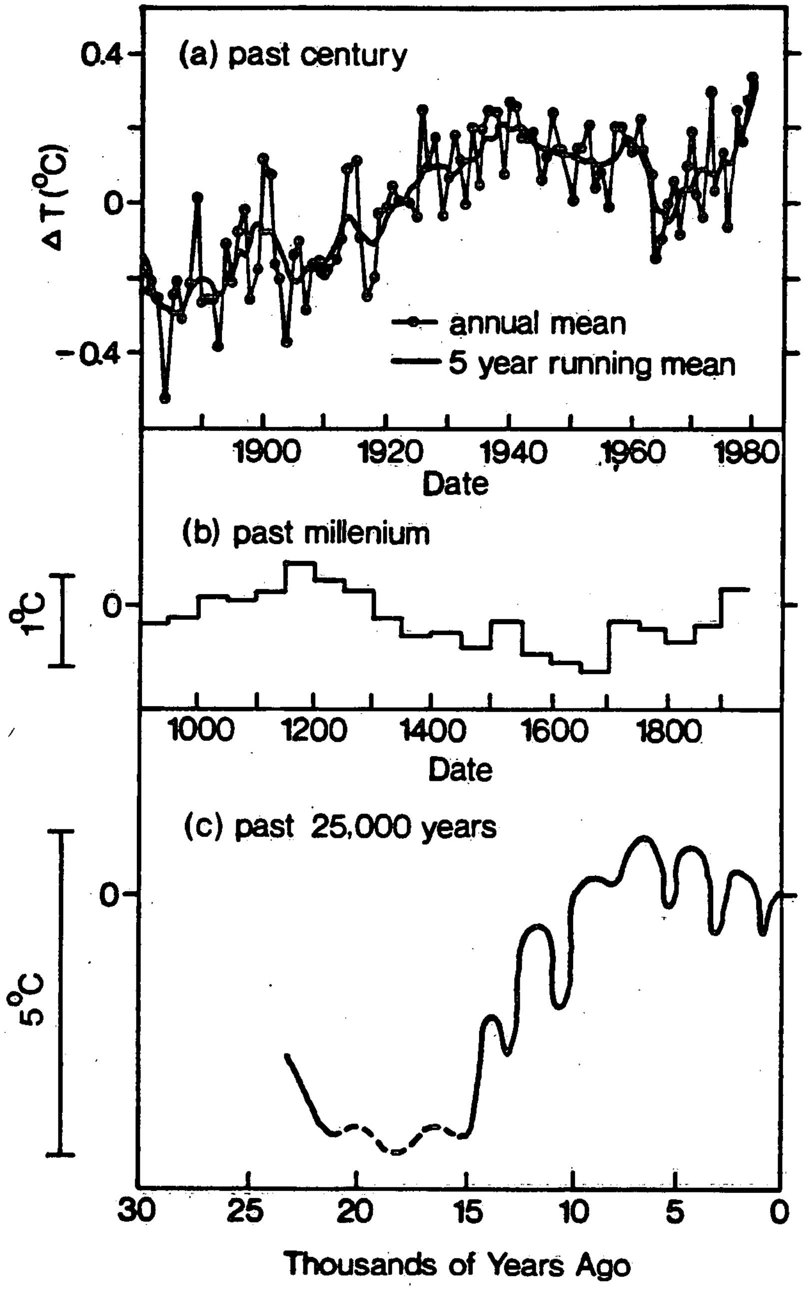

Figure 20: Global temperature trend for the past century (a), millenium (b), and 25,000 years (c). (a) is based on Hansen et al. (1981), updated through 1981. (b) is based on temperatures in central England, the tree limit in the White Mountains of California, and oxygen isotope measurements in the Greenland ice, with temperature scale set by the variations in the last 100 years. (c) is based on changes in tree lines, fluctuations of alpine and continental glaciers and shifts in vegetation patterns recorded in pollen spectra, with the temperature scale set by the 3° to 4°C cooling obtained in a 3-D climate model (Hansen et al. 1984) with the boundary conditions for 18,000 years ago. Thus the shapes of curves (b) and (c) are based only on Northern Hemisphere data.

other gases as discussed in Section 4.3. Another school of climatologists, which stresses the importance of volcanic aerosols on climate (Institute of Environmental Studies 1985) does not accept the premise of inevitably increasing temperatures resulting from greenhouse gases. Some researchers suggest that the 1930 to 1959 period was the warmest three decades in the past 1000 years (Bryson 1974, Bernabo 1981), and predict a return to cooler temperatures (Changnon 1984).

4.3 Greenhouse Effect

A planet's temperature is determined primarily by the amount of sunlight it receives, the amount it reflects and the extent to which the atmosphere retains heat. When sunlight strikes the earth, it warms the surface, which then re-radiates the heat as infrared radiation. However, water vapour, carbon dioxide (CO_2), methane, chloroflurocarbons (CFC's), nitrous oxide and other gases in the atmosphere absorb some of this reradiated energy rather than allowing it to pass undeterred through the atmosphere to space.

In recent decades, the concentrations of these so-called greenhouse gases have been increasing. For further information on the greenhouse effect, the interested reader can refer to Atmospheric Environment Service (1986), Maranto (1986), Revelle (1982) Seidel and Keyes (1983), and Titus (1986). Studies on the greenhouse effect generally discuss the impacts of a doubling of the atmospheric concentrations of carbon dioxide (2 x CO_2). Since the beginning of the industrial revolution, it is estimated that the atmospheric concentration of CO_2 has already increased by 20 percent. The term "effective doubling" is used to describe any combination of increases in concentrations of the various gases that causes a global temperature increase equal to that predicted for a doubling of CO_2 alone.

