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COMPARISON OF MEASURED AND SIMULATED FLOWS DURING THE 15 DECEMBER 1987 DETROIT RIVER FLOW REVERSAL

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ABSTRACT. Flow reversals in the Detroit River are unique hydraulic phenomena which disturb the normal flow patterns and which may cause high concentrations of waterborn pollutants by temporarily blocking their downstream transport and dilution. Until recently, flow reversals in the river have been implied from water level relationships and unsteady numerical flow models, but not directly measured. An acoustic Doppler current profiler deployed on the river bottom at Ft. Wayne, in Detroit, has provided the first opportunity to directly measure a flow reversal, which occurred for about 3 hours on 15 December 1987. The meter provided continuous measurements of the vertical velocity distribution for approximately 1-m depth segments in the overhead water column at quarter-hour intervals. These measurements provided an ideal data set to analyze river dynamics associated with flow reversals and to evaluate the importance of major factors necessary for the occurrence of flow reversals in the river. It was found that reasonably accurate simulation of flow reversals with the unsteady flow models require the inclusion of surface wind shear and the use of small time increments that are much shorter than the standard hourly water level data. Model simulation with specially obtained 5 and 15 minute water level and wind data produced generally similar model flows that are reasonably close to the measured values. Because short-period (15 minute or less) wind and water level data are not readily available, river flow reversals simulated using hourly data may be significantly underestimated.
INDEX WORDS: Wind-driven currents, water level fluctuations, flow measurements, mathematical models, lake stages, Detroit River.

INTRODUCTION

Occasional flow reversals in the Detroit River are unique hydraulic phenomena that may have important pollution implications. The normal river flow pattern moves relatively clean upper Great Lakes waters through Lake St. Clair into Lake Erie (Fig. 1). By temporarily blocking normal downstream transport and dilution of waterborn pollutants along the heavily industrialized Detroit River, flow reversals may cause high concentrations of various contaminants from industrial and municipal wastes discharged into the river. These concentrated contaminants are subsequently moved upstream by the reversing flows to the head of the river at Lake St. Clair, which may produce high periodic concentrations at water intakes located in the area. Because of potential pollution effects, flow reversals in the Detroit River have been studied previously using water level gradient analysis in conjunction with computerized unsteady flow models (Quinn 1988), but this is the first study where flow reversal was actually measured in the field. An acoustic Doppler current profiler deployed on the river bottom at Ft. Wayne, in Detroit, provided continuous measurements of the vertical velocity distribution in the overhead water column during the last flow reversal, which occurred on 15 December 1987. The acoustic profiler provides state-of-the-art high quality measurements (Derecki and Quinn 1987, 1988) which were not available for previous studies. In addition, pertinent meterological observations for the wind speed, wind direction, and air temperature

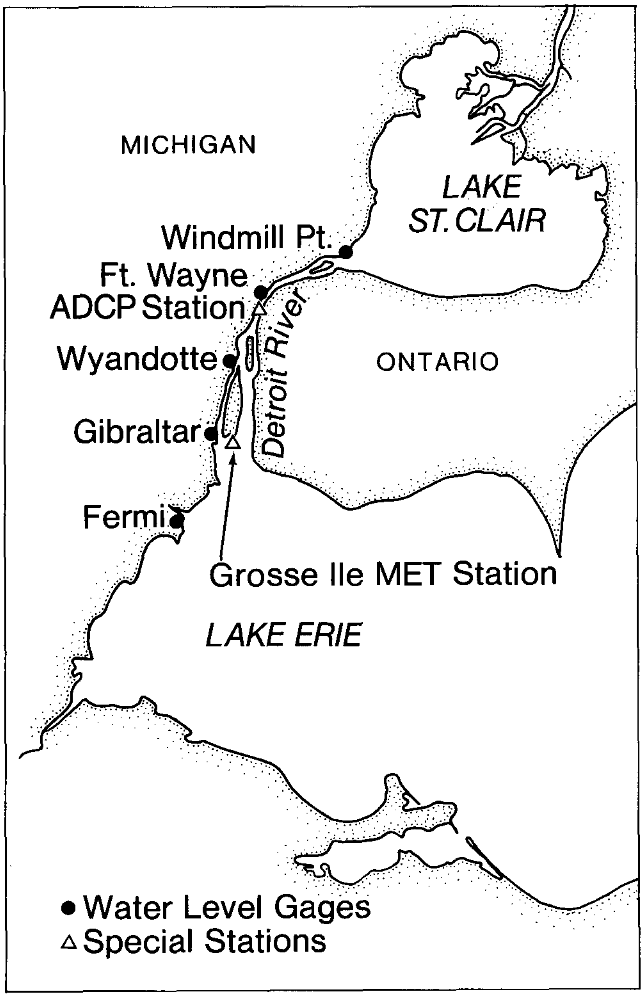

FIG. 1. Detroit River and surrounding area with locations of pertinent water level gages and special stations.

