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COMPARISON OF VERTICAL VELOCITY MEASUREMENTS IN THE GREAT LAKES CONNECTING CHANNELS WITH THEORETICAL PROFILES

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Vertical distribution of velocities was measured with an upward looking acoustic Doppler current profiler in the upper St. Clair River during November 1984 - April 1986 and the Detroit River from November 1986. The current meter stations are located approximately 1 km downstream of the Blue Water Bridge in Port Huron on the St. Clair River and about 2 km downstream of the Ambassador Bridge in Detroit on the Detroit River. The acoustic meter measures Doppler shift to provide continuous measurements of velocities throughout the water column, from about 1 m above the sensor (located near the bottom) to the surface. These averaged velocities are recorded at mid-points of the individual 1 m segments. Surface readings are not used because of large scattering at the air-water interface. With water depth of about 14 m at both meter locations, the profiler provides 11 vertical velocity readings at 1 m increments between about 2.5 m above the bottom and about 0.5 m below the surface. The measured data are recorded at 15 min intervals, from which hourly and daily values are derived. These velocity vectors are later combined to produce vertical velocity profiles of the two rivers. The velocity data for shorter periods indicate somewhat larger scatter, but the vertical velocity profiles for all periods illustrate high consistency and verification of the theoretical, logarithmic vertical distribution of velocities.

INTRODUCTION

Flows in many of the Great Lakes connecting channels are not directly measured but must be computed from either stage-fall-discharge equations or from unsteady flow mathematical models calibrated by periodic velocity and discharge measurements conducted over the years. These measurements typically consist of nine velocity measurements from a string of current meters suspended at different depths, one at each tenth of depth. These measurements define the vertical velocity distribution or profile, from which the average velocity at that location is determined. The velocity measurements are repeated at a number of locations or panels in a cross-section of the channel to determine the average river velocity and discharge. Because it takes a minimum of 2 to 3 hours to complete a river crossing, the steady flow assumption for computing river discharge may at times be invalid. Differences in meter characteristics and performance of meter strings may also contribute to difficulties in the reproduction of actual velocity distribution. Recent advances in acoustical instrumentation (using the Doppler principle) make nearly-

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instantaneous measurements of the vertical velocity profiles both feasible and practical.

FIELD MEASUREMENTS

Vertical velocity profiles in the St. Clair River have been measured during November 1984 - April 1986 and in the Detroit River from November 1986, in connection with the connecting channels experimental program conducted by the Great Lakes Environmental Research Laboratory (GLERL). The vertical distribution of velocities in the upper St. Clair River was measured continuously with an acoustic Doppler current profiler (ADCP) meter (RD Instruments, Model 1200 RDDR) at the GLERL current meter station located in Port Huron, MI, approximately 1 km downstream of the Blue Water Bridge. In November 1986, the ADCP meter was transferred to the Detroit River current meter station located in Detroit, MI, about 2 km downstream of the Ambassador Bridge. This meter permits remote velocity measurements throughout the water column above the sensor and provides averaged velocity data for sequential depth segments. The ADCP meter was installed about 60 m from the United States shore in the St. Clair River and about 90 m from shore in the Detroit River, with about 14 m of water at both locations. The meter housing is oriented horizontally, with the upward-looking sensor connected by a 90° elbow about 1 m above the bottom (Fig. 1).

The acoustic profiler measures water velocity by determining the Doppler frequency shift of sound waves. The Doppler principle states that the apparent wave length or frequency of a backscattered acoustic signal differs from the transmitted frequency by an amount proportional to the relative velocity of the transmitter/receiver (ADCP's transducer) and the backscattering object, where the scattering object is a multitude of tiny organisms and particles in the water. The ADCP meter operation is described by RD Instruments (1984). Briefly, it consists of averaging velocities for consecutive water column segments or range cells (bins) sampled by continuous sound signals (pings) along multiple acoustic beams of known geometry. The GLERL profiler emits pings continuously along four beams at a rate of five times per second and samples the water velocities from about 1 m above the sensor to the surface. The meter averages velocities over successive bins for each beam (oriented 30° off vertical in 90° horizontal increments) and records the velocity data at the mid-points of corresponding bins, which are approximately 1 m in length. This represents the maximum permissible resolution of the vertical cells (smallest bins), which was obtained by selecting adjusted ping duration equal to one bin length (about 1 m). In other words, the pulse length of the ping (1.57 ms) is also the time it takes for the sound to travel through one bin (1.15 m). The GLERL profiler averages data from the corresponding pairs of beams to give values for the horizontal velocity components (Y and X direction); these, along with the compass angle, are converted to North and East velocity components, and finally to the resultant velocity vector magnitude and direction (azimuth angle). The surface readings are eliminated because of large data scatter at the air-water interface (sound speed