Global climate models (GCM's) have been used to predict the impacts of climate change. The GCM of Hansen et al. (1983) divides the earth into gridboxes of 8° latitude by 10° longitude. Each gridbox is divided vertically into a number of layers, typically nine, in the atmosphere. Similarly, the ground or ocean in each gridbox is divided into several vertical layers. The mathematical equations describing the fundamental conservation laws of physics are solved numerically for each gridbox by a computer program.

GCM's can reproduce general features of the earth's climate such as temperature, winds, storm tracks and their spatial and temporal variations. However, the models are not sufficiently realistic to portray accurately regional patterns of precipitation, ocean currents, and other processes that are important for determining the practical consequences of climate trends because of greenhouse warming (Hansen et al. 1986). Decades of research are likely to be required to improve GCM's to the point that they can be used to predict local and regional climate changes with a high degree of confidence (Hansen et al. 1986). In the meantime, climate models can provide a useful indication of the possible magnitude of future climate trends.

REGIONAL IMPACT ASSESSMENT

Cohen (1986) has investigated the impact on water resources in the Great Lakes Basin of predicted climate scenarios for a doubling of CO_2 from two GCM's. The scenarios used were adapted from output from the Goddard Institute of Space Studies (GISS) model (Hansen _et al_. 1983), and from the Geophysical Fluid Dynamics Laboratory (GFDL) model (Manabe and Stouffer 1980). These scenarios were approved for use within the Canadian Climate Program in September 1984. The GISS output was modified to increase the spatial resolution to 4° latitude x 5° longitude (see Parry _et al_. 1987), thereby giving 10 data points in or near the Great Lakes Basin. The GFDL scenario, originally for 4 x CO_2, was modified to give values for 2 x CO_2 at 7 data points (4.4° latitude x 7.5° longitude). For the Great Lakes Basin, the modified GISS scenario predicts a 4.3°C to 4.8°C increase in mean annual temperature, and a 6.5% increase in mean annual precipitation. The modified GFDL scenario predicts increases of 3.1°C to 3.7°C and 0.8%, respectively.

The monthly temperature and precipitation data were used to compute changes in climatic water balance and lake evaporation. Water balance calculations were performed using the Canadian Climate Centre's version of the Thornthwaite model. Neglecting consumptive water use, and using present normal winds and relative humidity, GISS projects a decrease in Net Basin Supply (NBS) of 20.8%, while GFDL projects a decrease of 18.4% (Cohen 1986). These estimates have been updated (Cohen 1987) to 23.6% and 16.9%, respectively, after incorporating data for 1983 and 1984 in the estimate of normal NBS, and using a slightly different procedure to calculate land-based runoff. Consumptive use was estimated to increase from 170 m^3/s in 1985 to 720 m^3/s in 2035 (IJC 1981). However, in a later report (IJC 1985), it was concluded that projections of consumptive uses beyond the year 2000 are too uncertain to be useful for planning and policy decisions.

The sensitivity of these results to changes in wind speed (U) and atmospheric vapour pressure (VP) has been assessed by Cohen (1987). The GFDL model includes estimates of monthly wind speed, while the GISS model does not. They indicate decreases of 15 to 20% from September to December, increases of 6 to 15% from January to April and a mixture of increases and decreases from May to August. Cohen also investigated 10 hypothetical warming scenarios in which every month of the year is assumed to experience the same warming, 2°C or 4°C, and the same change in precipitation, -20%, -10%, 0%, +10% or +20%. Results are shown in Table 12.

To put the values of Table 12 in perspective, the NBS in 1964, one of the driest years this century, represented a decrease of about -25% (including consumptive use). Cohen (1987) also investigated the impacts on NBS due to several historical analogues from Brown and Walsh (1986). Two cases resulted in reductions in annual NBS similar to the GISS and GFDL results. These cases comprise temperature increases of less than 1°C and precipitation decreases of up to 23%.

TABLE 12: Projected percentage changes in NBS for a 2 x CO_2 scenario (Cohen 1987). Consumptive use not included.

Scenario	Wind/Vapour Pressure (N = Normal)						
	N/N	-20%/N	GFDL/N	N/+10%	N/-10%	GFDL/+10%	GFDL/-10%
GISS	-23.6	-7.0	-20.0	3.9	-51.1	6.7	-47.5
GFDL	-16.9	-2.7	-14.0	8.5	-42.3	11.3	-39.2
Temperature (°C)/Precipitation (%)							
+2/-20	-58.2	-44.5	-55.6	-34.9	-81.4	-32.6	-78.6
+2/-10	-36.3	-22.6	-33.7	-13.0	-59.5	-10.7	-56.7
+2/N	-12.5	1.1	-9.9	10.7	-35.8	13.1	-32.9
+2/+10	12.1	25.8	14.7	35.4	-11.1	37.7	-8.3
+2/+20	37.7	51.3	40.2	60.9	14.4	63.3	17.2
+4/-20	-70.9	-55.9	-68.0	-44.4	-97.5	-47.7	-94.3
+4/-10	-50.4	-35.4	-47.5	-23.9	-77.0	-21.2	-73.8
+4/N	-28.4	-13.3	-25.5	-1.8	-54.9	0.8	-51.7
+4/+10	-4.7	10.4	-1.8	21.8	-31.3	24.5	-28.1
+4/+20	19.7	34.8	22.6	46.3	-6.8	48.9	-3.9

Using the hypothetical scenarios for reference, the NBS impacts projected by GISS are most similar to a 2°C warming with -5% change in precipitation, or a 4° warming with +2% change in precipitation. For GFDL the corresponding numbers are 2°C and -2%, and 4°C and +5%, respectively.

