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DETROIT RIVER FLOW REVERSALS

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ABSTRACT. Detroit River flow reversals were investigated using a water surface gradient analysis in conjunction with Detroit River unsteady flow models. Three cases and five highly probable cases were simulated to occur between 1900 and 1986; the most recent episode occurred in April 1984. Flow reversals are likely only during St. Clair River ice jams, when the water supply to Lake St. Clair is severely restricted. The reversals appear to be of limited duration, less than 12 hours, with maximum flows less than 4,200 m^3s^{-1}. Flow reversals were most common during the first 40 years of this century and 46 years separate the last two occurrences. The decreased frequency probably results from the 7.6 m and 8.2 m navigation dredging projects on the St. Clair River. The use of the Gibraltar water level gage to represent the mouth of the river was found to be critical for the analysis.

ADDITIONAL INDEX WORDS: Water currents, mathematical models, water level recorders, Lake St. Clair.

INTRODUCTION

The Detroit River connects Lakes St. Clair and Erie and serves as the conduit for water flowing out of the upper Great Lakes (Fig. 1). Its banks are heavily industrialized, and industrial and municipal wastes are discharged into the river. The normal flow of the river is from Lake St. Clair to Lake Erie. However, under a combination of meteorological and ice conditions the flow can reverse. These flow reversals are interesting as hydraulic phenomena, but are more important because they disrupt the normal contaminant pathway. Flow reversals could transport contaminants into Lake St. Clair that would ordinarily flow into Lake Erie, which could potentially impact water intakes and lead to deposition of contaminants in Lake St. Clair near the head of the Detroit River. Interest in the impacts of flow reversals on pollution is not new (Vaughan and Harlow 1965). However the required technology for detecting flow reversals (either continuously recording current meters capable of operating in the connecting channels environment (Derecki and Quinn 1987b) or computerized unsteady flow models) was not available until the late 1970s and early 1980s. Until recently, the river flows were not continuously measured and had to be computed by either stage-fall discharge equations or flow models for monthly time scales and by unsteady flow models for hourly and daily time scales. This study uses a water level gradient procedure in conjunction with computerized unsteady flow models for the Detroit River to simulate the occurrence of flow reversals, i.e., their frequency, magnitude, duration, and prerequisite conditions.

UNSTEADY FLOW MODELS

Until recently, measurements of the flow in the Detroit River have consisted of periodic sets of discharge measurements which have been used for calibrating discharge equations and flow models, and for backwater computations. Prior to 1970, monthly flows were computed using stage-fall discharge equations. Since 1970, computerized unsteady flow models have been used to provide hourly, daily, and monthly flows in the Detroit River for both water quantity and water quality studies (Quinn 1976). Two models were used in the current study: a total river model (Quinn and Wylie 1972) with three idealized channels representing the upper river between Wyandotte and Windmill Pointe and the split channels between Wyandotte and Lake Erie, and an upper river model (Quinn and Hagman 1977) representing the upper river between Lake St. Clair and Grosse Isle. Model selection was dependent upon the availabil-