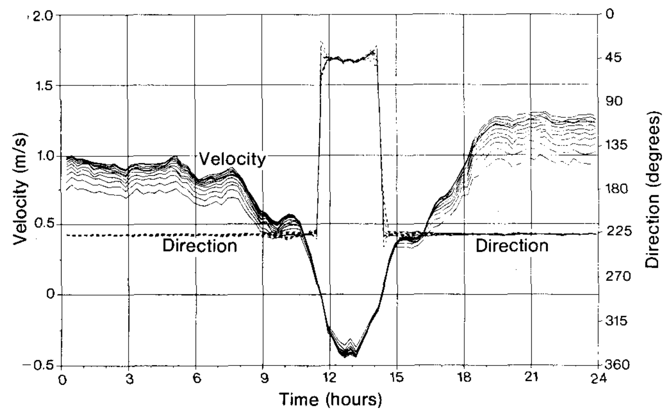

FIG. 2. Vertical distributions of the 15-minute current velocity and direction measurements at Ft. Wayne on 15 December 1987.

were made concurrently at the southern tip of Grosse Ile, near the mouth of the river. These measurements provide an ideal data set to analyze river dynamics associated with flow reversals and to evaluate the importance of major factors necessary for the occurrence of flow reversals in the Detroit River.

FIELD MEASUREMENTS

An acoustic Doppler current profiler deployed on the river bottom at Ft. Wayne, in Detroit, since November 1986 has provided the first opportunity to directly measure a flow reversal, which was observed for about 3 hours on 15 December 1987. The reversal achieved an average negative velocity reaching 0.4 m/s and a negative discharge exceeding 2,500 m^3/s. The meter provided continuous measurements of the vertical velocity distribution for approximately 1-m depth segments in the overhead water column, with the 15-minute averaged data recorded at quarter-hour intervals. The acoustic profiler is a remote sensor that is not affected by the frazil ice and weed problems normally encountered in the Great Lakes connecting channels during prolonged operations, and is capable of operating successfully in the connecting channels environment in a continuous recording mode (Derecki and Quinn 1987). Because the primary purpose of the field measurement program was to obtain measurements of flow reversals and use the data for possible recalibration of the existing unsteady flow models, pertinent meteorological measurements for the wind speed, wind direction, and air temperature were made concurrently at a specifically established micro-meteorological station located at the southern tip of Grosse Ile. The micro-met station was located near the mouth of the river to reflect over-lake meteorological conditions on Lake Erie, with a minimum of land obstructions, during possible flow reversals. The Detroit River and surrounding area with locations of pertinent water level gages and special stations are shown in Figure 1.

Results of the 15-minute flow measurements (velocity and direction) at the Ft. Wayne meter station, which is colocated with a water level gage location, are shown for 15 December 1987 in Figure 2. The figure, indicating vertical distribution of velocity and direction for 11 successive depth seg-

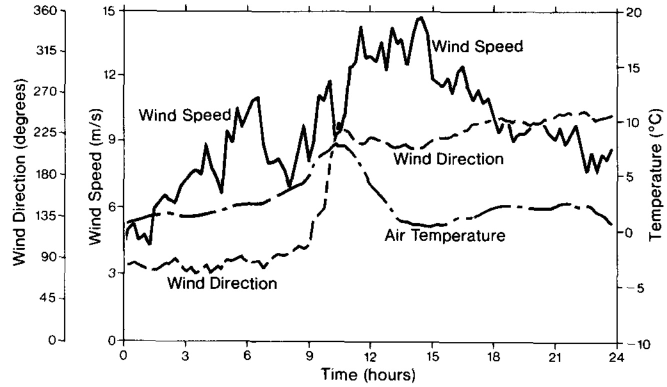

FIG. 3. Meteorological data for the 15-minute wind speed, wind direction, and air temperature measurements at Grosse Ile on 15 December 1987.

ments, clearly shows that the flow reversal process affected the entire water column, from the surface to the bottom. Current velocities in the entire water column were reduced sharply about 3 hours prior to the actual flow reversal, which occurred at about 1100 and lasted for approximately 3 hours until about 1400. The flow reversed again abruptly to normal downstream flow direction in the entire water column and remained at approximately half of its normal magnitude for the next 2 hours, then increased more gradually for the next 3 hours and at about 1900 reached steady velocities considerably higher than before flow reversal. The post-reversal higher velocity reflects increased river discharge due to higher hydraulic head or difference in elevations at the head and mouth of the river, caused primarily by dropping Lake Erie levels, as will be shown later (Fig. 6). The abruptness of flow reversal is shown even more vividly by the flow direction graph, which indicates that flow in the entire water column changed direction completely (180° out of phase) within one 15-minute data recording period.

Complementary meteorological data from Grosse Ile for the same period (15 December 1987), shown in Figure 3, indicate the forcing functions for this flow reversal. The wind speed over Lake Erie was blowing steadily from the east before the reversal, increasing gradually from about 5 m/s (approximate long-term normal) at the beginning of the day to about 11 m/s by 0700. This wind was forcing Lake Erie water into its shallow western basin resulting in a set-up along the western shores. For the next 2 hours the winds diminished somewhat, then increased rapidly again, reaching the highest speeds of about 14 m/s by 1200. After 0900 wind direction shifted to the north and after about 1 hour the winds started blowing steadily from the southwest, approximately parallel to the western lake shoreline and directly opposite to the river flow, forcing the set-up in western Lake Erie into the Detroit River. The air temperature at the mouth of the river increased gradually with the winds by about 7C°, from about 0°C at midnight, and reached its peak at about 1000, concurrently with the wind direction change to the southwest, then decreased in the next 3 hours to the pre-reversal range of 0–2°C for the rest of the day. Comparison of Figures 2 and 3 indicates approximately a 1-hour delay between the shift of strong winds to the north at the mouth of the river and the occurrence of the flow reversal at Ft. Wayne, about 45 km upstream. Since there were no ice jams at this time in the St. Clair or Detroit Rivers, the above flow and meteorological measurements demonstrate that meteorological factors alone are sufficient to force flow reversals and that ice jams in the St. Clair River are not a necessary requirement as hypothesized by Quinn (1988). The importance of the St. Clair River ice jams to flow reversals in the Detroit River are demonstrated by Derecki and Quinn (1986).