Although the consensus of opinion is that the Greenhouse Effect will reduce NBS in the Great Lakes Basin, Cohen's (1987) work shows that much more work is needed to accurately define future regional projections of wind speed and atmospheric vapour pressure, in addition to the previously mentioned precipitation. Reduced annual wind speeds may prevail in a 2 x CO_2 environment because of the anticipated reduction in the equator-pole temperature gradient. Present theory also suggests that the global temperature increase will be accompanied by increased atmospheric vapour pressure (VP) and relative humidity because of higher global scale evaporation (Schlesinger and Mitchell 1985). Table 12 indicates the sensitivity of predicted changes in NBS to reduced wind speeds and increased VP. Many scenarios, including GISS and GFDL, could project increases in NBS under such conditions, depending on the magnitudes of the increases in VP and relative humidity.

IMPACT ON WATER LEVELS

Using the modified GISS data set for 2 x CO_2, the impact of reduced NBS on Great Lakes water levels has been estimated using a numerical hydrologic response model (Great Lakes Institute 1986, Allsopp and Cohen 1986). Predicted changes in water levels are given with respect to a Basis of Comparison (BOC) data set. The BOC represents a reconstruction of lake levels and flows for the period 1900 to 1976, given present physical dimensions, diversions and regulation practices. Under the present regulation plan, Lake Ontario levels would decrease drastically during certain periods, e.g., 1931 to 1941 and 1963 to 1965. Consequently, assuming that a new regulation plan would be put into effect, no further predictions are made for Lake Ontario. Changes are given for GISS-type scenarios with decreases in NBS of 15 and 24 percent in Table 13. Predicted decreases in mean annual lake levels vary from 21 to 83 cm.

TABLE 13: Summary of changes to Great Lakes Levels from 77 years BOC mean level (Great Lakes Institute 1986).

Lake	Changes in NBS: -15%	-24%
Superior	-21 cm	-30 cm
Michigan-Huron	-59 cm	-83 cm
Erie	-44 cm	-68 cm

These changes can be put into perspective relative to the measured mean levels for 1963 to 1965, a period of unusually low levels. Results are given in Table 14. For a 24 percent decrease in NBS, the mean annual levels of Lakes Superior to Erie would all be at or below their respective 1963-1965 means about 80 percent of the time. Clearly the low levels experienced in 1963 to 1965 would become commonplace, under these scenarios.

TABLE 14: Percent of years with levels at or below 1963-65 means (Great Lakes Institute 1986).

Lake	BOC	NBS - 15%	NBS - 24%
Superior	10	61	79
Michigan-Huron	8	57	77
Erie	5	38	77

5.0 DESIGN WATER LEVELS

There are two main approaches to determining design water levels:

1. Frequency analysis.
2. Design event.

Frequency analysis applies statistical techniques, such as extreme value analysis, to a water level data set to develop a frequency distribution of water levels. Such an analysis ignores trends in climate but has been done for Great Lakes Water Levels using data from 1900 to 1976 under a Basis of Comparison (BOC) scenario (Ontario Ministry of Natural Resources 1986). The BOC scenario assumes that all diversions, outlet conditions and regulation plans were the same during 1900 to 1976 as at the time of the analysis (c. 1977). The monthly mean water levels for each lake were obtained by routing the measured net basin supplies through the system under the BOC scenario. Thus the effect of changing conditions during 1900 to 1976 in channel configurations, diversions and regulations has been removed from the data. No adjustments were made in the data for the progressive effects of crustal movement. Results from a Gumbel distribution frequency analysis of maximum annual monthly mean water levels are shown in Table 15 (Ontario Ministry of Natural Resources 1986).

The maximum monthly mean levels measured in 1986, taken from the Government of Canada Monthly Water Level Bulletins, are given in Table 16.

Table 15: Results of frequency analysis of maximum annual monthly mean water levels (OMNR 1986)

	Monthly Mean Water Levels (Metres IGLD)				
	Average Annual Recurrence Interval				
Lake	100 yr	50 yr	20 yr	10 yr	5 yr
Superior	183.47	183.43	183.38	183.33	183.27
Huron	177.79	177.59	177.30	177.08	176.85
St. Clair	175.76	175.67	175.52	175.39	175.24
Erie	175.21	175.03	174.79	174.61	174.32
Ontario	75.86	75.69	75.46	75.28	75.09

Table 16: Maximum monthly mean water levels measured in 1986

Lake	Water Level (m) IGLD	Return Period (years)
Superior	183.45	75
Huron	177.29	19
St. Clair	175.74	85
Erie	174.84	25
Ontario	75.14	6

The return periods in Table 16 have been estimated from Table 15. The unexpectedly short return periods for Lakes Huron and Erie cast doubt on the input conditions leading to Table 15. The BOC analysis is presently being redone by the Great Lakes Water Level Communications Centre in Burlington using data from 1900 to 1986. However, the fundamental problem of a changing climate within the years of the data set, and into the future, limits the usefulness of the results of such an analysis.

The second approach is that of the design event. For example, for many hydrologic studies in southern Ontario, the regulatory design event is a modified precipitation sequence from Hurricane Hazel. For some Great Lakes designs involving water levels, the recorded highs have been used, such as those of 1838, 1952 and 1973. This approach does not allow the estimation of risk as can be done from a correct frequency analysis. Moreover, each time the maximum recorded level is exceeded, there is a tendency to establish the new maximum as the design level.

5.1 Potential Variation in Great Lakes Levels

For the unregulated lakes and, to a large extent, the regulated lakes as well, changes in climate are the main driving force causing changes in water levels. Colder and wetter conditions generally result in higher water levels, while warmer and drier weather leads to lower levels. Accordingly, forecasts of lake levels can be no better than the climate forecasts on which they are based. Unfortunately, long range weather forecasting (in terms of decades) is still in an early developmental stage (e.g., Climate Forecast Group, Institute for Environmental Studies, University of Wisconsin-Madison). Furthermore, climate appears to be a non-stationary, multi-modal process with evidence of step-function changes thereby negating conventional statistical analysis.

