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Use of Current Meters for Continuous Measurement of Flows in Large Rivers

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Flows in the unregulated Great Lakes connecting channels, the St. Clair and Detroit Rivers, are normally determined using mathematical flow models with calibration based on periodic discharge measurements taken during the open-water seasons. Consequently, the calculated flows normally exhibit good accuracy during ice-free periods, but may contain large errors during winter months with extensive ice cover. The St. Clair River is particularly prone to large ice jams because of practically unlimited ice flow supply provided by Lake Huron and an extensive river delta that retards the passage of these ice flows. This study describes the experimental results of continuous flow measurements using electromagnetic (EM) current meters and an acoustic Doppler current profiler (ADCP) meter during the 1983–1985 period. A record ice jam in the St. Clair River occurred in April 1984 and provided an excellent opportunity for testing the current meter program. Verification of current meter results was provided by flows transferred from the Detroit River, which was ice-free and permitted accurate flow simulation. The current meter flow measurement program illustrated high consistency of exponential (logarithmic) vertical distribution of velocities. Results indicate that accurate estimates of mean river flows can be obtained with a single well-placed current meter. However, the EM current meters are direct contact single-point sensors that are affected by frazil ice during winter and weed effects during most of the year. The ADCP meter is a remote sensor of velocities in the overhead water column and is not affected by the frazil ice and weed problems.

INTRODUCTION

The Great Lakes constitute the largest fresh surface water resource in North America. A knowledge of the water balance of the individual lakes is critical for water resource and scientific studies of the system. In addition to the five Great Lakes and Lake St. Clair, the system includes five connecting channels: the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence Rivers. Three of these, the St. Marys, Niagara, and St. Lawrence Rivers, have either control works, diversions, power plants, or other partial controls so that all or a major portion of the flows can be measured. The St. Clair and Detroit River flows cannot be measured directly on an ongoing basis and must be determined from either stage fall discharge equations or from unsteady flow mathematical models. During the ice-free season, the mathematical models do an adequate job in determining hourly, daily, and monthly flows. However, during ice accumulations and jamming on the rivers, the models are no longer applicable and tend to greatly overestimate the river flows. To address this problem a field measurement program was implemented in the St. Clair and Detroit Rivers. The program tests the applicability of using continuously recording current meters to provide accurate velocity measurements on an ongoing basis, independent of river ice conditions.

DESCRIPTION OF ST. CLAIR–DETROIT RIVER FIELD EXPERIMENT

Flows in the St. Clair and Detroit Rivers (Figure 1) are normally determined using mathematical flow models with calibration based on periodic discharge measurements taken during the open-water season [*Derecki and Kelley*, 1981; *Quinn and Hagman*, 1977]. Consequently, the calculated flows normally exhibit good accuracy during ice-free periods but may contain large errors during winter months with extensive ice cover. Winter flow discrepancies are produced by heavy ice accumulation and/or ice jams. The rivers generally do not freeze over. Their ice covers are transient in nature, formed by the consolidation of ice flows supplied by the upstream lakes, Lakes Huron and St. Clair, respectively. The St. Clair River is particularly prone to large ice jams because of practically unlimited ice flow supply from Lake Huron and an extensive river delta which retards the passage of the ice flows.

A flow experiment was undertaken on the St. Clair and Detroit Rivers to produce more accurate estimates of winter flows by improving methods for determining these flows. The objectives of the experiment were (1) to accurately determine flow retardation in the rivers due to ice accumulation and ice jams; (2) to test the accuracy of water transfers between the St. Clair and Detroit Rivers (when at least one of the rivers is ice free); (3) to assess errors in present procedures for computing winter flows; (4) to provide better winter flows; and (5) to determine the feasibility of using in situ current meters for continuous flow monitoring. Accurate determination of flow during periods of heavy ice concentration and/or ice jams can only be accomplished by a time series of in situ winter current meter measurements. Practical requirements dictate the use of current meters without moving parts (to avoid clogging), which are capable of prolonged operation (6 months) at frequent sampling rates.

