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EFFECT OF CHANNEL CHANGES IN THE ST. CLAIR RIVER DURING THE PRESENT CENTURY

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ABSTRACT. Periodic man-made changes in the outlet of Lake Huron through the St. Clair River date back to the middle of the last century. These artificial channel changes have been well documented during the present century. They consist of dredging for commercial gravel removal in the upper river during 1908–25 and uncompensated navigation improvements for the 7.6-m (25-ft) and 8.2-m (27-ft) projects completed in 1933 and 1962, respectively. The total effect of these changes on the levels of Lakes Michigan and Huron (hydraulically one lake) and on the upper St. Clair River profile was determined with dynamic flow models. The ultimate effect of the above dredging was a permanent lowering of the Lake Michigan-Huron levels 0.27 m (0.89 ft), which represents a tremendous loss of freshwater resource [32 km^3 (7.7 mi^3)].
ADDITIONAL INDEX WORDS: Dredging, hydrologic models, outlet channels, flow models, lake outflows, water level.

INTRODUCTION

The Great Lakes represent a tremendous freshwater resource, and information on their levels and outflows is becoming progressively more important for water resource planning and the operation of the presently regulated lakes (Lakes Superior and Ontario). Currently, this information is available for over 120 years, 1860 to date. Man-made changes in the Great Lakes outflow channels go back to the middle of the last century. Artificial changes in the Lake Huron outlet through the St. Clair River (Fig. 1) for navigation improvements date back to 1856, when a channel was cut across sand bars in the St. Clair Flats area of the lower river to provide a 2.7-m (9-ft) draft (International Joint Commission 1976). The calculated outflows from the Great Lakes are based on stage-flow relationships derived from periodic flow measurements made after 1900. Since navigation improvements and commercial gravel dredging in critical locations could make the channel more efficient, the application of the post-1900 St. Clair River stage-flow relationships to the previous period would make the flows calculated for 1860–1900 artificially high. On the other hand, present regulation plans for Lakes Superior and Ontario, based on lake outflows for the relatively short post-1900 period, would fail under more severe natural conditions.

There is some controversy regarding the reasons for, and corresponding magnitudes of, the recorded drop in the levels of Lakes Michigan and Huron (which hydraulically are considered to be one lake) during the 1880–1900 period (Brunk 1961, 1963, 1968; Lawhead 1961; Quinn and Croley 1981). However, data available for the last century are insufficient to resolve the problem with direct hydraulic computations. Additional lowering of the Lake Michigan-Huron levels for the post-1900 period was estimated by the International Great Lakes Levels Board (1973) to total 0.27 m (0.89 ft). This consists of uncompensated dredging for waterway improvements for the 7.6-m (25-ft) and 8.2-m (27-ft) navigation channels completed in 1933 and 1962, respectively, and commercial gravel dredging in the upper St. Clair River in the vicinity of Point Edward, Ontario, between