Use of a range of climate conditions, derived from historic records as input to a hydrologic model, can provide a perspective on the potential for future water level variations. The Great Lakes Environmental Research Laboratory has simulated potential variations in the levels of the unregulated lakes (Michigan-Huron, St. Clair and Erie) using a numerical hydrologic response model (Quinn 1978). In an early study (Quinn and Croley 1981), the response model was run with the present hydraulic regime and recorded estimates of annual precipitation from 1870 to 1886. The initial boundary conditions used were the individual mean lake levels for January 1962. The model gave a mean annual level for Lake Michigan-Huron that was 0.3 m higher than the recorded mean for 1973; the 1973 mean level was the highest on record since 1886. This indicated that the 1870 to 1886 precipitation regime, from a lake level viewpoint, was the most severe experienced on the middle Great Lakes during the period of record from 1860 to 1979.

Recently, Hartmann (1987) has used the same response model to assess potential variations in lake levels. Results are summarized in Table 17. The first four scenarios examine the potential for the unregulated Great Lakes to return to more moderate levels. The specified values of monthly net basin supply (NBS) were input to the model repeatedly over a 20-year period. All applications of the model began with actual January 1986 beginning-of-month water levels (176.97 m for Lake Michigan-Huron and 174.45 m for Lake Erie).

TABLE 17: **Potential variation in levels of Lakes Michigan-Huron and Erie (Hartmann 1987).**

Background	Lake Michigan-Huron (m) IGLD	Lake Erie (m) IGLD
Mean annual level 1900 - 1969	176.18	173.78
1900 - 1985	176.26	173.88
Mean maximum monthly level 1900 - 1969	176.36	174.01
1900 - 1985	176.44	174.11
Maximum monthly level 1900 - 1985	177.28	174.86

Scenario	Mean Annual/Years		Maximum Monthly/Years		Mean Annual/Years		Maximum Monthly/Years	
1. Mean monthly NBS 1900 - 1985	176.38	5	176.54	5	174.00	7	174.21	5
2. Mean monthly NBS 1900 - 1969	176.26	7	176.44	5	173.88	7	174.01	10
3. Actual NBS 1960 - 1964 (precip. 7% less than 1900 - 1985 mean)	176.26 175.69	3.5 5	175.78	5	173.88 173.60	3.5 5	173.9	5
4. Mean monthly NBS 1971 - 1985 (precip. 7% above 1900 - 1985 mean)	176.71	10-13	176.86	10-13	174.34	10-13	174.74	10-13
5. Actual NBS for 1985 (precip. 26% above 1900 - 1985 mean)	177.55	10	177.74	10	174.87	10	175.05	10
6. Mean monthly NBS 1900 - 1985 increased by 25%	177.16		177.32		174.58		174.96	
7. Increased by 50%	177.99		178.22		175.14		175.39	
8. Increased by 75%	178.76		178.88		175.68		175.86	
9. Increased Niagara River outflow by 10%	176.15	16			173.61	12		

From Table 17 it can be seen that a return to average NBS would allow lake levels to return to near-normal in five to seven years. Drought conditions similar to those of 1960 to 1964 would allow levels to return to their 1900 to 1985 means in about 3.5 years. A continuation of the relatively wet regime conditions of 1971 to 1985 does not allow lake levels to return to their 1900 to 1985 means, but keeps them approximately 0.5 m higher.

Scenarios 5 to 8 examine the lake level response to continued high water supplies. Scenario 5 is for the actual NBS values of 1985, repeated year after year. Interestingly, the maximum monthly level of Lake Erie stabilizes after about 10 years at only 0.19 m above the recorded maximum monthly level of 1986. However, the level of Lake Michigan-Huron is more sensitive, going up 0.46 m above the recorded maximum monthly level of 1986. The 1985 basin precipitation is the largest in 100 years of record for the Great Lakes Basin and is approximately 26 percent larger than the mean for 1900 to 1985. While a probability of experiencing conditions similar to Scenario 5 cannot be estimated, Scenario 5 must be considered an extremely severe set of conditions.

Scenarios 6 to 8 use the mean NBS values from 1900 to 1985 increased by factors of 1.25, 1.50 and 1.75, respectively. Results from Table 17 show that the ensuing lake levels for Scenario 6 are lower than those from Scenario 5. Under Scenarios 7 and 8, levels stabilize after about seven years and are considerably higher than those of Scenario 5. The probability of experiencing the conditions of Scenario 7 or 8 must be extremely remote - a drastic climate change would seem to be necessary in order to experience such conditions.

Scenario 9 examines the impact of an increase in the discharge capacity of the Niagara River similar to that possible with Niagara Plan 25-N (IJC 1983). For this Scenario, the discharge equation constants for the Niagara River were increased by 10 percent. The level of Lake Erie falls the most - approximately 0.19 m after the second year, stabilizing at 0.27 m lower after 11 to 12 years.

5.2 Potential Upper Limits in Great Lakes Levels

A review of available water level measurements since 1815 provides recorded mean monthly water level ranges as given in Table 18.