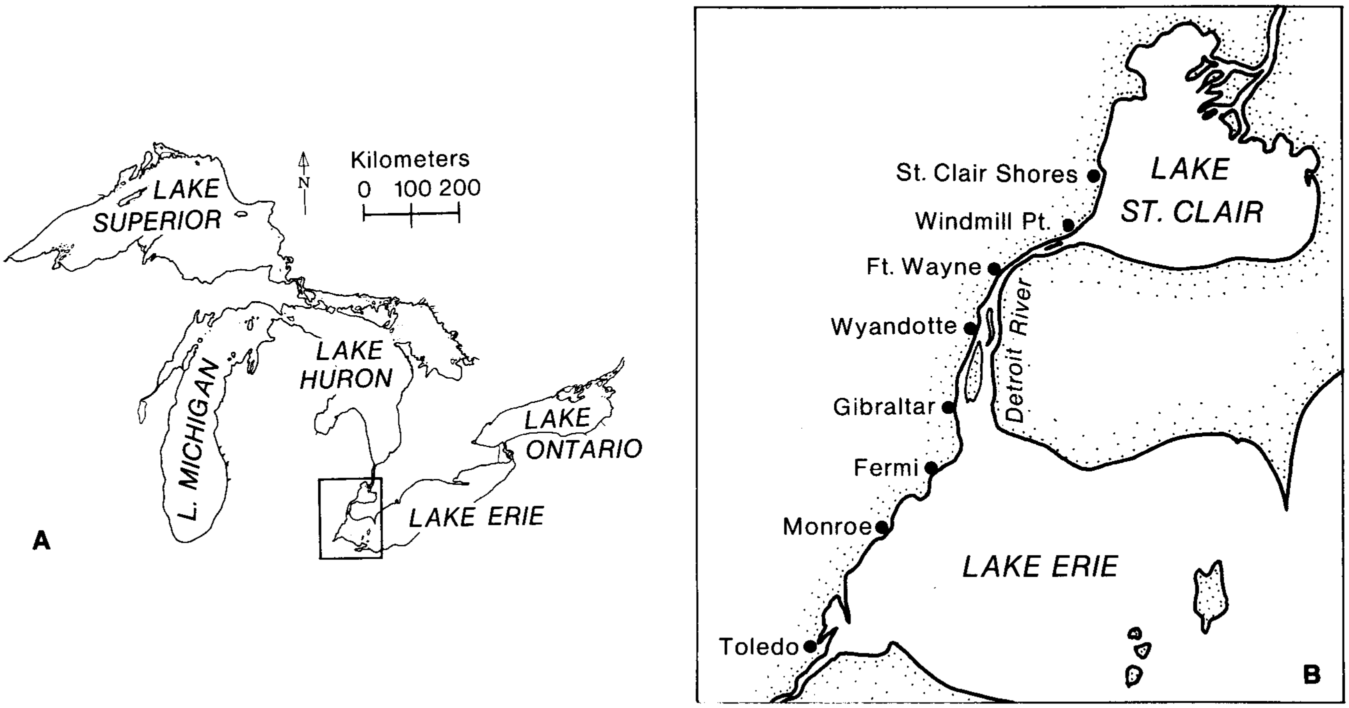

FIG. 1 (a) The Great Lakes basin. (b) Enlargement of the rectangular area in Figure 1(a) showing the water level gage locations.

ity of appropriate water level data; preference was given to the upper river model. Both models provide flows at the head of the river which are used for the analysis. The upper river model requires water level data from the Wyandotte and Windmill Pointe water level gages, and the total river model requires data from the Fermi and Windmill Pointe water level gages (Fig. 1). The models were calibrated by computing Manning's roughness values from river discharge measurements taken during the present hydraulic regime, 1959-present. Roughness values were modified for model runs using data from the Gibraltar and St. Clair Shores water level gages. Model applications prior to 1959 may yield flow rates slightly larger than actual flows because of decreased channel capacity prior to navigation channel dredging and the construction of the current compensating works. Model accuracy may also be degraded during reversals because discharge measurements used for calibration were normally taken during optimum conditions, and not during high winds and storm surges.

For this study, the Gibraltar gage was used instead of the Fermi gage to represent the water levels in the lower river during dynamic storm surge conditions because it is situated in the river proper. Water levels at the Gibraltar gage are considered more representative of the forcing elevations than the Fermi or Toledo gages. The isopleths shown in Figure 2 indicate that the Fermi and Toledo water level gages are not representative of the level at the mouth of the river during storm surges which result from easterly winds along the axis of the lake. Because of its location, the Toledo gage, which is used as the reference gage for Lake

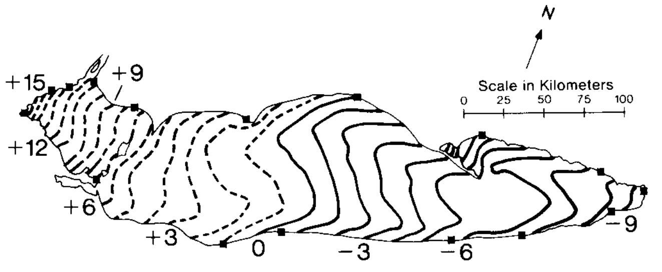

FIG. 2. Lake Erie non-dimensional water level variations (from Croley 1987).