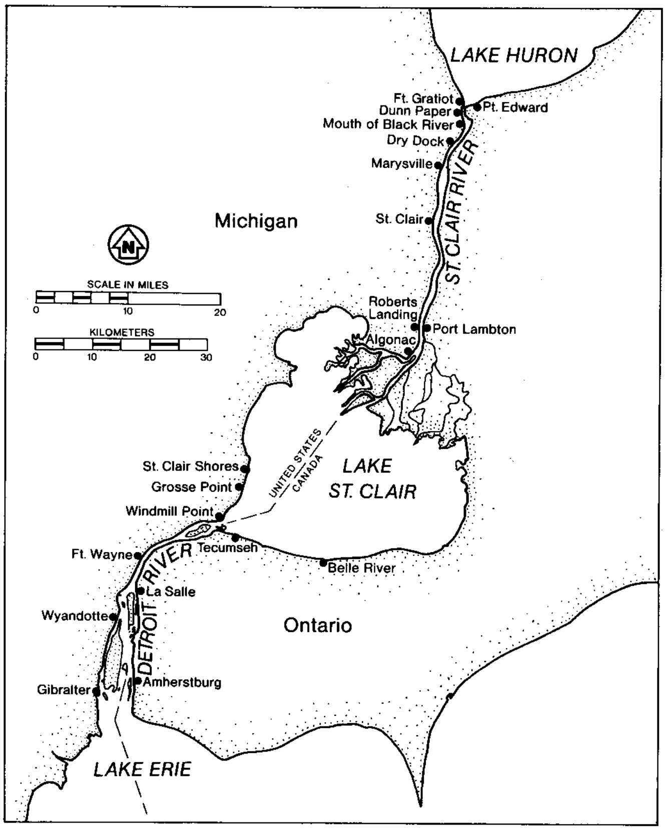

FIG. 1. St. Clair-Detroit River system with location of water level gages.

1908 and 1925. The effect of gravel dredging is estimated by the Levels Board to be about 0.09 m (0.3 ft), which leaves 0.18 m (0.59 ft) of the total lowering during this period to be attributed to uncompensated navigation dredging in the St. Clair River. Dikes were used to compensate for navigation dredging in the Detroit River.

The present study was conducted to verify the effects of uncompensated dredging after 1900 with the St. Clair River dynamic flow models. Although there is generally no controversy and sufficient documentation regarding the effects of this later uncompensated dredging (International Joint Commission 1976, International Great Lakes Levels Board 1973, U.S. Senate 1955, Joint Board of Engineers 1927), the use of flow models for this purpose represents a more sophisticated approach than those employed in previous estimates. The requirements for such a verification study are the channel cross-sectional areas and channel roughness coefficients for the appropriate periods. Determination of channel roughness coefficients requires river flow measurements. Historic hydrographic surveys and flow measurements for the Great Lakes were made by the U.S. Lake Survey, a former U.S. Army Corps of Engineers District. Archive records for the hydrographic surveys are presently maintained by the National Ocean Survey, National Oceanic and Atmospheric Administration (NOAA), while those for flow measurements are stored by the Detroit District, Corps of Engineers. The hydrographic survey of the St. Clair River conducted in 1900 provided cross-sectional areas before there was any known uncompensated dredging during this century (7.6-m and 8.2-m [25-ft and 27-ft] channels and gravel removal). Channel roughness for this period was determined from flow measurements conducted during 1908–10.

METHOD

The Great Lakes Environmental Research Laboratory (GLERL) dynamic flow models for the St. Clair River are described by Derecki and Kelley (1981). These models are one-dimensional transient flow models based on equations of continuity and momentum, with an option for the surface wind stress effects. Disregarding wind stress effects (not used in this study), the equations of continuity and momentum are expressed in terms of flow and stage

$$\frac{\partial Z}{\partial t} + \frac{1}{T}\frac{\partial Q}{\partial X} = 0 \qquad (1)$$

and

$$\frac{1}{A}\frac{\partial Q}{\partial t} - 2\frac{QT}{A^2}\frac{\partial Z}{\partial t} + \left(g - \frac{Q^2T}{A^3}\right)\frac{\partial Z}{\partial x} + \frac{g\, n^2\, Q|Q|}{2.208\, A^2\, R^{4/3}} = 0, \qquad (2)$$

where Z = stage above fixed datum (ft),
t = time (s),
T = top width of the channel (ft),
Q = flow rate ($ft^3\ s^{-1}$),
X = distance in the positive flow direction (ft),
A = channel cross-sectional area (ft^2),
g = acceleration due to gravity (32.2 ft s^{-2})
n = Manning's roughness coefficient, and
R = hydraulic radius (ft).