Table 18: Ranges of recorded mean monthly lake levels

Lake	Maximum Monthly Mean (m) IGLD (1955)	Year	Minimum Monthly Mean (m) IGLD (1955)	Year
Ontario	75.61	1952	73.97	1934
Erie	174.85	1986	173.01	1934-1936
			173.0 (est)	1819-1921
Michigan-Huron	177.70	1838	175.37	1964
Superior	183.51	1876	182.34	1926
	183.94 (est)	1838		

The results from Scenarios 5 and 6 in Section 5.1 indicate a realistic upper bound for the next 50 years for Lake Erie maximum monthly mean levels of around 175.0 m IGLD. Lake Erie levels appear quite insensitive to the input of realistically high values of NBS. On the other hand, Lake Michigan-Huron levels are quite sensitive to changes in high NBS input, e.g., compare results of Scenarios 4, 5 and 6. Taking a maximum monthly level midway between the results of Scenarios 5 and 6 gives an elevation of 177.5 m IGLD. This might be used as a realistic upper bound for Lake Michigan-Huron over the next 50 years. However, no probabilities of exceedance can be assigned to these levels.

For the regulated lakes, Hartmann's (1986) investigation indicates a probable upper limit for Lake Superior at 183.64 m. For Lake Ontario the upper limit might exceed the highest monthly mean of record at 75.61 m. The six-month forecast level for May 1987 was 75.85 m. If maximum levels for the regulated lakes are approached, it would almost certainly result in deviations from the respective regulation plans.

5.3 Potential Lowering of Great Lakes Levels by Diversions

Existing diversions, described in Section 2.1, have a small effect on Great Lakes levels. Further manipulation of these diversions for the purpose of alleviating high lake levels was found to be without merit on the basis of conventional benefit-cost ratio (IJC

1985). The potential impacts of larger-scale interbasin diversions have been assessed using a numerical hydrologic response model by Loucks et al. (1987). Impacts on Lake Ontario were not investigated because Lake Ontario levels are strongly dependent on the regulation plan and do not affect the levels of the upper lakes.

Loucks et al. (1987) used data from 1900 to 1978 to establish base case data. Then eight diversion scenarios were investigated (Table 19). Ultimate annual mean water level impacts relative to the base case are presented in Table 20. Scenario SU5 is comparable to shutting off the Ogoki-Long Lac diversion into Lake Superior. This results in a lowering of Lakes Superior and Erie by 6.7 cm and Lake Michigan-Huron by 11 cm. A diversion of 30,000 cfs from Lake Erie (scenario ER30), which is of the same magnitude as the proposed Plan 25-N, results in a lowering of Lake Erie by 41 cm. This is comparable to the results of Hartmann (1987), who used a different method of simulating Plan 25-N, which gave a lowering of Lake Erie of 27 cm.

TABLE 19: **Plan 1977 parameter changes used in simulation runs of Loucks _et_ _al_. (1987)**

			Changes to Lake Superior Regulation Plan 1977			
					St. Marys River	
Scenario	Lake Diverted From	Flow Rate (m^3/s)	Superior Target Stage (m)	Michigan-Huron Target Stage (m)	Target Outflow (m^3/s)	Minimum Outflow (m^3/s)
SU5	Superior	142	-0.09	-0.11	-142	-142
SU10	Superior	283	-0.15	-0.20	-283	0
SU10L	Superior	283	-0.15	-0.20	-283	-283
SU30	Superior	850	-0.55	-0.61	-850	-850
MH10	Michigan-Huron	283	-0.076	-0.21	0	0
MH30	Michigan-Huron	850	-0.30	-0.64	0	0
ER10	Erie	283	0	-0.61	0	0
ER30	Erie	850	-0.076	-0.40	0	0

TABLE 20: **Changes in average lake level relative to the base case (in metres) from Loucks et al. (1987)**

Scenario	Superior	Michigan-Huron	Erie
SU5	-0.067	-0.11	-0.067
SU10	-0.22	-0.21	-0.14
SU10L	-0.18	-0.21	-0.14
SU30	-0.54	-0.64	-0.41
MH10	-0.15	-0.21	-0.14
MH30	-0.30	-0.64	-0.41
ER10	-0.015	-0.052	-0.14
ER30	-0.14	-0.15	-0.41

6.0 CONCLUSIONS

A review of recorded water level measurements for the Great Lakes shows good data for all the lakes back to 1860, and limited data of poorer quality back to 1819 for Lakes Erie and Michigan-Huron, and back to 1815 for Lake Ontario. Plots of annual maximum monthly mean levels are provided in Figures 2 to 5. The ranges of recorded mean monthly lake levels are given in Table 18.

Review and interpretation of water level information from several historical, archeological and geologic sources suggests that the levels of Lakes Erie and Michigan-Huron have not been significantly different from those in Table 18 over approximately the past 350 years. This evidence is in distinct contrast to a theory of Dr. Curtis Larsen (U.S. Geological Survey) which postulates a long-term fluctuating trend in the mean annual level of Lake Michigan, lasting for periods of centuries, with variations as large as two metres above and below the approximate modern mean level of 177 m IGLD (1955).

Climate change literature has been reviewed. Recorded climatological data for parts of the Great Lakes Basin are available from 1854. Moderate, but distinct, changes in the regional climate over this period are evident and can be seen to be mirrored by changes in the levels of the Great Lakes.

Future climate change predictions using numerical global circulation models have been reviewed for the Great Lakes Basin. For an effective doubling of atmospheric carbon dioxide concentrations, possibly occurring by the middle of the next century, two different models predict increases in mean annual temperatures in the Basin of 3 to 5°C. Predictions of changes in precipitation, wind patterns and relative humidity are far less certain. However, using the most likely predictions from the two models, the impact on Great Lakes water levels has been estimated by others using a numerical hydrologic response model. The predicted results show decreases in mean annual lake levels of 21 to 83 cm. Under this climate regime, lake levels could be expected to be at or below their respective mean levels for 1963 to 1965, a period of unusually low levels, for approximately 40 to 80 percent of years. However, a sensitivity analysis of net basin supplies to changes in temperature, precipitation, wind speed and relative humidity indicates that net basin supplies could conceivably increase, not decrease, under a warmer climate regime depending on the changes in the other three parameters; this, in turn, would lead to higher lake levels.