CURRENT METER PROGRAM

After examination of the types of meters available, an electromagnetic (EM) current meter was selected (Marsh McBirney, model 585) for the first phase of the program limited to the St. Clair River (Figure 2). The standard meter was modified to include an externally located recording system, which provides unlimited, continuous operational capacity and access capability via the telephone recorder to both the meter and a cable-connected recording system (cassette tapes) located on the shore. After field testing and several meter modification, a data collection program was started in September

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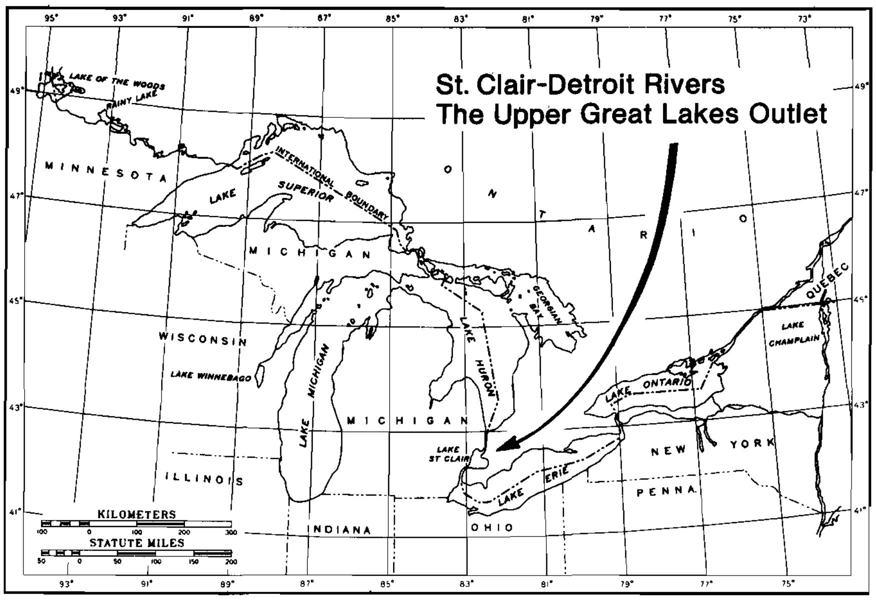

Fig. 1. Great Lakes basin.

1981 with the deployment of two EM current meters in the upper St. Clair River, near the river's head at Port Huron, Michigan (Figure 3). The meters were installed on the United States side of the river, outside the navigation channel about 50 and 70 m from shore, in 13 and 15 m of water. Meter sensors were positioned 2 m above the bottom. Deployment and subsequent removal of meters took place with the assistance of the USCGC *Bramble* and a commercial diver, who guided the underwater operation. The U.S. Army Corps of Engineers, Detroit District, also participated in the project by making discharge measurements during the open-water seasons. These measurements were intended to provide data for calibration of the point velocities measured by the meters with the mean river velocity at the meter location. They were not used in this study, because several conducted measurements either encountered operational problems or indicated considerable discrepancy in the data.

The meters in this study sample ambient river velocity at 1-s intervals for Y and X axis velocity components, and an azimuth angle. These raw data are converted to the north and east velocity components, which are recorded with an accompanying azimuth angle at 15-min intervals. The 15-min input data are monitored daily, stored in a computer file, and converted to hourly and/or daily resultant velocity magnitude and direction. The field seasons during the first phase of the program normally covered late fall, winter, and spring months (November–June). The meters were redeployed for the 1982–1983 and 1983–1984 winter seasons. However, velocity measurements during the first two seasons contained some unresolved problems and questionable data and were excluded from this study. High-quality river velocity measurements during the 1983-1984 season coincided with the record ice jam of April 1984. This jam, which lasted nearly the entire month (April 5–29), established records for both magnitude and late-

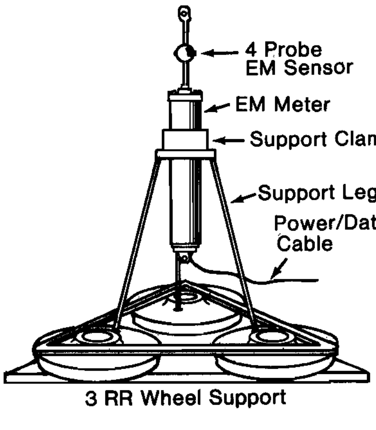

Fig. 2. Deployment arrangement for the EM current meter and support.