Basic model computations are performed in English units since all input data come in English units; the final results are converted to the desired system. The model solution uses an implicit finite-difference method with Newton-Raphson iterative algorithms for initiating the computations, which can be operated with variable time steps. Several versions of the models incorporating different river reaches are all confined to the upper one-third of the river, between a gage at Fort Gratiot (FG), Michigan, at the head of the river and a gage at St. Clair (SC), Michigan, 23 km (14.3 mi) downstream (Fig. 1). This portion of the river contains most of the river slope and is usually free of ice concentrations during winter. The model programs are written in a generalized manner and can be easily modified or adapted to other rivers by appropriate substitution of physical characteristics (cross-sectional areas, channel widths, roughness coefficients, etc.) and boundary conditions (downstream and upstream controls). Model computations incorporate detailed channel definition to indicate the actual river channel. For the purpose of this study, it was necessary to use a model that would cover the entire upper river reach between Fort Gratiot and St. Clair, two of the oldest river gages in the system. Since none of the existing operational models covered this reach, they were modified to obtain two desired models, each comprising upper and lower reaches with intermediate locations at the Mouth of Black River (MBR) and Dry Dock (DD) gages. These models are identified by a three-gage designation as FG-MBR-SC and FG-DD-SC.

The procedure for determining channel changes involved using current water level data to compute river flows with the present channel configuration and then matching these flows with the previous channel configuration modified by appropriate cross-sectional areas and channel roughness coefficients. The difference in water levels for the same flow with present and previous channel configurations represents the effect of channel changes due to dredging. The ultimate effect of channel changes on the water levels should be nearly the same during periods of low or high water supply. This is demonstrated by computing the channel-change effects for 1970, a year of mid-range or average water levels, and for 1973, a year of high water levels. To eliminate possible ice effects, the computations were limited to the open water season and, furthermore, were restricted to the June–August period, which represents annual peak water levels.

The upper St. Clair River hydraulic parameters for the 1900 and present channels are given by Derecki (1982). The 1900 and present areas at the section corresponding to the Mouth of Black River gage location were compared to indicate channel changes (Fig. 2). As indicated, the present channel at this section has a nearly uniform depth as a result of substantial dredging over most of its width. It is apparent from Figure 2 that final stages of this dredging were part of the 8.2-m (27-ft) navigation project completed in 1962. The present navigation channel at this location covers slightly over half of the river on the United States, or western, side. The actual channel depths are lower than 8.2 m (27 ft) because it is common practice to provide approximately 0.6-m (2-ft) overdraft when deepening navigation channels. During both the 7.6-m (25-ft) and the 8.2-m (27-ft) projects, dredged material was deposited in river areas where it would not interfere with navigation to partially offset some of the effects on upstream water levels. This explains the filling of the deeper portion of the river along the eastern bank. Thus, present river depth in this location is approximately 8.8 m (29 ft), with the exception of a reduction in depth to 7.9 m (26 ft) along the eastern boundary of the navigation channel and the overbanks. The assumption of a 0.6-m (2-ft) overdraft is verified by the average depth of the present channel at this section, which is also about 8.8 m (29 ft). This compares with a value under 7.6 m (25 ft) in 1900, giving an 18% increase in the cross-sectional area for the present period.

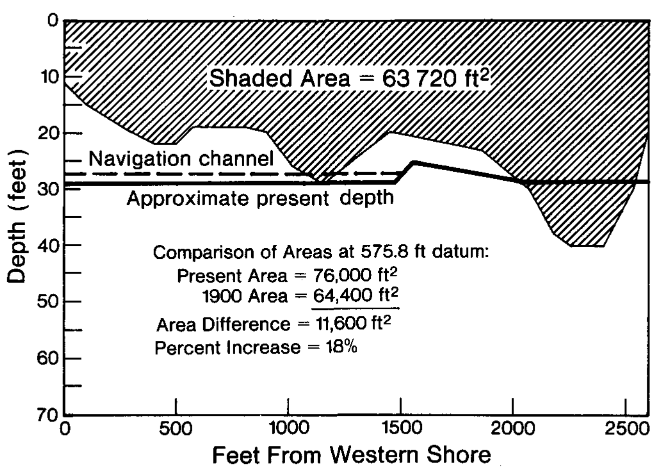

FIG. 2. Comparison of 1900 and present areas at the Mouth of Black River gage section.