The potential upward variation in Great Lakes levels over the next 50 years has been estimated from results of a study which used a numerical hydrologic response model and several scenarios for above average net basin supplies. These estimates assume present diversions, hydraulic controls and that climate variations over the next 50 years will be similar to those of the past two centuries. Lake Erie levels appear quite insensitive to the input of realistically high values of net basin supplies. Simulation results indicate a probable upper bound for Lake Erie maximum monthly mean levels of around 175.0 m IGLD (1955). On the other hand, Lake Michigan-Huron lake levels are much more sensitve to changes in high net basin supplies. A probable upper bound for Lake Michigan-Huron maximum monthly mean levels of around 177.5 m IGLD (1955) is suggested. For the regulated lakes, a probable upper limit for Lake Superior of 183.64 m IGLD (1955) has been suggested. For Lake Ontario the highest recorded monthly mean of 75.61 m IGLD (1955) could be surpassed but is dependent on discretionary deviations from its regulation plan.

ACKNOWLEDGEMENTS

I wish to thank the many people who provided ideas, help and encouragement during the course of this study, including the following:

Gary Boyd
John Coakley
Stewart Cohen
Holly Hartmann
Conrad Heidenreich
Donald Heldman
Henry Hengeveld
Elsie Jury
Harry Lippincott
Jack McGregor
Ralph Moulton
Arnold Pilling
Michelle Quealey
Frank Quinn
Dennis St. Jacques
Rick Sandilands
Chuck Southam
Peter Yee

REFERENCES

Allsopp, T.R. and Cohen, S.J. 1986. CO_2-Induced Climate Change and its Potential Impact on the Province of Ontario. Proc. Conf. on Climate and Water Management, American Meteorological Society, Boston, Mass., 285-290.

Atmospheric Environment Service. 1986. Understanding CO_2 and Climate. Annual Report 1985. Canadian Climate Centre, Downsview, Ontario, 22 pp.

Bernabo, J.F. 1981. Quantitative Estimates of Temperature Changes Over the Last 2700 Years in Michigan Based on Pollen Data. Quaternary Research, 15: 143-159.

Brown, R. and Walsh, K. 1986. Canadian Seasonal Climate Scenarios for a CO_2-Induced Global Warming. Canadian Climate Centre Report 86-14, Atmospheric Environment Service, Downsview, Ontario.

Bruce, J.P. 1984. Great Lakes Levels and Flows: Past and Future. J. Great Lakes Research, 10(2): 126-134.

Brunk, I.W. 1968. Evaluation of Channel Changes in St. Clair and Detroit Rivers. Water Resources Research, 4(6): 1335-1346.

Bryson, R.A. 1974. A Perspective on Climatic Change. Science, 184: 753-760.

Changnon, S.A., Jr. 1984. Climate Fluctuations in Illinois: 1901-1980. Bulletin 68, Illinois State Water Survey, Champaign, Illinois.

Clark, R.H. and Persoage, N.P. 1970. Some Implications of Crustal Movement in Engineering Planning. Canadian J. of Earth Sciences, 7: 628-633.

Cohen, S.J. 1986. Impacts of CO_2-Induced Climatic Change on Water Resources in the Great Lakes Basin. Climate Change, 8: 135-153.

Cohen, S.J. 1987. Sensitivity of Water Resources in the Great Lakes Region to Changes in Temperature, Preciptation, Humidity and Wind Speed. Proc. IUGG/IAHS Symposium on The Influence of Climate Changes and Climatic Variability on Hydrological Regime and Water Resources.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. 1957. Crustal Movement in the Great Lakes Area. Vertical Control Subcommittee.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. 1969. History of Water Level Gauges, Lake Erie and the Niagara River.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. 1977. Apparent Vertical Movement Over the Great Lakes.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. 1978. History of Water Level Gauges, Upper Great Lakes and the St. Clair-Detroit Rivers.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. 1987. History of Water Level Gauges, Lower Great Lakes and International Section of the St. Lawrence River.

Croley, T.E., II. 1986. Understanding Recent High Great Lakes Water Levels. Great Lakes Enviornmental Research Laboratory, No. 499, Ann Arbor, Michigan, 11 pp.

Demeter, C.S. and Weir, D.J. 1983. A Cultural Resources Investigation of the Chene Park II Site - Detroit, Michigan. Recreation Department, City of Detroit.

Derecki, J.A. 1982. Effect of Channel Changes in the St. Clair River Since 1900. NOAA Technical Memorandum ERL GLERL-40, 20 pp.

Fitting, J.E. 1976. Archaeological Excavations at the Marquette Mission Site, St. Ignace, Michigan, in 1972. The Michigan Archaelogist, 22(2-3), Ann Arbor, Michigan.

Fleming, C.A. 1983. Lake Erie Water Level Trends 1819-1982. Public Works Canada, Toronto, Ontario.

Fraser, G.S., Larsen, C.E. and Hester, N.C. 1975. Climatically Controlled High Lake Levels in the Lake Michigan and Huron Basins. Anais. Academia Brasileira Ciencias, 47 (Suplemento): 51-66.

Fritts, H.C. and Lough, J.M. 1985. An Estimate of Average Annual Temperature Variations for North America, 1602 to 1961. Climatic Change, 7(2): 203-224.

Great Lakes Institute. 1986. Socio-Economic Assessment of the Implications of Climatic Change for Commercial Navigation and Hydro-Electric Power Generation in the Great Lakes - St. Lawrence River System. University of Windsor, 122 pp.

