DISCHARGE ESTIMATION IN TIDAL RIVERS WITH PARTIALLY REVERSE FLOW

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ABSTRACT

In tidal rivers with comparatively large width, estimation of the instantaneous discharge is a formidable task. In order to estimate the discharge a large number of measured velocity points are needed. Each point should be collected in a reasonable time interval. The flow characteristics in a tidal river with partially reverse flow are much more complicated. Maghrebi (2006) has previously introduced a model for the production of isovel contours in a normalized form, which can be used for estimation of discharge in artificial and natural channels. It is assumed that the velocity at each arbitrary point in the flow section is affected by the hydraulic characteristics of the boundary. In the present study, for the first time, the model is applied to a tidal river with partially reverse flow, which is caused by opening a sluice gate located asymmetrically close to the right bank of the Ohta floodway in Hiroshima, Japan. An acoustic Doppler current profiler (aDcp) was used to measure the velocity profiles at different verticals. Then, the actual discharge in the river is estimated as the summation of the product of point velocity multiplied by the representative area over the whole section. In addition, the estimated discharge based on each measured point and the predicted isovels of flow cross section is obtained. The results show that the corresponding errors for the measured points away from the solid boundaries and the boundary of flow between the two opposite directions along a vertical, which are associated with lower absolute values of isovels, are reasonable.

Keywords: isovel contours; reverse flow; discharge estimation; tidal river

1 INTRODUCTION

The difficulties of understanding the instantaneous flow characteristics in tidal rivers are mainly associated with the conventional invasive instruments, expense and considerable time consumption (Chen & Chiu, 2002). Discharge measurement in tidal rivers has to be completed quickly, due to the fact that flow conditions vary rapidly. The flow in tidal estuaries is three dimensional and very complicated which is particularly due to tidal oscillations associated with changes in depth, mean velocity, direction of flow, and density gradients affected by salt, heat and suspended particles. A major requirement for understanding the characteristics of a tidal stream is to have the knowledge of water flow. Estimation of discharge in a tidal river is one of the significant issues of flood management. However, engaging this issue in a river with reverse flow requires a good knowledge of hydraulics. The problem comes from the boundaries, where flow is almost stagnant. The boundaries are recognized as two types: solid boundary and imaginary boundary between two adjacent flows with opposite directions. It has always been difficult to estimate some quantities close to zero, and velocity is not an exception. This will have more profound influence on the discharge estimation.

Observing the time variation of water stage and discharge have shown that during ebb and flood flow the sign of discharge Q will be positive and negative, respectively (Chen & Chiu, 2002; Kawanisi, 2004). The general form of stage discharge is a looped curve. Meanwhile at a certain time the sign of discharge will be unique. However, the complexity of flow is much higher in a tidal stream with partially reverse flow because in this case, at any time two different regions of flow with positive and negative signs can be discerned. Therefore, to deal with such a complex flow two kinds of tasks should be deployed. The field measurements should be conducted by a rapid, accurate and multi-point measurement instrument such as an aDcp (acoustic Doppler current profiler). The other task is data processing at the office. A method, which works with a small number of velocity samples, is required. Maghrebi (2006) has proposed the method of single point measurement for estimation of discharge. A combination of these two will be the solution for complicated flow characteristics such as a tidal flow with partially reverse flow.

The objective of this paper is the application of the single point measurement in discharge estimation of the instantaneous flow in a tidal river with partially reverse flow.

2 CROSS SECTIONAL ISOVEL CONTOURS

The proposed method is able to predict the normalized isovel contours at the cross sections of straight ducts and irregular open channels with different roughness and geometry (Maghrebi & Ball, 2006; Maghrebi & Rahimpour, 2005). It is assumed that each element of boundary influences the velocity at an arbitrary point on the cross section. Then, the total effect of boundary can be obtained by integration along the wetted perimeter. It is suggested that:

$$u\mathbf{i} = \int_{boundary} f(\mathbf{r}) \times c_1 d\mathbf{s} \tag{1}$$

where u is the streamwise velocity at a point at the channel section, **i** is a unit vector along the streamwise coordinate x, $f(\mathbf{r})$ is a velocity function which is similar to the dominant velocity profile over a flat plate with infinity large width, $d\mathbf{s}$ is the vector notation along the wetted perimeter and c_1 is a constant related to the boundary roughness.