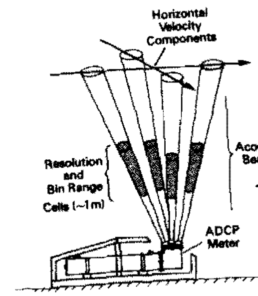

Fig. 1. Acoustic Doppler Current Profiler and Schematic of its Operation

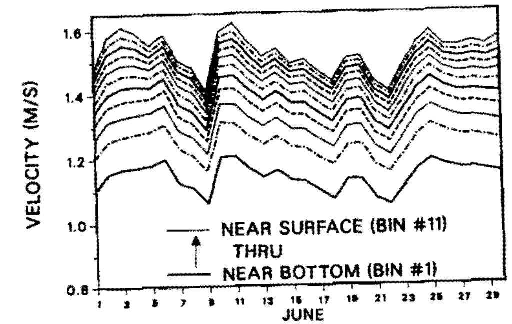

Fig. 2. Vertical Distribution of Measured Velocity, June 1985

is approximately 5 times faster in water than in air).

For a depth of about 14 m, the above procedure produces averaged velocity and direction values for 11 levels (one per bin) between approximately 2.5 m above the bottom and 0.5 m below the surface. The data and identification information are recorded on a cable-connected shore station at 15-minute intervals (on the quarter-hour periods). The 15-minute data records are monitored daily and stored in a computer file (by direct computer interrogation during night-time hours). These 15-minute data inputs are checked and converted to hourly and daily resultant velocity magnitudes and directions. Apart from some interruptions for the initial instrument testing and later minor malfunctions of the recording system, the profiler has been recording data continuously during its deployment. In contrast to electromagnetic current meters (Derecki and Quinn, 1987), data collected with the profiler appear to be unaffected by frazile ice or weed fouling problems, most likely because of the meter's physical characteristics. Both the outgoing and reflected sound waves of the acoustic profiler travel through frazil ice, if the sensor is coated; 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. The profiler records, therefore, have no short-term (hours or days) data gaps in the winter due to elimination of bad data during frazil ice episodes nor long-term gaps (weeks or months) due to elimination of questionable or erroneous data during the heavy weed transport season in summer and fall.

VELOCITY DISTRIBUTION

The nature and qualilty of the collected data are illustrated by data samples presented in the following discussion. The vertical distribution of velocity in the water column measured with the profiler during June 1985 is indicated in Figure 2. This figure shows the progression of daily velocities at 11 successive levels in about

1 m depth increments, from approximately 2.5 m above the bottom to about 0.5 m below the surface. The 11 velocity curves show a high degree of consistency between velocities at different depths throughout the month even during rapid changes in velocities. When the near-surface velocity is reduced by strong counter-current winds (southerly at the meter location and generally limited to relatively short periods), the highest velocity occasionally occurs 2-3 m below the surface. A more frequent occurrence is the nearly uniform velocity in the top water layer which extends to a few (occasionally several) meters in depth.

Because the variations in vertical velocity and depth are generally synonymous, as indicated for June 1985, vertical sections along the horizontal time scale (Fig. 2) are equivalent to the vertical velocity profiles, which express the relationship between water velocity and the 1 m depth increments for the corresponding time periods. A number of such velocity profiles (about two dozen), grouped by high and low velocity episodes to encompass the whole range of velocity measurements, were selected and analyzed in detail to test the agreement of measurements with the theoretical vertical velocity distribution. The theoretical distributions of vertical velocity used most frequently for the Great Lakes connectiong channels are those developed by Prandtl (1925) and von Karman (1934). For analysis it is customary to express the relationship between velocity and depth on a semi-log scale, relating velocity with a logarithmic function of depth, so that the relationship can be simplified to a linear regression of the two variables.