Calibration of the models for both periods consisted of computing roughness coefficients for each reach of the river bounded by water level gages. The roughness coefficients were determined from Manning's formula

$$n = \frac{1.486\ A\ R^{2/3}}{Q} \left(\frac{Z_u - Z_d}{L} + \frac{Q^2\ \triangle A}{g\ L\ A^3} \right)^{1/2}, \quad (3)$$

where n = Manning's roughness coefficient,
A = mean channel area (ft^2),
R = hydraulic radius (ft),
Q = flow rate ($ft^3\ s^{-1}$),
Z_u = water surface at upstream gage (ft),
Z_d = water surface at downstream gage (ft),
L = length of channel reach between gages (ft),
$\triangle A$ = change in channel area between gages (ft^2), and
g = acceleration due to gravity (32.2 ft s^{-2}).

The roughness coefficients for the present channel are based on 14 sets of flow measurements taken by the Corps of Engineers during 1959–77. For the 1900 channel, seven sets of flow measurements made during 1908–10 were used. Although commercial gravel dredging in the upper St. Clair River started in 1908, there are no indications that channel changes in the first few years were significant; thus, these measurements should provide satisfactory indication of channel roughness conditions for the 1900 period. The relationships between computed roughness coefficients for channel reaches along the upper St. Clair River and the river stages at adjacent water level gages for the FG-MBR, FG-DD, MBR-SC, and DD-SC reaches were derived for the 1900 and present channel conditions. The relationships for downstream reaches during the 1959–77 flow measurements were affected by regimen changes associated with dredging for navigation improvements. For these reaches, separate roughness coefficients were derived for each regime, representing 1900, pre-project (through 1963), and present (starting in 1964) conditions. The calibrated roughness coefficients for the four reaches are described in more detail by Derecki (1982) and are summarized in Table 1.

RESULTS

Results of computations for the effects of channel changes in the upper and total St. Clair River by dredging during the present century (since 1900) for commercial gravel removal (1908–25) and navigation improvements (1933 and 1962) are presented in Tables 2 and 3. These tables show June–August average values for an average water level year (1970) and a high water level year (1973), respectively, given by two dynamic flow models developed specifically for this purpose. Results from the two models agree closely, with a maximum variation of 0.01 m (0.03 ft), which is well within limits of expected accuracy. Flow measurement accuracy for the Great Lakes connecting channels is generally considered to be 2%, which is about 100 $m^3\ s^{-1}$ (3,500 $ft^3\ s^{-1}$) for the normal St. Clair River range of flows and is equivalent to about a 0.03 m (0.10 ft) difference in head or water

TABLE 1. St. Clair River Manning's roughness coefficients for present and 1900 channel conditions. Gages: FG = Fort Gratiot, MBR = Mouth of Black River, DD = Dry Dock, SC = St. Clair.

Reach	Channel	Flow measurements	Roughness coefficient (n)
FG-MBR	Present	1959–77	n = 0.0003506 (FG) - 0.17218
	1900	1908–10	n = 0.0003506 (FG) - 0.16810
FG-DD	Present	1959–77	n = 0.0002037 (FG) - 0.09053
	1900	1908–10	n = 0.0002037 (FG) - 0.08803
MBR-SC	Present	1964–77	n = 0.0236 (starting 1964)
	Pre-project	1959–63	n = 0.0245 (through 1963)
	1900	1908–10	n = 0.0263
DD-SC	Present	1964–77	n = 0.0240 (starting 1964)
	Pre-project	1959–63	n = 0.0252 (through 1963)
	1900	1908–10	n = 0.0274

TABLE 2. Results of computations for upper St. Clair River profile with present and 1900 channel conditions during average water levels (1970). Gages: FG = Fort Gratiot, MBR = Mouth of Black River, DD = Dry Dock, SC = St. Clair.