The vector direction of velocity on the left hand side of Eq. (1) is the same as the vector product of $\mathbf{r} \times d\mathbf{s}$ on the right hand side, which is a normal to flow section towards downstream. $f(\mathbf{r})$ is replaced by a power law relationship that is commonly used to fit velocity profile in closed conduits and open channels (Yen, 2002), so Eq. (1) can be rewritten as:

$$u(z,y) = \int_{boundary} c_1 . c_2 \sin\theta . u_* \left(r^{1/m}\right) . ds \tag{2}$$

where θ is the angle between the positional vector and the boundary elemental vector, c_2 is a constant related to the nature of flow and $u(z,y)$ is a local point velocity at an arbitrary position in the channel section, and $u_* = \sqrt{\tau_0 / \rho}$ is the boundary shear velocity, where τ_0 is the boundary shear stress and ρ is the mass density of fluid. The exponent m usually ranges between 4 and 12 depending on the intensity of turbulence (Yen, 2002). However, the sixth root of power law profile has been found to be equal to the Manning's formula, which can be well applied to the natural streams i.e. m= 6 (Chen, 1991). The key point in application of the model to a partially reverse flow is that on the bed region where the flow occurs in opposite directions, the sign of shear stress which is affected by the direction of velocity vector, will be changed. According to the field velocity profile the shear stress distribution along the wetted perimeter is considered as shown in Fig. 1(b). Reverse flow occurs on the left part of the river bed, so the sign of shear stress is negative. On the right boundary as the flow is directed toward downstream, the shear stress has a positive sign. Finally, by using the average velocity, the normalized point velocity, $\widetilde{U}(z,y)$ is given by:

$$\widetilde{U}(z,y) = \frac{u(z,y)}{V} = \frac{\int\limits_{boundary} c_1.c_2 \sin\theta . u_* \left(r^{1/m}\right) ds}{\frac{1}{A}\int\limits_{A}\left(\int\limits_{boundary} c_1.c_2 \sin\theta . u_* \left(r^{1/m}\right) ds\right) dA} \tag{3}$$

Eq. (3) provides the normalized velocity at a point as a simple function of the boundary geometry and relative roughness. An advantage of the Maghrebi's model is that it allows the consideration of the hydraulic characteristics of the boundary and their influences on the flow.

3 STUDY SITE AND INSTRUMENT DISCRIPTION

The Ohta River is divided into six branches before discharging to Hiroshima Bay. Gion diversion channel is a branch of Ohta River. At the Gion Bridge location, to control the flow, three sluice gates are installed between the piers. Two gates on the left and the center are closed. The freshwater runoff from the right gate, which is located at about 9 km upstream from the mouth, is limited by fixing the gate opening at a height of 0.3 m from the bottom. The observation site, which was located at the immediate downstream of the Gion gate, is shown in Fig. 1(a). Due to unsteadiness of flow in tidal rivers, a rapid velocity measurement across a wide river is essential. Application of aDcp is a great help to solve the problem of the flow unsteadiness. An aDcp, which was developed by Nortek Inc., was used to measure accurate vertical profiles of mean velocities. The aDcp belongs to a class of acoustic current profilers usually referred to an incoherent Doppler profiler (Lhermitte & Serafin, 1984; Verson & Melville, 1999; Zedel et al., 1996). The aDcp is operating at 2.0 MHz and 23 Hz pinging rate. The three transducers, which are equally spaced at 120° azimuth angles, generate a beam oriented 25° off the vertical axis. Using a compass and a two-axis tilt sensor, the beam Doppler velocities are transformed into earth coordinates by an internal processor. The aDcp allows one to measure the currents and acoustic scattering strength in depth cell sizes of 0.03 m (Kawanisi, 2004). The directions of aDcp axes (the x, y and z axes) are based on the definition of a right-handed coordinate system. The x axis shows the main stream direction, and the streamwise velocity, u, is positive during the flood and negative during the ebb. The vertical axis, y, originates at the bottom and points upward. The water depth was measured using a pressure transducer of aDcp.