Erie surges, does not represent the forcing water levels at the mouth of the river; it tends to record larger positive and negative surges than those that actually occur at the river mouth.

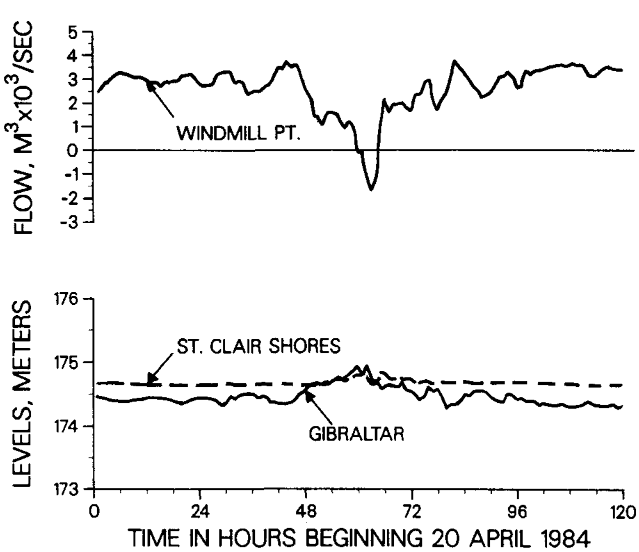

FIG. 3. Model simulation of the April 1984 flow reversal.

WATER LEVEL GRADIENT ANALYSIS

A water level gradient procedure was used to select possible flow reversal episodes for analysis using the unsteady flow models. Water level data for the study area were obtained from the National Ocean Service water level gages shown in Figure 1b (excluding Monroe and Toledo). Hourly data were used whenever possible. When they were not available, tri-daily data were interpolated to provide an hourly time series. During many episodes prior to 1970 the water level data recorded at the Windmill Pointe gage are missing. In these instances water level data at the St. Clair Shores gage or its predecessor, the Grosse Pointe Yacht Club gage on Lake St. Clair, were substituted. The water level gradient analysis was first applied to the period 1973–1986 which has computerized hourly water level data. The procedure consisted of computing the fall between various water level gages in the upper river and flagging incidents of negative values. A negative fall is required for a flow reversal. Gage pairs consisted of Windmill Pointe-Fort Wayne, Windmill Pointe-Wyandotte, and Fort Wayne-Wyandotte. Fifty-nine days were flagged during the 14-year period as having negative falls for 1 hour or more. Fifty-three of these days were selected for flow simulation with the upper Detroit River model. The model simulations indicated that most of the negative gradients were caused by small gravity waves in the river, ice jamming, and gage errors or other gage problems. Only one flow reversal was identified, occurring on 22 April 1984 during the record St. Clair River ice jam (Derecki and Quinn 1987a). No reversals were noted during times of high positive storm surges in western Lake Erie. The April 1984 flow reversal resulted from a small positive storm surge that occurred while Lake St. Clair water levels were depressed by about 60 cm due to the ice jam. Figure 3 shows the model flow simulation for 20–25 April. During the 6-hour period beginning at 1200 hours on 22 April (60 hours on Fig. 3) the simulated flow reversed and flowed into Lake St. Clair. The maximum simulated reversed flow was about 2,000 m^3s^{-1}, approximately 40% of the average Detroit River flow. A volume a 1.5 x 10^6 m^3s^{-1} of Detroit River water was transported into Lake St. Clair. The study was expanded to include data from 1911 using a gradient analysis conducted by the Lake Survey District, Corps of Engineers (Vaughan and Harlow 1965). This analysis indicated 12 potential flow reversals between 1911 and 1964 (Table 1). Simulations with the unsteady flow models for the 1939, 1944, and 1948 episodes indicated flow reversals on 30 January 1939 and 9 to 10 February 1939. Both reversals were larger than the 1984 event. The February 1939 reversal is depicted in Figure 4. The maximum inflow into Lake St. Clair was about 3,820 m^3s^{-1} and the episode lasted for 12 hours. Thus, this reversal was both larger and longer in duration than the April 1984 episode. Prior to 1939 the

TABLE 1. Times of possible gradient reversals, 1911-1964, identified by Vaughan and Harlow (1965).