			Elevation in meters			Dredging effects (m)	
	Flow	River	Present	1900 Channel		Upper	Total
Model	m^3s^{-1}	gages	channel	Upper	Total	river	river
FG-MBR-SC	6014	FG	176.49	176.67	176.76	-0.18	-0.27
		MBR	176.27	176.35	176.44	-0.08	-0.17
		SC	175.75	175.75	175.87	0	-0.12
FG-DD-SC	6023	FG	176.49	176.66	175.75	-0.17	-0.26
		DD	176.15	176.21	176.31	-0.06	-0.16
		SC	175.75	175.75	175.87	0	-0.12
Combined	6019	FG	176.49	176.66	176.75	-0.17	-0.26
		MBR	176.27	176.35	176.44	-0.08	-0.17
		DD	176.15	176.21	176.31	-0.06	-0.16
		SC	175.75	175.75	175.87	0	-0.12

TABLE 3. Results of computations for upper St. Clair River profile with present and 1900 channel conditions during high water levels (1973). Gages: FG = Fort Gratiot, MBR = Mouth of Black River, DD = Dry Dock, SC = St. Clair.

			Elevation in meters			Dredging effects (m)	
	Flow	River	Present	1900 Channel		Upper	Total
Model	m^3s^{-1}	gages	channel	Upper	Total	river	river
FG-MBR-SC	6567	FG	176.99	177.18	177.27	-0.19	-0.28
		MBR	176.75	176.83	176.93	-0.08	-0.18
		SC	176.23	176.23	176.35	0	-0.12
FG-DD-SC	6586	FG	176.99	177.17	177.26	-0.18	-0.27
		DD	176.63	176.69	176.79	-0.06	-0.16
		SC	176.23	176.23	176.35	0	-0.12
Combined	6577	FG	176.99	177.17	177.26	-0.18	-0.27
		MBR	176.75	176.83	176.93	-0.08	-0.18
		DD	176.63	176.69	176.79	-0.06	-0.16
		SC	176.23	176.23	176.35	0	-0.12

levels. These values represent zero computational errors and may be doubled for acceptable errors. The agreement for the two years is also very good, with maximum deviations at Fort Gratiot of 0.01 m (0.03 ft), showing that the effect of channel changes on water levels is nearly the same regardless of water supply conditions. The effect of dredging in the upper St. Clair River on the levels of Lake Huron, indicated by the Fort Gratiot gage at the head of the river, is a lowering of lake levels by 0.18 m (0.59 ft). Effects computed by the FG-MBR-SC and FG-DD-SC models vary, respectively, from 0.18 m to 0.17 m (0.59 ft to 0.56 ft) for 1970 and from 0.19 m to 0.18 m (0.62 ft to 0.59 ft) for 1973. These effects at the Mouth of Black River and Dry Dock gages, about 4 km (2.5 mi) and 8 km (5.0 mi) downstream, respectively, are reduced to a lowering of river stages by 0.08 m (0.26 ft) and 0.06 m (0.20 ft).

The above determinations, when adjusted for the lower river dredging effects on Lake Huron levels, agree well with previous total estimates published by the International Great Lakes Levels Board (1973). The Board lists the overall effect for the total river as 0.27 m (0.89 ft), about 0.09 m (0.3 ft) of which is attributed to commercial gravel removal and 0.18 m (0.59 ft) to uncompensated lowering of lake levels by the 7.6-m (25-ft) and 8.2-m (27-ft) navigation projects. The uncompensated dredging in the lower St. Clair River is limited mainly to the construction of the Cutoff Channel in the St. Clair Flats area for the 8.2-m (27-ft) project and exerts an additional negative effect on the levels of the upper river and Lake Huron. This is verified in a study conducted by the U.S. Lake Survey (1961). It shows that, although the two navigation projects have a lower overall effect with similar amounts, the effects of the 7.6-m (25-ft) project are restricted mostly to the upper river, and those associated with the 8.2-m (27-ft) project occur mainly in the mouth of the river.