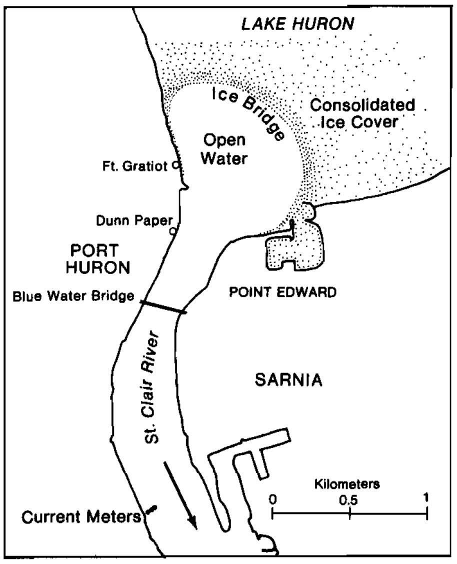

Fig. 3. Location of St. Clair River current meters and ice bridge.

ness of occurrence and provided an excellent opportunity for testing the current meter program [*Derecki and Quinn*, 1986].

The second phase of the study included simultaneous velocity measurements in both rivers, starting in November 1984, with redeployment of meters in the St. Clair River for the 1984–1985 winter season. Previous point velocity measurements indicated a need for vertical distribution of velocities, and recent advances in acoustical instrumentation made such measurements practical. Consequently, the St. Clair River installation was augmented during the 1984 redeployment with one acoustic Doppler current profiler (ADCP) meter (RD Instruments, model 1200 RDDR), which permits measurements of velocities at approximately 1-m intervals in almost the entire vertical water column (Figure 4). The ADCP meter was installed between the two EM current meters, about 60 m from shore in 14 m of water. The meter housing was oriented horizontally and the upward-looking sensor was connected by a 90° elbow about 1 m above the bottom. The ADCP meter continuously samples overhead velocities at a rate of 5 times/s with four beams, starting about 1 m above the sensor. The raw data from the four beams are averaged to produce Y and X axis velocity components, along with an azimuth angle, for approximately 1-m increments of depth to the surface. These data are converted to the north and east velocity components for the 1-m progressive data segments, which are recorded at the mid points of each vertical segment. In a total water depth of about 14 m, this procedure provided vertical velocity and direction values for 11 levels between approximately 2.5 m above the bottom and 0.5 m below the surface. The data are recorded at a cable-connected shore station at 15-min intervals (similar to the EM current meters).

The Detroit River installation consists of two EM current meters, which were deployed and tested during the summer of 1984 in the upper portion of the river at Fort Wayne COE Boatyard (Figure 5). The two meters were installed outside the navigation channel about 60 and 90 m from the United States shore. Meters were placed in 12 and 14 m of water with upward positioned sensors 2 m above the bottom. Similar operation and deployment procedures are used on both rivers, with the USCGC *Mariposa* or the USCGT *Bristol Bay* providing assistance in the Detroit River. During this phase of the study the meters were not removed for the summer but were left operating throughout the year to test the effects of weed transport and accumulation on the velocity measurements.

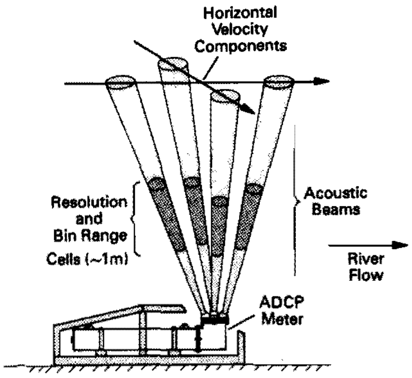

Fig. 4. Schematic diagram showing the remote sensing operation of the ADCP meter.

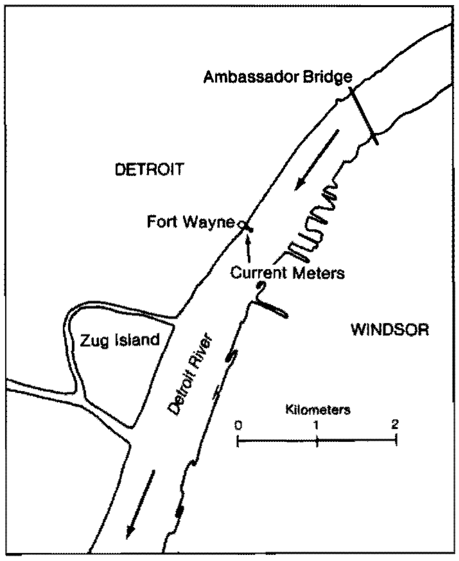

Fig. 5. Location of Detroit River current meters.