To facilitate later comparison of measured and model-simulated flows, which are normally derived as discharge, the river discharge based on velocity measurements was computed from the measurements of river bathymetry and water levels at this section, and the average cross-section velocity extrapolated from the meter measurements. The extrapolated cross-section velocity is a product of the average vertical velocity and the model to meter velocity ratio. The average vertical velocity was obtained by integration of the measured data and the model to meter velocity ratio was derived from comparison of measured (vertical average) and model-simulated (cross-section average) velocities during normal flow conditions. This method was used successfully to derive highly variable flows during a major ice jam on the St. Clair River (Derecki and Quinn 1987) and should be satisfactory in other river channels with uniform velocity variations across the channel. The average hourly and 15-minute values of the measured resultant velocity and discharge, integrated for the total depth at the meter location and extrapolated to the cross-section of the river at this location, respectively, for 15 December 1987 are shown in Figure 4. The graphs for both parameters indicate some

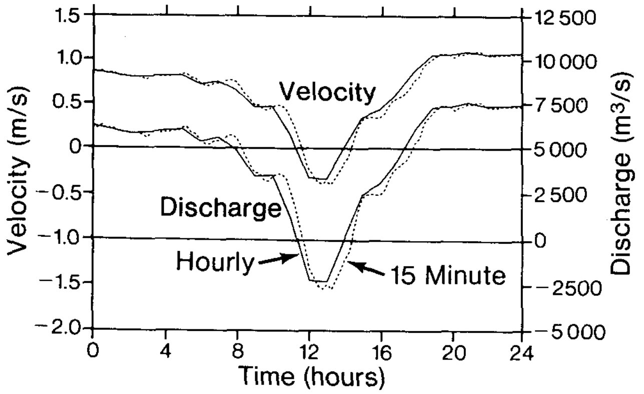

FIG. 4. Measured resultant velocity and discharge at Ft. Wayne on 15 December 1987 for hourly and 15-minute data.

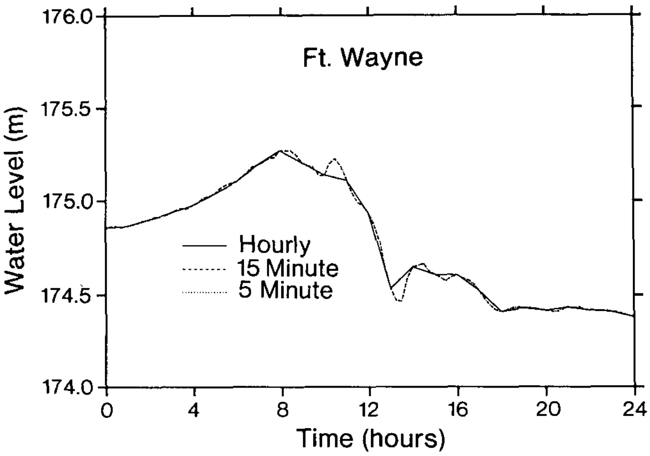

FIG. 5. Measured water levels at Ft. Wayne on 15 December 1987 for hourly, 15-minute, and 5-minute data.

smoothing in the hourly curves, but generally show similar magnitude of values for both periods. Substantial flow variability for the two periods would normally be expected during conditions of extreme flow variation, such as those that contain flow reversal. Another comparison provided in the figure is that between the velocity and discharge curves, which are very similar. This means that changes in discharge depend primarily on the variation in velocity and the effect of variation in the cross-section area, the other factor affecting discharge, is secondary even during extreme variations in flow.

The variation in the cross-section areas of the river along its course is solely a function of water depth, as indicated by the surface water levels along its longitudinal profile, since the river bottom and its banks are stable and do not change with flow. Comparison of the hourly, 15-minute, and 5-minute instantaneous water levels at the Ft. Wayne section for 15 December 1987 is shown in Figure 5. In this case, the 5- and 15-minute graphs are identical because water levels at the Ft. Wayne gage are read at quarter-hour intervals and the 5-minute data were extrapolated from the 15-minute curves. Normally, hourly instantaneous water level readings are the shortest period that data are generally available, from which averages for daily and other periods are derived. This procedure may be adequate during relatively stable conditions, but is inadequate for the flow reversal analysis. Since all permanent water level gages along the Great Lakes and connecting channels are read at 5- to 15-minute intervals, these unpublished records were obtained specially for the flow simulation analysis of the present study (next section) from the National Ocean Service (NOS), the NOAA agency responsible for the U.S. water level gage network. As indicated in Figure 5, the largest difference between hourly and 15-minute water levels is about 0.1 m, which is less than 1% of the total depth (about 14 m at the meter and 12 m for the cross-section). In contrast, similar differences for the velocity and discharge are more than an order of magnitude larger, varying by at least 20% (Fig. 4). The total change in the water levels at the Ft. Wayne gage during the flow reversal was about 0.8 m or less than 10% of the total depth, while similar changes in the velocity and discharge approach 150%. These figures show emphatically that changes in the river cross-section areas have only minor influence on short period changes in flow. It should be pointed out that the reported velocities for all periods represent resultant values of continuous measurements (vector sums), while the water levels are instantaneous readings at the times indicated. This procedure is sufficient, provided the water levels are read often enough to capture the physical process involved.