Hansen, J., Johnson, D., Lacis, A., Lebedeff, S., Lee, P., Rind, D. and Russell, G. 1981. Climate Impact of Increasing Atmospheric Carbon Dioxide. Science, 213: 951-966.

Hansen, J., Russell, G., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R. and Travis, L. 1983. Efficient Three-Dimensional Global Models for Climate Studies: Models I and II. Monthly Weather Review, III: 609-662.

Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R. and Lerner, J. 1984. Climate Sensitivity: Analysis of Feedback Mechanisms. In: Hansen, J.E. and Takahashi, T. (editors), Climate Processes and Climate Sensitivity. American Geophysical Union, Washington, D.C.

Hansen, J., Lacis, A., Rind, D., Russell, G., Fung, I., Ashcroft, P., Lebedeff, S., Ruedy, R. and Stone, P. 1986. The Greenhouse Effect: Projections of Global Climate Change. In: Titus, J.G. (editor), Effects of Changes in Stratospheric Ozone and Global Climate, U.S. Environmental Protection Agency, Volume 1, 199-218.

Harrington, C.R. and Rice, G. (editors). 1984. Climate Change in Canada 4: Annotated Bibliography of Quaternary Climatic Change in Canada. Syllogeus 51. National Museum of Natural Sciences, Ottawa.

Hartmann, H. 1987. Potential Variations of Great Lakes Water Levels: A Hydrologic Response Analysis. Great Lakes Environmental Research Laboratory, Ann Arbor, MI.

Hartmann, H.C. 1986. Historical Basis for Limits on Lake Superior Level Regulations. Great Lakes Environmental Research Laboratory, Open File Report, Ann Arbor, Michigan, 25 pp.

Heidenreich, C. 1970. Huronia: A History and Geography of the Huron Indians 1600-1650. McClelland and Stewart Ltd., Toronto, Ontario.

Heldman, D.P. 1977. Excavations at Fort Michilimackinac, 1976: The Southeast and South Southeast Row Houses. Archaeological Completion Report Series, Number 1, Mackinac Island State Park Commission, Mackinac Island, Michigan.

Heldman, D.P. 1978. Excavations at Fort Michilimackinac, 1977: House One of the South Southeast Row House. Archaeological Completion Report Series, Number 2, Mackinac Island State Park Commission, Mackinac Island, Michigan.

Heldman, D.P. 1986. Michigan's First Jewish Settlers: A View from the Solomon-Levy Trading House at Fort Michilimackinac, 1765-1781. New World Archaeology V1(4): 21-33, University of California, Los Angeles.

Heldman, D.P. and Minnerly, W.L. 1976. Fort Michilimackinac Archaeological Investigations 1974 and 1975. Archaeological Completion Report Series, Number 7, National Park Service, Technical Preservation Services Division, Washington, D.C.

Heldman, D.P. and Grange, R.T., Jr. 1981. Excavations at Fort Michilimackinac: 1978-1979. The Rue de la Rabillarde. Archaeological Completion Report Series, Number 3, Mackinac Island State Park Commission, Mackinac Island, Michigan.

Hoeller, A.E. 1982. The Role of Environmental and Historical Evidence in Climate Reconstruction: A Preliminary Review and Appraisal. Canadian Climate Centre Report 82-3, Atmospheric Environment Service, Downsview, Ontario, 113 p.

Hough, J.L. 1958. Geology of the Great Lakes. University of Illinois Press, Urbana, Illinois, 313 p.

Hough, J.L. 1963. The Prehistoric Great Lakes of North America. American Scientist, 51: 84-109.

Hunter, A.F. 1911. Historic Sites of Tay. Bulletin of the Simcoe Pioneer and Historical Society, Barrie, Ontario.

Institute for Environmental Studies. 1985. Climatic Outlook No. 1, U.S. July-December 1985. Bulletin of the Experimental Long-Range Forecasts of the Climate Forecast Group, University of Wisconsin - Madison.

International Joint Commission. 1981. Great Lakes Diversions and Consumptive Uses.

International Joint Commission. 1983. Limited Regulation of Lake Erie. Report to the Governments of the United States and Canada, Washington, D.C.

International Joint Commission. 1985. Great Lakes Diversions and Consumptive Uses. A report to the Governments of the United States and Canada under the 1977 Reference, 82 pp.

International Lake Ontario Board of Engineers. 1958a. Effects on Lake Ontario Water Levels of the Gut Dam and Channel Changes in the Galop Rapids Reach of the St. Lawrence River. Report to the International Joint Commission.

International Lake Ontario Board of Engineers. 1958b. Water Levels of Lake Ontario. Final Report to the International Joint Commission.

International Niagara Board of Control. 1986. Letter from Brigadier General Joseph Pratt to Mr. David A. La Roche, Secretary, U.S. Section, International Joint Commission, Washington, D.C.

Jury W. and Jury, E.M. 1954. Sainte Marie Among the Hurons. Oxford University Press, Toronto, Ontario.

Kidd, K.E. 1949. The Excavation of Ste. Marie I. University of Toronto Press, Toronto.

Lamb, H.H. 1977. Climate Present, Past and Future, Volume 2, Climatic History and the Future. Methuen & Co. Ltd., London, 835 pp.

Larsen, C.E. 1985a. A Stratigraphic Study of Beach Features on the Southwestern Shore of Lake Michigan: New Evidence of Holocene Lake Level Fluctuations. Environmental Geology Notes 112, Illinois State Geological Survey, Champaign, Illinois.

Larsen, C.E. 1985b. Lake Level, Uplift, and Outlet Incision, the Nipissing and Algoma Great Lakes. In: Karrow, P.F. and Calkin, D.E. (editors), Quaternary Evolution of the Great Lakes, Geological Association of Canada, Special Paper 30, p 63-77.