Discussion of Results

Electromagnetic Current Meters

During this period of study, data were collected from the EM current meters for more than 2 years on the St. Clair River and for more than 1 year on the Detroit River. These data underwent preliminary analysis and comparison with model simulated flows. The meters' operation is monitored daily to detect and correct any instrument problems in order to eliminate or reduce data gaps.

Operation of the current meter program on both rivers throughout the year and monitoring of the meter records indicated that frazil ice and weeds affect the operation of the EM current meters. Although frazil ice episodes on the St. Clair and Detroit Rivers are relatively infrequent (about 5–10 occurrences on each river per winter), they drastically affect the meter data, which have to be eliminated from the data records. The formation of frazil ice is a supercooling phenomenon, with distinct characteristics, and can be easily identified. During cold spells in the winter months (December–February), an additional sudden drop in temperatures causes the formation of frazil ice. This jellylike ice formation is sticky and adheres to objects; it coats the meter sensors, reducing their sensitivity and producing low readings, at times approaching zero. The sudden drop in the EM meter velocities associated with frazil ice normally starts after sunset (before midnight) and disappears rapidly after sunrise (before noon). However, severe episodes of frazil ice may last continuously for a few days at a time.

Serious weed effects on the EM current meter operations were not at first apparent during the initial phase of the program (limited to the St. Clair River) because the meters were deployed in late fall (November), the Lake Huron water is relatively clean, and the water velocity is high in the upper river. These factors contributed to reduced weed accumulation around the sensors. However, weed problems were encountered during the subsequent operations, particularly during summer and fall. Weed accumulation reduces meter readings and requires divers to inspect and clean the sensors at frequent intervals for reliable data records. Problems with weed accumulation became readily apparent on the Detroit River during the second phase of the program, with continuous meter operation throughout the year. The weed content in the Detroit River is much higher and the river velocities are considerably lower, contributing to more weed accumulation and higher weed effects. The EM current meter velocity records taken immediately before and after cleaning of sensors by divers indicate that weed accumulation may reduce meter velocities by more than 50% on the Detroit River and 25% on the St. Clair River. The records also show that this weed accumulation may occur in less than 1 week following deployment or cleaning of meters. However, weed accumulation is generally gradual and difficult to identify during initial stages. Since diver operations are expensive, this type of meter is not suitable for prolonged/continuous operations in rivers with high weed content, particularly during the high weed transport season.

Discussion and presentation of the EM current meter results in this paper are limited to the 3-month period around the record April 1984 ice jam on the St. Clair River. This jam vividly demonstrates the effectiveness of the in situ current meter velocity measurements in estimating the river flows.

The collection of high-quality current meter data during the ice jam represents a major accomplishment and invaluable information on the winter flow regime of the St. Clair River. Results of the current meter program in operation at that time are indicated in Figure 6, which shows the effect of the ice jam on the upper river flows (velocity and direction). The velocity was reduced by about 50% during most of April, changing near the river bottom at the meter location from about 1.0 to 0.5 m s^{-1}. Higher velocities at the beginning of May, following the jam breakup, were produced by the increased head (water level difference) between Lakes Huron and St. Clair.

Verification of the current meter results on the St. Clair River is provided by flow transfer from the Detroit River, which was free of ice during the April ice jam period and enabled accurate flow simulation with a numerical model. Conversely, good agreement in derived flows by two independent methods demonstrates that the St. Clair–Detroit River flow transfer method is a very useful technique, provided that one of the rivers is free of ice problems. Comparison of flows transferred from the Detroit River with the St. Clair River flows derived from the current meter measurements is shown in Figure 7. Extrapolation of the average river velocity and discharge from the current meter point measurements is discussed in the following paragraphs. The transfer factor, shown in the figure, represents a summation of the hydrologic factors that determine the difference between the flows in the St. Clair and Detroit Rivers, namely, the precipitation on Lake St. Clair plus tributary runoff minus evaporation from the lake and the storage of water on the lake. The agreement between the meter and transferred flows is good during most of the March–May period, particularly during the ice jam in April. In the few instances when the two sets of flows deviate substantially, it is probably the transferred flows that are in error. Thus the high peak in transferred flow at the beginning of May is caused by an extreme high storage of water on Lake St. Clair, which appears to be overestimated. Larger deviations at the beginning and during the second week of March appear to be caused by model oversimulation of the Detroit River flows, probably due to the presence of some ice in the river (March ice cover was not observed).