The profiles of the entire river, indicated by water levels at the river gages, on 15 December 1987 for the hourly, 15-minute and 5-minute data are shown in Figure 6. There appears to be very little difference between the 5-minute and 15-minute intervals, indicating that 15-minute measurements may be sufficiently short for the flow

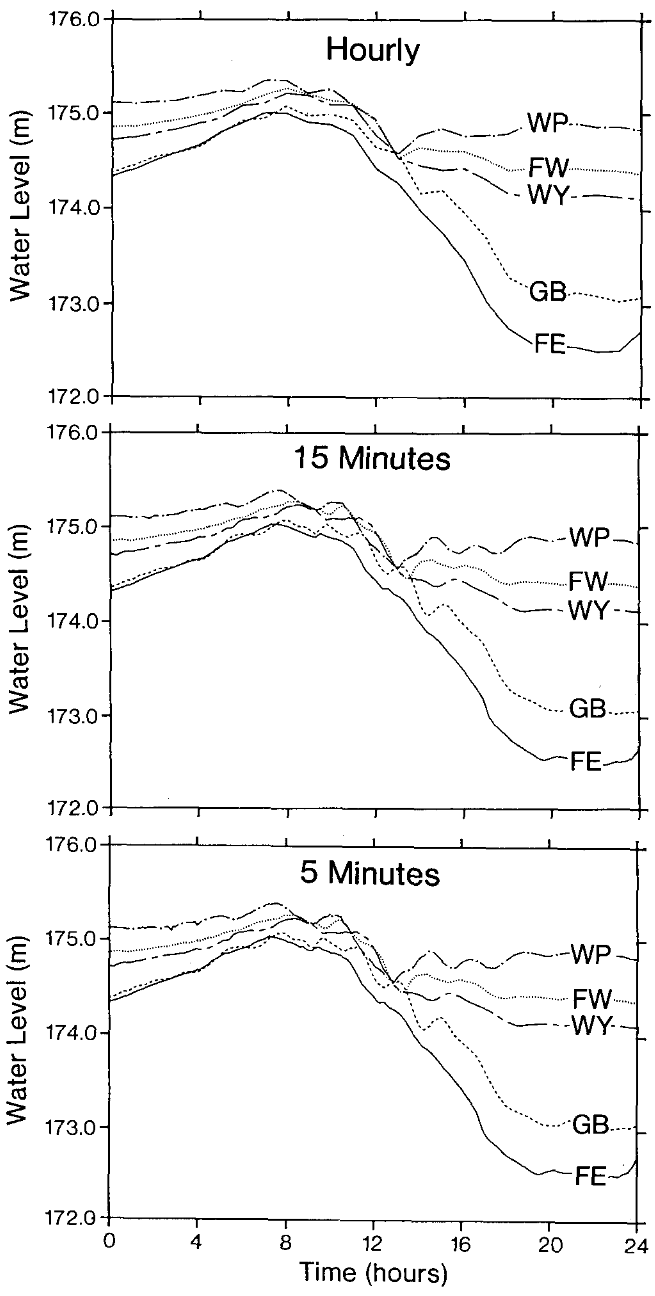

FIG. 6. Measured Detroit River surface profiles at indicated gage locations (abbreviated) for 15 December 1987 from: (a) hourly water levels; (b) 15-minute water levels; (c) 5-minute water levels.

reversal analysis. In contrast, the hourly graphs are considerably different, especially during the actual flow reversal process. This indicates that hourly intervals are too long and their use in the flow reversal analysis or simulation would tend to mask the occurrence of flow reversals, especially during shorter episodes. The water level gages used in this figure represent all U.S. Detroit River gages, from Windmill Pointe at the head of the river to Gibraltar at its mouth, plus the Fermi gage in Lake Erie (Fig. 1). The Fermi gage is shown because it is normally used as a downstream boundary in one of the Detroit River unsteady flow models. As indicated in the figure and pointed out by Quinn (1988), the use of the Fermi gage for this purpose during storm surges on Lake Erie may produce large errors in the river's fall and computed flows. The Gibraltar gage is located in the river proper and is better situated to indicate dynamic water conditions at the mouth of the river, but water level data from this gage during development of the model contained some problems.

MODEL SIMULATIONS

Computed Detroit River flows during the reversal were simulated with three available unsteady flow models. Model simulations were performed for the gravity flows without the influence of the surface wind shear for the three periods of data (hourly, 15-minute, and 5-minute), and then repeated with the surface wind shear included. It should be pointed out that such wind data are normally not available and were specially collected at Grosse Ile in a field program designed for this study. The regular, local meteorological stations with wind data are located at the Windsor and two Detroit airports, but these wind records consist of hourly observations and are not available for shorter intervals. Also, of the two Detroit airports (Metro and City), only the Metro data are published and generally available. Because short-period winds are highly variable, especially during stormy periods, at times there are considerable differences in the hourly wind data from these stations (Windsor and Detroit Metro), and both of these records differ considerably from the Grosse Ile data. The wind data from the airport stations contain considerable land and urban effects, but probably the most significant difference is that the Detroit and Windsor records represent short-period observations (1 and 2 minutes, respectively) while the Grosse Ile wind data represent vector sums for all periods employed. These airport wind data were tested in the hourly simulation of flows to evaluate their effectiveness.