Year	Month	Day
1911	February	5-6
1914	January	31-31
1915	December	29-30
1918	April	10-11
1918	September	4-5
1927	February	19-20
1928	March	8-9
1932	March	21-22
1939	January	29-30
1939	February	9-10
1944	March	4-5
1948	January	1-2

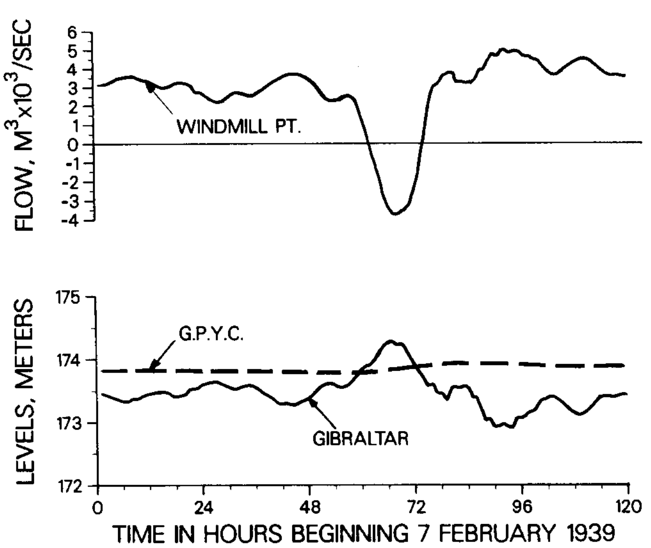

FIG. 4. Model simulation of the February 1939 flow reversal.

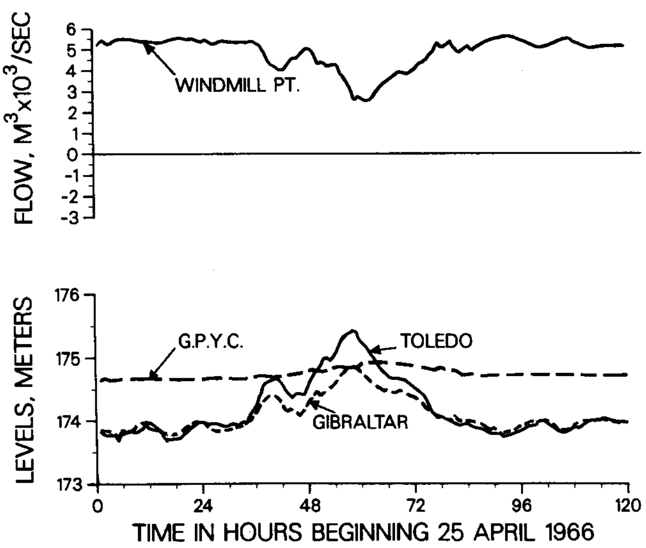

FIG. 5. Model simulation of April 1966 wind seiche.

Gibraltar gage was not in existence, and a Canadian water level gage at Amherstburg, Ontario, was used for the analysis. Because no flow models are calibrated for the use of the old Amherstburg gage, flow simulations of the earlier episodes could not be undertaken. Analysis of the 1984 and 1939 reversals indicates that approximately 2 to 3 hours are required to overcome the positive momentum and reverse the flow following the establishment of a negative gradient. On this basis and the duration and water level data provided by Vaughan and Harlow (1965), it appears that flow reversals were likely in 1911, 1914, 1915, 1918, and 1927. It should be noted that all of the potential flow reversals as well as those in 1939 and 1964 occurred during the Great Lakes ice season of December-April.