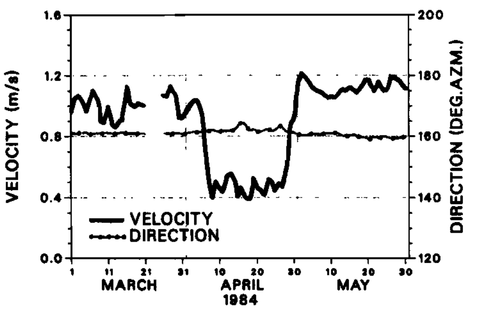

Fig. 6. St. Clair River current meter velocity and direction, March–May, 1984.

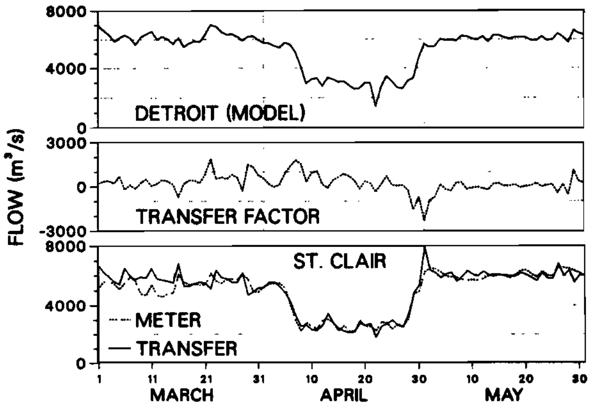

Fig. 7. St. Clair–Detroit River flows, March–May, 1984.

Comparison of the current meter velocities with the St. Clair River numerical model results during the 1983–1984 field season (November–July), expressed as a ratio of the two velocities, is shown in Figure 8. As was expected, the figure shows a complete breakdown of the St. Clair River model following the development of the ice jam in April. During other times, firstcut estimates of the average river velocity at the meter location could be obtained by applying the velocity ratio to the current meter point measurements. The relationship between the normal model and the meter velocities for the 1983–1984 field season, after elimination of the bad model results in April, is indicated in Figure 9. The two equations shown in the figure are for a linear regression of the data points (least squares) and for a velocity forced through a zero intecept. The equations agree closely and either one could be used to produce acceptable average river velocities. The equa-

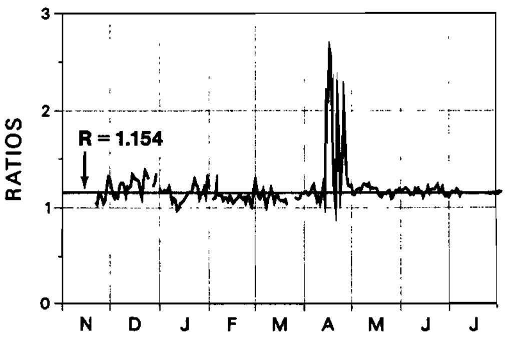

Fig. 8. Ratio of model to meter velocity, November–July, 1983–1984.

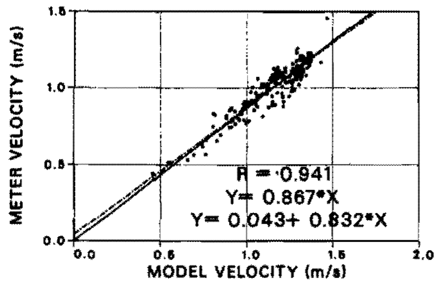

Fig. 9. Relationships between normal model and meter velocity, November–July, 1983–1984.

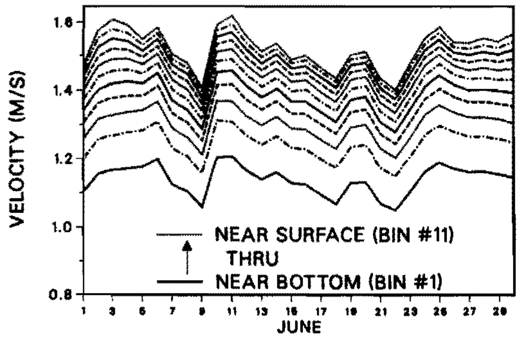

Fig. 10. Vertical distribution of velocity, June 1985.

tion constant from the zero intercept equation also agrees very closely with the reciprocal of the average model-to-meter ratio (Figure 8). The high correlation coefficient (0.94) indicates that over 88% (R squared) of the variation between the average river velocity (simulated by model) and the current meter velocity measured at a single point near the river bottom is explained by a simple regression.