The three Detroit River models either cover different river reaches or contain different treatment of flows. Two of the available models cover the upper river between Windmill Pointe and Wyandotte, and one is for the total river, which normally is operated between Windmill Pointe and Fermi as the upstream and downstream model boundaries, respectively. However, as mentioned previously, Fermi water levels are not suitable for the flow simulations with strong storm surges on Lake Erie and were replaced in the flow reversal study by Gibraltar levels, with corresponding recalibration of the model. Also, the lower reach of the river contains complicated flow distribution patterns around lower river islands, which are not replicated in the model, making the model less accurate for simulation of flows with large and rapid variations. Thus, preference for computing flow reversals in the present and previous (Quinn 1988) flow reversal studies was given to the upper river models.

The standard upper river and total river models used in both flow reversal studies are described by Quinn and Hagman (1977). These models employ idealized river channels consisting of averaged upstream and downstream reaches, with flow and water level computations for the outside boundaries and a mid-point between the two reaches. Because lateral inflow to the Detroit River and other connecting channels is insignificant, flow changes along the river during normal flow conditions are also generally insignificant, and only average velocities at the model-node locations (outside boundaries and mid-point) are simulated in these idealized channel models. However, this particular physical configuration used for the model simplification is not relevant in this study, because during flow reversals the river discharge changes rapidly along the river, despite lack of significant lateral inflow. The second model for the upper river, used in the present study only, provides valid values for both discharge and velocities along the river. This model, referred to as the island model, covers the same reach as the standard upper model but uses the actual river bathymetry, with flow separation around Belle Isle at the head of the river. Derivation of this model is based on model improvements developed for the St. Clair River (Derecki and Kelley 1981). Results from both the standard and island upper river models are generally similar, as will be shown in the comparison of measured and simulated flows. Values presented in the following discussion of flow simulation are those from the standard upper river model, which makes them compatible with Quinn's, at least for the hourly simulation without wind shear.

Results of model simulations for the upper river from the standard gravity flow computations, which do not contain the effect of surface wind shear, are shown in Figure 7. This and other flow reversal graphs presented later show that although the flow reversal process or flow reduction starts at the downstream end, the largest change or highest negative flows occur at the upstream end, probably because of smaller hydraulic head or water level difference which affects flow momentum and decreases progressively upstream. Without wind shear, hourly computations indicate a small flow reversal (about -500 m^3/s) only at Windmill Pointe and reduced but positive flows at other locations (about +900 m^3/s at Ft. Wayne and about +2,100 m^3/s at Wyandotte). Computations with a 15-minute interval increase the flow reversal at Windmill Pointe (about -1,500 m^3/s) and the flow reductions downstream (approximately +400 and −200 m^3/s at Ft. Wayne and Wyandotte, respectively). The 5-minute computations indicate flow reversal at all locations (approximately -200, -20, and -1,800 m^3/s in a downstream order, respectively), but all the simulations with purely gravity flows produced considerable underestimation of flow reversal indicated by the measurements at Ft. Wayne. Quinn (1988) in his flow reversal analysis used flows at Windmill Pointe, thus employing highest negative flows for a particular flow simulation. However, his computations are for hourly periods using gravity flows only; therefore, his flow reversal values for that location may contain underestimation, especially for smaller episodes with short duration.

The Detroit and Windsor airport wind data tested in the hourly simulation of flows produced some improvements, but the results were generally inferior to those obtained with the Grosse Ile winds, which were generally twice as effective in reducing the flow differences between measured and simulated values. The present study shows that hourly intervals are too long for the simulation of flow reversals, but shorter period winds are not available from the airport stations. Thus, actual effectiveness of these stations could not be determined. Discussion of the wind shear effects on flow simulation, presented in this study, is based on the wind data from the Grosse Ile micro-met station.

The effect of surface wind shear on the computations is shown in Figure 8, which repeats the flow