Larsen, C.E. 1987. Long-term Trends in Lake Michigan Levels, A View from the Geologic Record. U.S. Geological Survey, Reston, VA. Unpublished manuscript.

Lawhead, H.F. 1961. Discussion of "Changes in the levels of Lakes Michigan and Huron" by I.W. Brunk. J. Geophysical Research, 66(10): 4324-4329.

Loucks, E.D., Joeres, E.F., Potter, K.W., David, M.H. and Rosenthal, S.S. 1987. Diversion of Great Lakes Water, Part I: Hydrologic Impacts. Institute for Environmental Studies, Report 130, University of Wisconsin-Madison.

Manabe, S. and Stouffer, R.J. 1980. Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere. J. of Geophysical Research, 85, C10: 5529-5554.

Maranto, G. 1986. Are We Close to the Road's End? Discovery, 7(1): 28-50.

Moulton, R.J. and Cuthbert, D.R. 1987. Great Lakes Water Levels: Man and Nature in the Shore Zone. Proc. Canadian Coastal Conference, National Research Council of Canada, 19-30.

National Ocean Survey. 1982. Great Lakes Water Levels, 1860-1980. National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce, Washington, D.C., 258 pp.

Olson, J.S. 1958a. Lake Michigan Dune Development: 3, Lake Level, Beach, and Dune Oscillations. J. of Geology, 66: 473-483.

Olson, J.S. 1958b. Rates of Succession and Soil Development on Southern Lake Michigan Sand Dunes. Botannical Gazette, 119: 125-170.

Ontario Ministry of Natural Resources. 1986. How to Protect Your Shore Property. Toronto, Ontario.

Parry, M.L. and Carter, T.R. 1986. Effects of Climatic Changes on Agriculture and Forestry: An Overview. In: Titus, J.G. (editor), Effects of Changes in Stratospheric Ozone and Global Climate, U.S. Environmental Protection Agency, Volume 1, 257-298.

Parry, M.L., Carter, T.R. and Konijn, N.T. (editors). 1987. The Impact of Climatic Variations on Agriculture. Vol. 1. Assessments in Cool Temperate and Cold Regions. Reidel, Dordrecht, Holland.

Quinn, F.H. 1978. Hydrologic Response Model of the North American Great Lakes. J. of Hydrology, 37: 295-307.

Quinn, F.H. 1981. Secular Changes in Annual and Seasonal Great Lakes Precipitation, 1854-1979, and Their Implications for Great Lakes Water Resource Studies. Water Resources Research, 17(6): 1619-1624.

Quinn, F.H. and Croley, T.E., II. 1981. The Role of Precipitation Climatology in Hydrologic Design and Planning on the Laurentian Great Lakes. Proc. 4th Conf. on Hydrometeorology, American Meteorological Society, 218-223.

Revelle, R. 1982. Carbon Dioxide and World Climate. Scientific American, 247(2): 35-43.

Ruellan, A. 1971. The History of Soils: Some Problems of Definition and Interpretation. In: Paleopedology, Yaalon, D.H. (editor), pp. 3-13.

Russell, W.A. 1965. A Mill at Ste. Marie I. Ontario Archaeology, Series B, 3(8): 11-17.

Schlesinger, M.E. and Mitchell, J.F.B. 1985. Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide. In: MacCracken, M.C. and Luther, F.M. (editors), Projecting the Climatic Effects of Increasing Carbon Dioxide, 81-148. U.S. Dept. of Energy, Washington, D.C.

Seidel, S. and Keyes, D. 1983. Can We Delay a Greenhouse Warming? U.S. Environmental Protection Agency, Washington, D.C.

Select Committee of the Ontario Legislature. 1953. Lake Levels of the Great Lakes. Queen's Printer, Toronto, Ontario.

Stewart, D. 1981. The Coastline from Long Point to Rondeau in Lake Erie. The Historical Geography 1615 to 1821. Public Works Canada, Toronto, Ontario.

Tait, B.J. 1983. Conversion of Historical Lake Erie Water Level Elevations to International Great Lakes Datum (1955). Public Works Canada, Toronto, Ontario.

Tait, B.J. and Bolduc, P.A. 1985. An Update on Rates of Apparent Vertical Movement in the Great Lakes Basin. Dept. of Ocean Science and Surveys, Fisheries and Oceans, Ottawa, Ontario.

Thomas, M.K. 1957. Changes in the Climate of Ontario. In: Changes in the Fauna of Ontario. Royal Ontario Museum, University of Toronto, Ontario, 57-75.

Titus, J.G. (editor). 1986. Effects of Changes in Stratospheric Ozone and Global Climate. U.S. Environmental Protection Agency. 4 Volumes.

U.S. Army Corps of Engineers. 1861. Report of the Secretary of War. Executive Documents, Printed by the Order of the Senate of the United Sates for the Second Session of the Thirty-sixth Congress and of the Special Session 1860-61, Part 2, 2: 305-479. Washington, D.C.

U.S. Deep Waterways Commission 1987. Document No. 192, 54th Congress, 2nd Session House of Representatives, Washington, D.C.

Wahl, E.W. 1968. A Comparison of the Climate of the Eastern United Sates During the 1830's with the Current Normals. Monthly Weather Review, 96(2): 73-82.

Wahl, E.W. and Lawson, T.L. 1970. The Climate of the Midnineteenth Century United States Compared to the Current Normals. Monthly Weather Review, 98(4): 259-265.

Water Planning and Management Branch. 1983. The Effects of Landfills in the Niagara River on the Water Levels of Lake Erie. Environment Canada, Burlington, Ontario.