Determination of river discharge, based on measurements, was made by multiplying derived average river velocities from current meters by the corresponding cross-section areas, obtained from model computations. These areas were readily available, since in either velocity extrapolation method (ratio or regression) the flows (discharge or velocity) were also simulated by the models. At the meter location, most changes in the river discharge are produced by corresponding changes in velocity, and errors introduced in the derived discharge due to omission of the corresponding cross-section area changes are relatively small. In the most extreme cases, connected with prolonged massive ice jams, the velocity and corresponding discharge changes (reduction) could exceed 50%; similar cross-section area and corresponding discharge changes would be under 5%. During large ice jams, to which the St. Clair River is particularly prone, the above meter-derived flows represent a tremendous improvement over uncorrected model results, which may oversimulate actual flows by a factor of 2 (Figure 8). Availability of similar measurements during such ice jam episodes, especially in conjunction with flow transfers (if feasible), may provide acceptable flow estimates.

Acoustic Doppler Current Profiler

The ADCP meter was placed in operation during November 1984. Data collected with this instrument appear to be unaffected by the frazil ice and weed problems, most likely because of the meters' physical characteristics. Both the outgoing and reflected sound waves travel through any frazil ice coating the sensor. The same applies to weed accumulation. Meter characteristics also permit its deployment in a low-profile horizontal position on a support structure designed to reduce weed accumulation. Very little weed accumulation was actually noticed during divers' inspections. This eliminates data gaps during winter and questionable or outright erroneous data periods during heavy weed transport/accumulation (summer–fall and after storms). The upper St. Clair River vertical velocity profile measurements obtained with this meter represent high-quality, unique data not previously available on the Great Lakes connecting channels. The profiler is expensive but produces a data set which could not be duplicated with a dozen of the EM current meters, since they could not be deployed at 1-m intervals and operated continuously near the surface throughout the year (navigation and ice problems). The quality of ADCP meter data is also better. The following discussion and presentation of the profiler results is limited to a few data samples that illustrate the nature and quality of collected data.

The vertical distribution of velocity in the water column measured with the profiler during June 1985 is indicated in Figure 10. It gives the progression of daily velocities at 11 levels with 1-m depth increments between approximately 2.5 m above the bottom and 0.5 m below the surface, the practical limits of vertical measurements. Figure 10 shows a high degree of consistency between velocities at different depths throughout the month. This consistency indicates that good estimates of velocities in the entire water column or at different depth levels could be obtained with single point measurements, such as those made with the EM current meters (provided problems are eliminated). Highest velocities normally occur near the surface, with a smooth progression of increasing velocities from the bottom toward the surface, unless surface flow is opposed by substantial wind shear. With strong countercurrent winds (southerly), which are generally limited to relatively short periods, the velocity near the surface is occasionally retarded sufficiently so that the highest velocity occurs 2–3 m below the surface. A more frequent occurrence is the nearly uniform velocity in the top water layer spanning a few (occasionally several) meters.

The smooth transition of velocities between progressive water layers is indicated even more vividly in Figure 11, which shows two vertical velocity profiles. A typical high-velocity profile is shown by June 10, 1985, which was selected because of sharp increase in velocities on that day (Figure 10); the

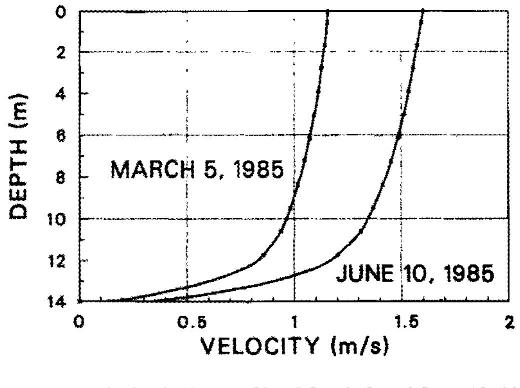

Fig. 11. Vertical velocity profiles, March 5 and June 10, 1985.