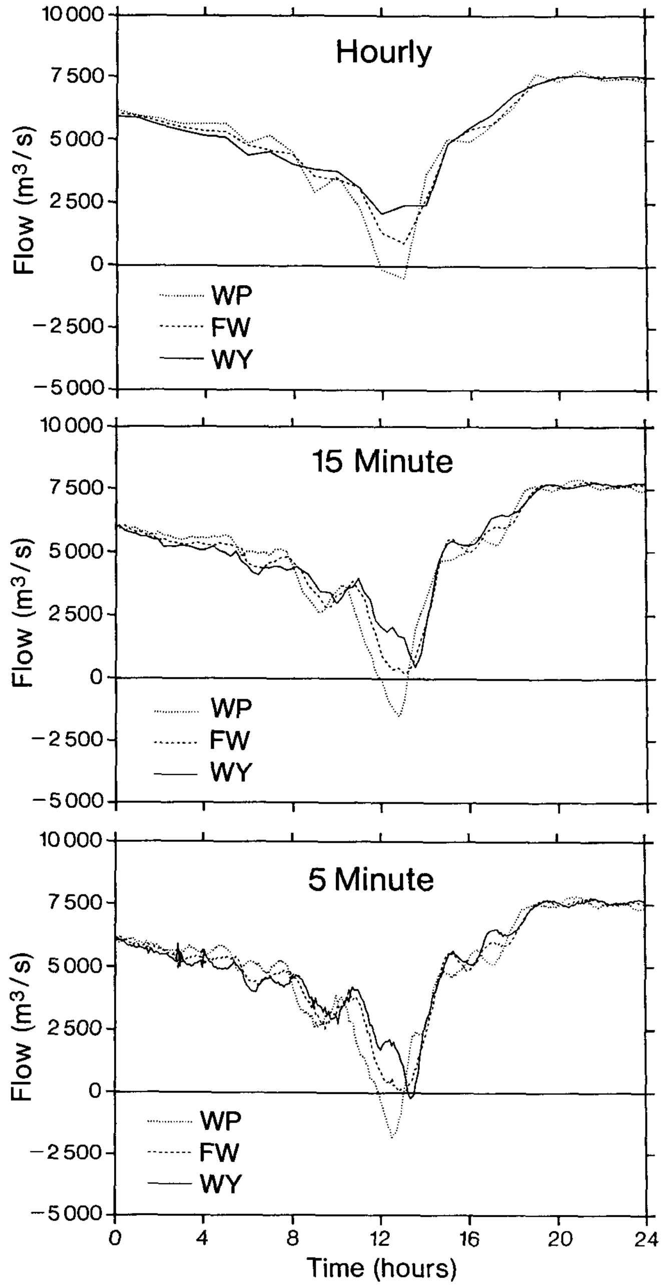

FIG. 7. Simulated Detroit River gravity flows (no surface wind shear) at indicated gage locations (abbreviated) for 15 December 1987 from: (a) hourly water levels; (b) 15-minute water levels; (c) 5-minute water levels.

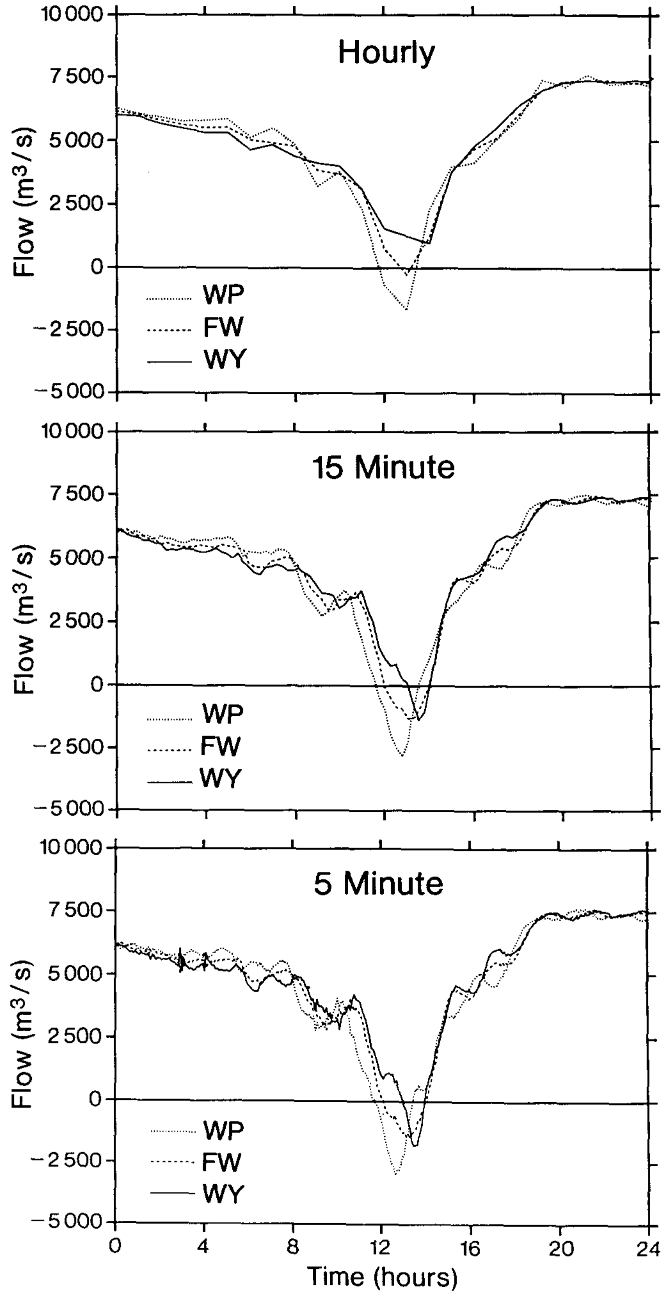

FIG. 8. Simulated Detroit River flows with surface wind shear at indicated gage locations (abbreviated) for 15 December 1987 from: (a) hourly water level and wind data; (b) 15-minute water level and wind data; (c) 5-minute water level and wind data.

simulations from the previous figure but with the inclusion of wind forcing. In this case, only the hourly computations for Wyandotte fail to show flow reversal, and the negative flows at Windmill Pointe for the 15- and 5-minute simulations are in the range of 2,500–3,000 m^3/s, the magnitude of flow reversal indicated by the measurement at Ft. Wayne. However, the model underestimates the flow reversal at Ft. Wayne and presumably other locations for all computation intervals. The underestimation exceeds 1,000 m^3/s for the 15- and 5-minute simulation time steps and is about 2,000 m^3/s for hourly computations. Thus, although available unsteady flow models fail to replicate flow conditions precisely during periods of large and rapid flow variations associated with flow reversals, the inclusion of surface wind shear and sufficiently small computational time steps permits a simulation that is compatible with measurements.

COMPARISON OF RESULTS

Comparison of measured and simulated results for the river flows and water levels at Ft. Wayne, for the 15 December 1987 period that includes the flow reversal, is presented in the next two figures. Figure 9 shows that discharge differences between measured and simulated values are considerable, as indicated in the preceeding discussion, but there is a marked improvement for shorter computational time steps. Only the hourly and 15-minute graphs shown in this figure are for identical periods; because the 5-minute data are not available for flow measurements, the 5-minute graph includes a profiler curve from the 15-minute data as an estimate for the shorter interval, which should be satisfactory in view of general agreement in results for the two periods. The figure also shows that there is generally little difference between the two upper river models (standard and island), which indicates that model improvements from idealized to actual channel configuration did not have much effect in the determination of flows. The primary benefit of the island model is its ability to provide valid velocity values along the river channel.