Figure 3 shows the semi-logarithmic relationships between velocity and depth function for a typical high velocity profile of June 10, 1985 and a typical low velocity profile of March 5, 1985, using Prandtl's distribution. Both profiles show an extremely smooth transition in the vertical distribution of measured velocities and a nearly perfect correlation with depth, with correlation coefficients approaching unity (R = 0.999). The use of daily profiles provides some smoothing, but velocities obtained for shorter periods (hourly and 15-minute intervals) indicate similar basic trends in the distribution of vertical velocities. Similar relationships are obtained for the agreement of measured velocities with the von Karman distribution. Prandtl's distribution was selected for this demonstration analysis because of the simplicity of its depth function term (ln y/D), which becomes rather complicated in the von Karman distribution. In the Prandtl's distribution the function of depth is expressed in dimensionless units as a natural logarithm of (y/D) ratio, where "y" is the known value of depth measured from the bottom up and "D" is the total depth, which is not known precisely because of water level fluctuations. In the vertical velocity profile analysis the selected value of "D" was 13.72 m, which represents river depth during meter deployment at both river locations.

The constants of the least squares equations for the individual profiles are the slope and y-axis intercept, from which other information pertinent to the vertical velocity distribution, namely, roughness length and friction velocity can be derived. These

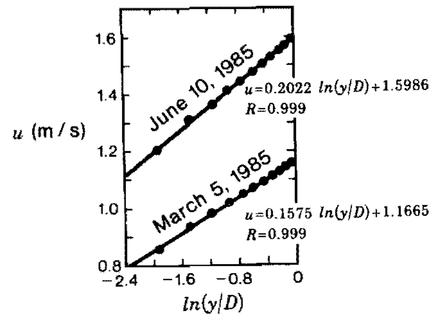

Fig. 3. Relationship between Measured Velocity and Depth Function for March 5 and June 10, 1985 with Prandtl's Velocity Distribution

parameters are indicative of channel roughness and because velocity measurements were obtained at the same location, in a well established river channel section, it would be logical to assume that they would be or should approach constants for a series of continuous velocity measurements. However, measured data produced considerable variation for the individual profiles (for whatever reason), especially in the roughness length (y_o). This parameter is of particular interest, because it represents depth intercept for zero velocity and is needed in the derivation of average vertical velocity, which is obtained by integrating area under the velocity profile curve. Computed friction velocity values were generally between 0.05-0.07 m/s for low velocities and 0.08-0.09 m/s for high velocities. Derived roughness length values generally varied between 0.005-0.013 m but were predominantly around 0.006-0.008 m. Thus, while friction velocity was generally limited within about 25%, the roughness lengths were at times more than doubled, exceeding 100%. To test the effect of this large variation in the roughnes length on the average vertical velocity, average velocities were computed for a profile with a roughness length of 0.006 m, the roughness length was than doubled to 0.012 m, the velocity equation constants were readjusted to the new roughness length value and the average velocity recomputed. The effect of this extreme variation in the roughness length on the average vertical velocity was found to be less than 1% for the Prandtl distribution, which is well within limits of acceptable accuracy for the connecting channels velocity measurements (±2%). The meter accuracy is ±0.2% or ±0.5 cm/s. The variability in roughness length is somewhat smaller with the von Karman distribution, therefore, the exterme effect of this variation on the average vertical velocity is also smaller for the von Karman than for Prandtl's distribution (both less than 1%).

Another source of error in the average vertical velocity computations is the assumption of 13.72 m for the total river depth (both rivers), made in the velocity profile analysis, since actual river depths are not known at the time of velocity measurements. The normal daily variation in the river depth due to seasonal lake level fluctuations is about 0.6 m (about 1.0 m for the instantaneous hourly levels). Changing the total river depth by 0.6 m will produce only a small difference in the roughness length (about 5%), which will have only a very small effect on the average vertical velocity (considerably less than 1%). The above results for the roughness length and total depth effects indicate that any reasnable assumption with regard to these values will not change the resulting average vertical velocity significantly.

CONCLUSION AND RECOMMENDATIONS

Analysis of vertical velocity data collected in the upper St. Clair and Detroit Rivers with the ADCP meter indicates that good estimates of the vertical velocity distribution can be obtained with a single well-placed meter. These ADCP measurements were not affected by frazil ice problems during winter or by weed effects during summer and fall and produce high quality data for nearly the entire water column. The vertical velocity profiles measured with this meter show a high consistency in the logarithmic vertical distribution of velocities in the water column, starting a short distance above the bottom.

Because of the high quality of data for nearly the entire water column the meters lend themselves to operational deployment and monitoring. Data from the meters could be collected either continuously or on demand, using either fixed-bottom-point (as in this study) or moving-boat deployment. With sufficient instrumentation and proper calibration, the meters can provide a suitable high quality substitute for the labor-intensive periodic measurements conducted on many rivers by responsible agencies.

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