The temporal distribution of verified and potential flow reversals is of particular interest. All but the 1984 reversal occurred during the first 40 years of this century, with the last two occurrences separated by 46 years. The decreased frequency since 1940 is probably attributable to the 7.6m and 8.2m navigation dredging projects in the St. Clair River in the mid-1930s and late 1950s, respectively. These projects increased the flow efficiency of the river, reducing the potential for ice jams. Ice jams usually result from the breakup of a natural ice arch at the head of the St. Clair River by meteorological conditions, releasing Lake Huron ice flows into the river where they tend to accumulate and jam above the delta. Very little of the ice in the jams is formed in the river proper. Five of the potential reversals occurred during the first 31 years of this century. This period was characterized by a very cool temperature regime, which enhanced the potential for ice formation. One episode occurred during the subsequent 30 years, a relatively warm period. The last 27 years have been relatively cool again, but have resulted in only one reversal. Thus there appears to be little correlation between ice jams and winter temperatures. This is a strong argument for the channel projects being the main factor in the reduction of flow reversals.

An episode was selected to test the hypothesis that large positive storm surges in the west end of Lake Erie are not sufficient, in themselves, to trigger flow reversals. This event, 27 April 1966, is the largest positive surge that has occurred in the last 45 years (Pore *et al.* 1975; updated by Quinn through 1986). The simulated flows are shown in Figure 5 and no flow reversal is indicated. At 1100 hours on 27 April a minimum flow of 900 m^3s^{-1} occurred at the head of the river. For the 3-hour period beginning at 0900 hours, the water surfaces of Lake St. Clair and the mouth of the Detroit River at Gibraltar were at approximately the same elevation. The maximum storm surge occurred at 1000 hours and was 91 cm above the monthly mean May water level at Gibraltar. For comparison, the maximum storm surge for the episode was 162 cm at Toledo and 113 cm at Fermi. This emphasizes the importance of using a water level gage that accurately represents the mouth of the river, because the use of either the Fermi or Toledo gages would have resulted in a false simulated flow reversal.

CONCLUSIONS

This study shows that Detroit River flow reversals, although relatively rare, are likely to occur. The simulated reversals appear to be of limited duration, less than 12 hours, with maximum flows in the order of 4,250 m^3s^{-1} or less. Their relatively low frequency is due to the unique conditions that appear to be prerequisite for a flow reversal. A severe ice jam must first take place on the St. Clair River, substantially reducing the river flow, and must be of sufficient duration to lower the water level of Lake St. Clair to within 55 cm of Lake Erie. A positive storm surge or wind setup at the western end of Lake Erie, of relatively small magnitude, is then all that is required to establish the negative gradient in the river and reverse the flow.

Flow reversal conditions were most common during the first 40 years of this century. Forty-six years separate the last two occurrences. The higher frequency of events earlier in this century is probably the result of the cool temperature regime prior to 1930 coupled with a decreased capacity of the St. Clair River before navigation dredging projects in the mid-1930s and late 1950s, respectively. Because of the channel dredging, flow reversals will likely be infrequent in the future. An additional future factor may be a major decrease in the Great Lakes ice cover due to global warming. This would reduce the potential for ice jams and thus flow reversals.

The study also demonstrates that large positive storm surges or wind setups on western Lake Erie will not by themselves result in flow reversals. They will greatly diminish the river flows but are not sufficient in magnitude or duration to create a reversal. Water level data representative of the mouth of the river (e.g., the Gibraltar gage) must be used as input for the models and for gradient analysis. The water level setup at Toledo and Fermi can be much higher than at the mouth of the river, and the use of these gages may falsely indicate flow reversals.

The study shows the importance of measuring flow during extreme events to provide accurate model calibration and flow monitoring. Currently the Great Lakes Environmental Research Laboratory has a Doppler profiler flow meter in operation near the Fort Wayne water level gage and flow-measuring section. The meter has been shown (Derecki and Quinn 1987b) to be extremely effective in the continuous measurement of river velocities. It is currently used to compare measured velocity profiles and flow variations with model results during extreme flow conditions. One flow reversal, in December 1987, has been indicated by the current meter. Model and meter results will be compared and reported upon as data become available.

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