The lower St. Clair River is below the physical limits of the available models and the dredging effects in this reach of the river have to be supplied as model input before the total effects can be computed with the models. These effects were determined from a gage relationship based on available data that shows that the water level at the St. Clair gage was about 0.12 m (0.4 ft) higher during 1900. With this input, the total dredging effects were recomputed; there is about 0.09 m (0.30 ft) additional drop in Lake Huron levels due to dredging in the lower river. The ultimate effect of dredging in the entire St. Clair River since 1900 for gravel removal and the two navigation projects is a lowering of lake levels (Fort Gratiot) by about 0.27 m (0.88 ft) or almost exactly the amount listed by the International Great Lakes Levels Board. The amount of lowering is reduced downstream to 0.18 m (0.59 ft) and 0.16 m (0.52 ft) at the Mouth of Black River and Dry Dock gages, respectively. Maximum deviations between the two models due to different water supply conditions are 0.01 m (0.03 ft), as indicated previously for the upper river dredging effects. The upper St. Clair River water surface profiles for the present and 1900 channel conditions computed for both years are shown in Figure 3. The profiles are nearly identical despite large differences in flows and water levels.

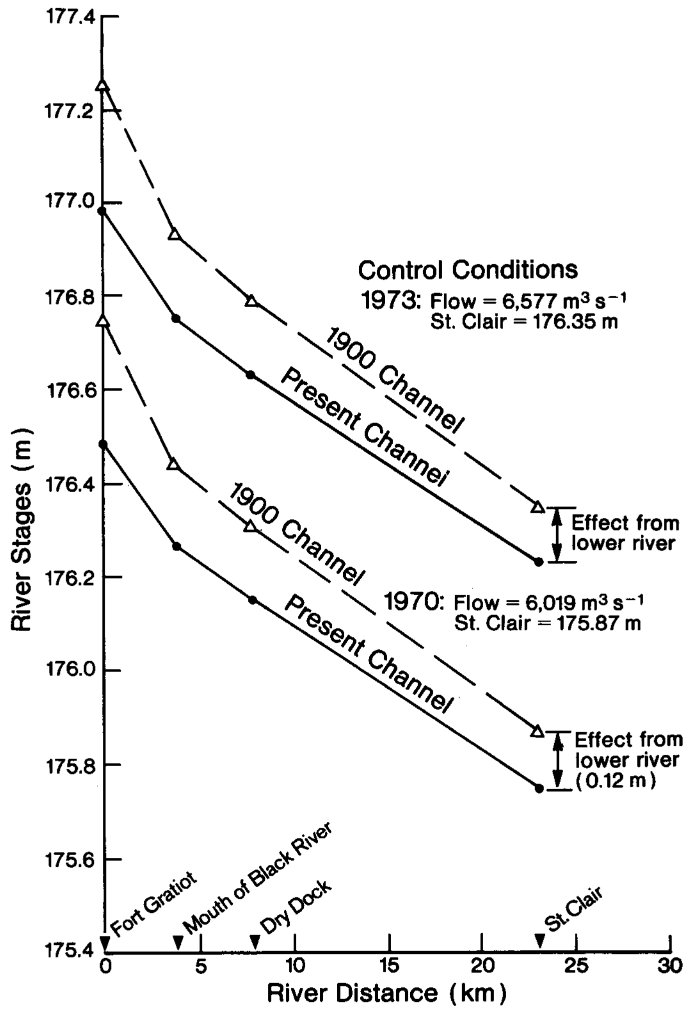

FIG. 3. Upper St. Clair River water surface profile for present and 1900 channel conditions.

CONCLUSIONS

Artificial channel changes in the St. Clair River since 1900 include dredging for commercial gravel removal between 1908 and 1925 and uncompensated navigation improvements for the 7.6-m (25-ft) and 8.2-m (27-ft) projects completed in 1933 and 1962, respectively. These channel changes increased the efficiency of the Lake Michigan-Huron outlet through the St. Clair River and caused permanent lowering of the lake's levels. The total effect of these man-made channel changes is the lowering of the levels of Lake Michigan-Huron by 0.27 m (0.89 ft). This depth superimposed on the combined area of Lakes Michigan and Huron represents a permanent water loss of 32 km^3 (7.7 mi^3), which is more than nine times greater than the volume of Lake St. Clair.

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