The bed profile is plotted in Fig. 1(b). The top width of the river at the observation site is about 130 m and the maximum depth of water is 2.68 m, which is located at a distance of 62 m from the left bank of the river. The assumed shear stress distribution which is used to produce the isovel contours from Eq. (3), is also shown in this figure. The positive shear stresses are attributed to the right half of the bed profile where the sluice gate is opened and negative values are assumed to occur on the left. The corresponded relative values of shear stress for each segment of the bed profile from left to right are -0.55, -0.55, -0.55, -0.5, -0.5, -0.4, 0, 0, 0, 0.3, 0.5, 0.6, 0.7, 0.8 and 1.0, respectively.

4 DISCHAGRE ESTIMATION

The discharge often can not be measured directly and is usually calculated from a stage-discharge curve, derived from gauging station records (Sulzer et al., 2002). Enough discharge measurements during rises and sequent recessions must be made at the gauging station to calibrate the parameters and to check on the computed discharge, which is a time consuming task. On the other hand, the flow conditions of tidal streams are rarely steady or uniform.

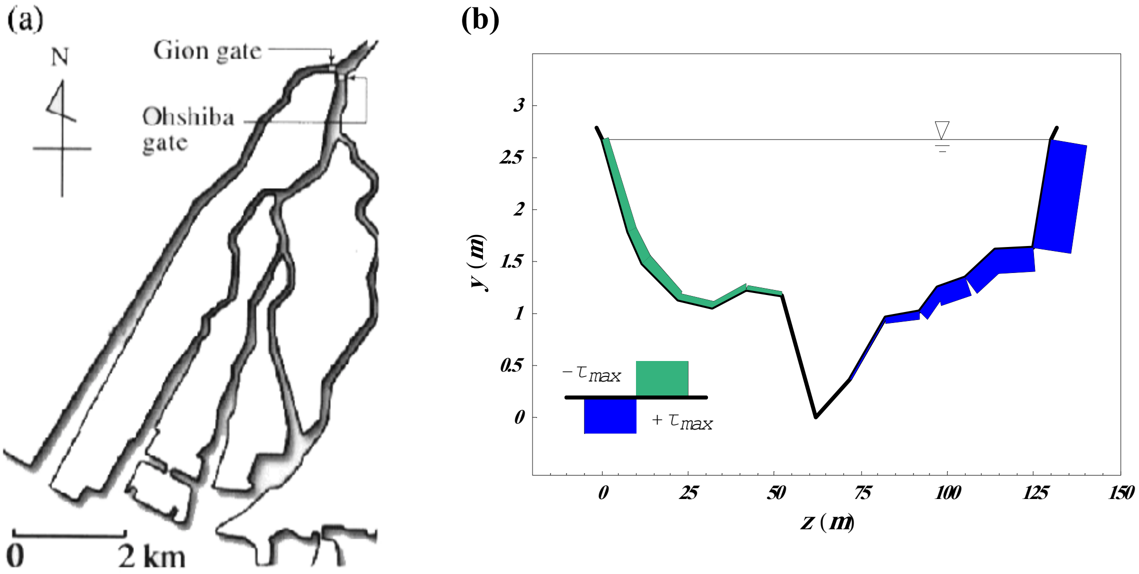

Fig.1 (a) Ohta estuary (Kawanisi, 2004) and (b) river bed profile at the immediate downstream of the Gion Gate with the assumed shear stress distribution.

(a) (b)

Fig.2 Moving aDcp across the Gion diversion channel using a piece of rope (a) a close view and (b) a far view

It make stage discharge relations complex. In addition, the accuracy of stage-discharge curves would be questionable as the hydraulic characteristics of river are changing gradually. Therefore, to estimate the discharge accurately, direct measurements are needed.

The unsteadiness of flow in a tidal river dictates that the measurements should be completed as soon as possible. To overcome the difficulties of rapid measurements, an aDcp has been used to measure accurate vertical profiles of mean velocity. In order to float the instrument on the water surface, it was fixed on flat and light plate. The supporting system was formed in a streamlined shape to minimize the drag and disturbance (Fig. 2a). Then a piece of rope was used to displace the probe across the river section manually (Fig. 2). The preferred method of measuring discharge in a large tidally affected stream is the moving boat method (Rantz, 1983; IOS, 1979). At each transverse location, the probe was remained stationary for duration of 60 s to collect the instantaneous velocity at a sampling rate of 23 Hz.