Because the water levels are generally within the same range of elevations (Fig. 6), even during such extreme flow variations as those containing flow reversal, model recalibration does not appear to provide a workable solution for the simulated flow reversal discrepancies. As indicated by the graphs, increased channel roughness is needed during the reversal, while the roughness already appears to be too high prior to the reversal and about proper after the reversal. Examination of the channel roughness parameter in the model development studies (Quinn and Hagman 1977, Derecki and Kelley 1981) shows that this is a lumped parameter which contains the effects of errors in measuring water levels and discharge, as well as the channel roughness itself, and is not very responsive to changing flow conditions. Calibration of the models is derived from the standard flow measure-

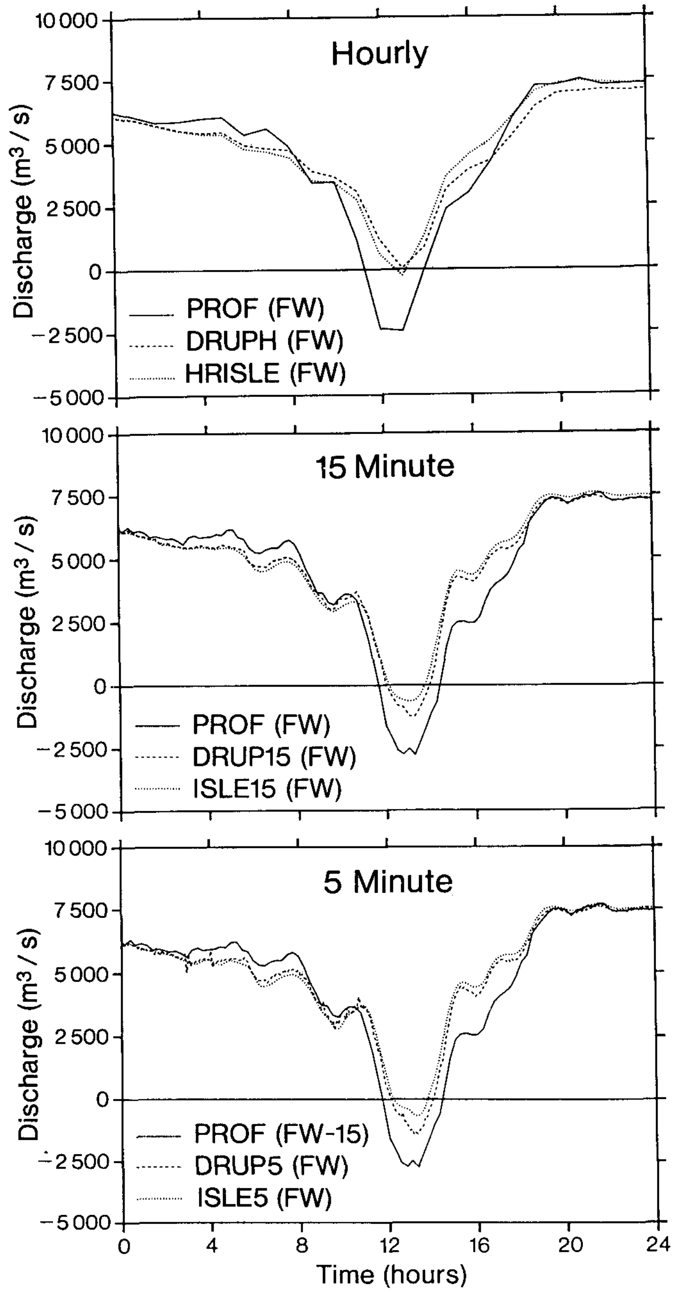

FIG. 9. Comparison of measured (PROF) and model-simulated flows, using Upper River (DRUP) and Island (ISLE) model versions, at Ft. Wayne (FW) for 15 December 1987 from: (a) hourly data; (b) 15-minute data; (c) 5-minute data.

ments conducted periodically over the years by the Corps of Engineers during relatively stable flow conditions and the model accuracy is reduced during periods of abnormal flows, such as those induced by high winds, storm surges, or flow reversals.

Differences in water levels at Ft. Wayne on 15 December 1987 between measured and simulated values by the two upper models, for the three computational periods, are shown in Figure 10. The agreement in water levels is much better than for flows but generally follows the same pattern of marked improvement for shorter time steps and similar results from both models. The largest difference between measured and simulated water levels is about 0.1 m, which represents less than 1% of the river depth at this section, while similar difference for discharge is about 2,000 m^3/s or more than 30% of normal flow. Since water levels at the model boundaries are the model's forcing functions, this relative insensitivity of the water levels may be part of the problem. The accuracy of measurements for water levels is considered to be about 0.01 m and for discharge about 100 m^3/s, which in relation to the above deviations represents a factor of two and suggests that water level data may not be sufficiently accurate for determination of flows during rapid changes. Water level data are normally provided to the nearest 0.003 m (0.01 ft).