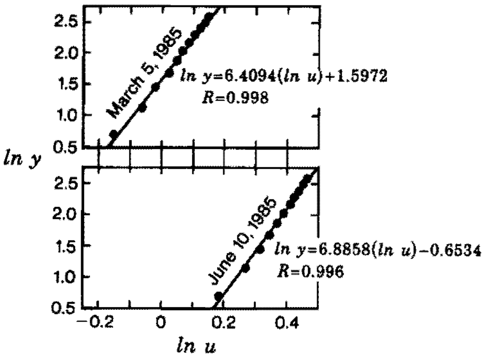

Fig. 12. Logarithmic vertical distribution of velocity, March 5 and June 10, 1985.

March 5, 1985, profile was added to show a typical low-velocity profile. Despite rapid change in velocities on June 10, the graph shows an extremely smooth transition in the vertical distribution of velocities. The use of daily velocities provided some smoothing of the graphs, but generally similar profiles are obtained for shorter periods (hourly and 15-min data). To extend the profiles to the bottom and the surface, where velocities could not be measured, these points were estimated and incorporated in the graphs. The surface point was estimated by extending the curve indicated by the preceding three measured points to the surface. The bottom point was estimated by forcing a similar curve near the bottom through a maximum depth and zero-velocity intercept. The profiles show that the vertical velocity distribution is definitely exponential, which agrees with theoretical derivations for turbulent flow [*Prandtl*, 1925; *von Karman*, 1934].

There has been some argument and disagreement as to the exact nature of the vertical velocity distribution in the rivers. The accepted theoretical distributions used for the Great Lakes connecting channels are the *Prandtl* [1925] and *von Karman* [1934] distributions. Using the 11 points for vertical velocities based on measurements (disregarding estimated surface and bottom points), the logarithmic vertical velocity distribution was tested for the two discussed profiles; results are shown in Figure 12. The linear regression for logarithmic distribution is nearly perfect ($R = 0.998$ and 0.996) and indicates that very little (less than 1%) of the variability between depth and velocity measurements remains unexplained. This includes most of the depth but excludes the boundary layer, where the distribution could not be logarithmic because of theoretical considerations.

SUMMARY AND RECOMMENDATIONS

Flows in the St. Clair–Detroit River system, the outlet from the upper Great Lakes, are needed for a variety of hydraulic and water resource studies. Applications include hydrologic water balance, lake regulation, lake level forecasts, navigation, transport of pollutants, recreation, and consumptive water use. During the open-water season, acceptably accurate estimates for these flows are provided with available mathematical unsteady flow models. However, these models may produce large errors during winter months when rapid transport of ice flows causes formation of ice jams in the lower river reaches. The St. Clair River is particularly prone to large ice jams because of the potentially large ice flow supply from Lake Huron and an extensive river delta which retards the passage of these ice flows. Flow estimates during ice conditions can best be obtained from in situ meter measurements.

Analysis of data collected during the 1983–1985 period indicates that acceptable estimates of river flows can be obtained with a single, well-placed current meter. However, the EM current meters are susceptible to frazil ice problems during winter and to weed effects during summer and fall, making them of dubious value on rivers with high weed content, such as the Detroit River. These problems can be avoided with the ADCP meter, which is not affected by the frazil ice and weed effects and produces better quality data for nearly the entire water column. The vertical velocity profiles measured with the ADCP meter show a high consistency in the logarithmic vertical distribution of velocities.

Because of the high quality of data for the overhead water column, deployment of the ADCP meters should be considered by agencies responsible for flow measurements in large rivers, such as the Corps of Engineers for the Great Lakes connecting channels. Data from such meters could be collected either continuously or on demand. With proper calibration, the ADCP meters may provide a suitable substitute for the labor-intensive periodic measurements now conducted by these agencies. The quality of such measurements would also be higher.

Acknowledgments. From the beginning of the current meter field experiment, a number of people, too numerous to be individually mentioned here, contributed to the successful operation of the project. The authors thank all the contributors and acknowledge specifically those who made especially valuable contributions. Several people from GLERL but especially H. K. Soo, R. D. Kistler, and R. W. Muzzi are acknowledged for their extensive involvement in instrumentation, while R. N. Kelley and B. M. Slizewski are acknowledged for data collection and analysis. Finally, the authors thank the U.S. Ninth Coast Guard District for the deployment support provided on both rivers, without which this project would not have been possible. GRERL Contribution 492.

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