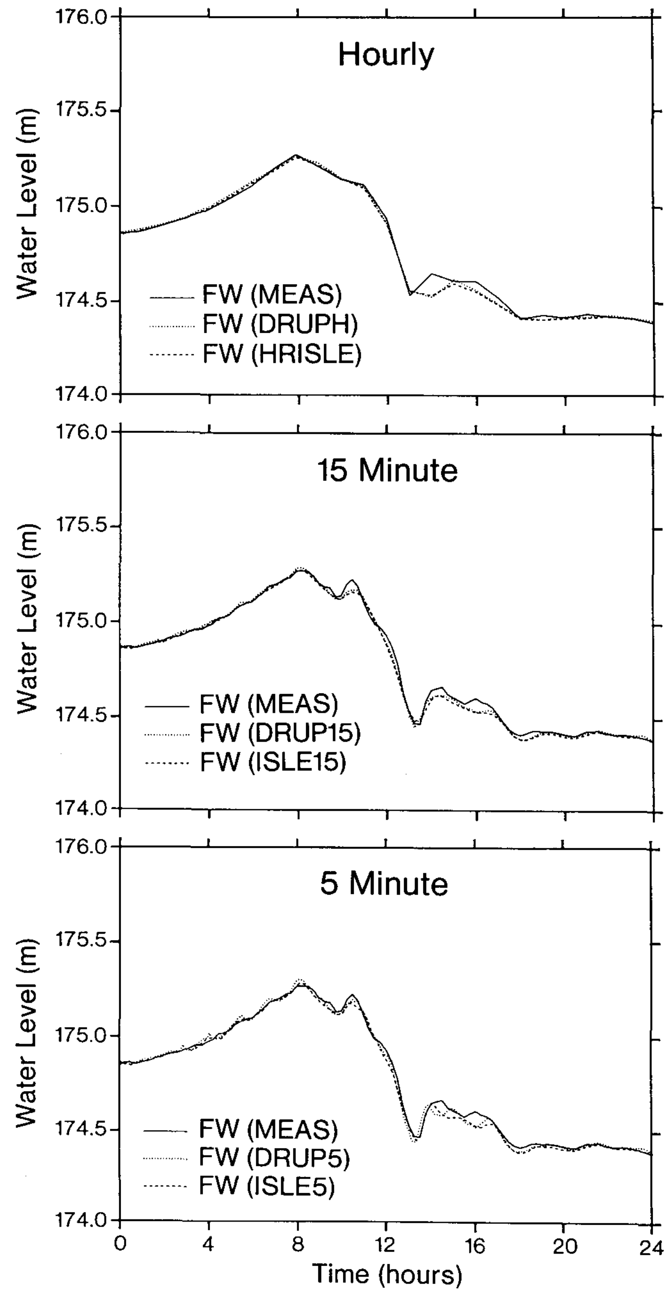

FIG. 10. Comparison of measured (MEAS) and model-simulated water levels, using Upper River (DRUP) and Island (ISLE) model versions, at Ft. Wayne (FW) for 15 December 1987 from; (a) hourly data; (b) 15-minute data; (c) 5-minute data.

CONCLUSIONS

Occasional flow reversals in the Detroit River may cause high concentrations of waterborne pollutants and degrade water quality at critical locations, such as water intakes, in both the river and adjacent Lake St. Clair. Previous analyses of the Detroit River flow reversals have been conducted using water level relationships and computed river flows, more recently with the unsteady flow models that permit simulation of river flows under varying flow conditions (Quinn 1988). These determinations have been made using hourly instantaneous water levels, which represent the shortest period of data normally available, and without the wind shear effect on flows, because appropriate wind data are normally not available. The present study is based on the first actual field measurement of the flow reversal, which occurred on 15 December 1987. The measurements were made with an acoustic Doppler current profiler, which was deployed in the Detroit River and operated with an accompanying micro-met station established precisely for this purpose. These flow reversal measurements were used to substantiate flow simulations with the unsteady flow models that include wind shear effects and were conducted for the hourly, 15-minute, and 5-minute computational periods. The study shows that inclusion of wind shear is essential and that 15-minute data are generally sufficient for flow reversal simulations that are in reasonable agreement with the measurements. However, available Detroit River models underestimated the magnitude of negative flows associated with the flow reversal. Results from the present and previous flow reversal or related studies (Quinn 1988, Derecki and Quinn 1986) indicate that flow reversals may occur during large wind set-ups in western Lake Erie, especially with a sudden upriver wind shift to the north, or with a more moderate western Lake Erie wind surge and a large ice jam in the St. Clair River, which substantially reduces the inflow to Lake St. Clair and its outflow through the Detroit River.

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REFERENCES

Derecki, J. A., and Kelley, R. N. 1981. *Improved St. Clair River dynamic flow models and comparison analysis*. NOAA Tech. Memo. ERL GLERL-34.

________, and Quinn, F. H. 1986. The record St. Clair River ice jam of 1984. *J. Hyd. Eng.* 112: 1182–1194.

________, and Quinn, F. H. 1987. Use of current meters for continuous measurement of flows in large rivers. *Water Resour. Res.* 23:1751–1756.

________, and Quinn, F. H. 1988. Comparison of vertical velocity measurements in the Great Lakes connecting channels with theoretical profiles. In *Proceedings, 1988 National Conference HY Div. ASCE*, pp. 276–281. Colorado Springs, Colorado, August 8–12, Hyd. Eng. Vol.

Quinn, F. H. 1988. Detroit River flow reversals. *J. Great Lakes Res.* 14:383–387.

________, and Hagman, J. C. 1977. *Detroit and St. Clair River transient models*. NOAA Tech. Memo. ERL GLERL-14.