The measured discharge at the river section is estimated as the summation of the product of point velocity multiplied by the representative area over the whole section, which is called actual discharge, Q_a. Accordingly, the velocities are measured at different verticals with the distances of 8, 12, 22, 32, 42, 52, 82, 92, 97, 105, 114 and 125 meters from the left bank. The cross sectional area of the river and the average velocity are computed as 194.06 m^2 and 10.7 cm/s, respectively. The corresponded discharge is $20.76\,\mathrm{m}^3/\mathrm{s}$.

The isovel contours shown in Fig. 3(a) are calculated based on the experimental data. As shown, the direction of the velocity at the left part of the river section is headed towards upstream, while the flow on the right part flows downstream. The reason is to control the flow, out of three sluice gates installed across the river section installed at the Gion bridge spans, only the right gate is opened. Fig. 3(b) shows the predicted isovel contours calculated based on the proposed model (Maghrebi, 2006). The adopted shear stress distribution is shown on the bed (Fig. 1b). Negative shears are advocated to the bed profile on the left and positive shows to the right, which is consistent with the flow characteristics of the observed section. A good agreement can be observed between the isovel contours produced by experimental data and model. Determination of the roughness coefficients in natural rivers is a difficult task. In this study the roughness of river boundary over each segment of the cross-section is assumed to be uniform.

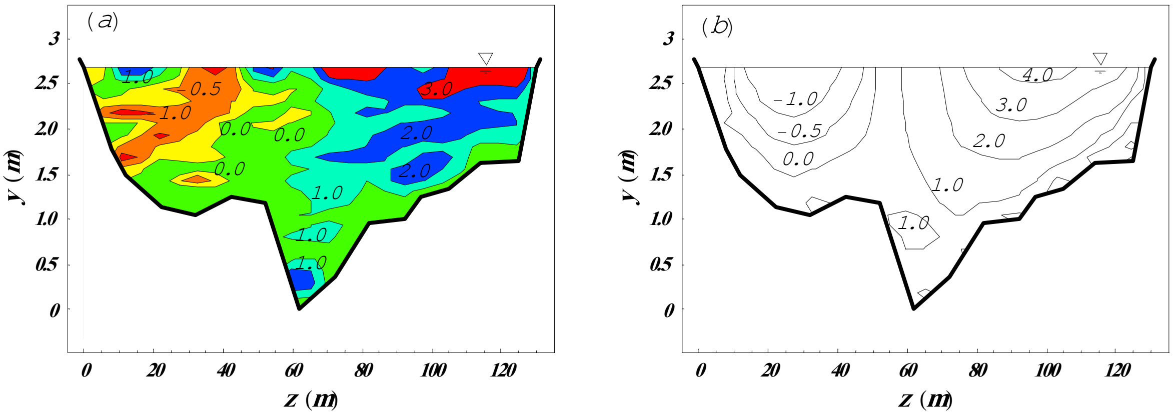

Fig.3 Isovel counters at the observation section of the Gion diversion channel based on (a) field data and (b) Maghrebi's model

Fig. 4 shows the measured velocity profiles at different verticals with solid circles connected to each other with broken lines. Positive sign for velocity shows that the direction of flow is towards downstream and the negative sign refers to the opposite direction. Due to the probe limitations, velocity could not be measured at a vertical distance of less than 0.2 meter from the water surface and 0.1 m to the bottom of the river.

In addition, velocity profiles according to the proposed model, which are shown with thick solid lines, are plotted against the field data (Fig. 4). Close to the left and right walls of the river, larger differences between the predicted velocity profile and the measured data can be observed. Using a single point of velocity measurement in combination with the isovel contours produced by the proposed model, it is easy to estimate the discharge (Maghrebi, 2006). The magnitude of normalized corresponding isovel contour passing through a given measured point can be found. The measured velocity at a point in channel cross section is *u(z,y)* and the magnitude of the normalized corresponding isovel contour is $\widetilde{U}(z,y)$, then the total discharge can be obtained by:

$$Q_c = A.\frac{u(z,y)}{\widetilde{U}(z,y)} \tag{4}$$

where Q_c is the total calculated discharge passing through the cross sectional area *A* and $\widetilde{U}(z,y) = u(z,y)/V$ with *u(z,y)* and *V* as the local point velocity and the mean cross-sectional velocity, respectively.

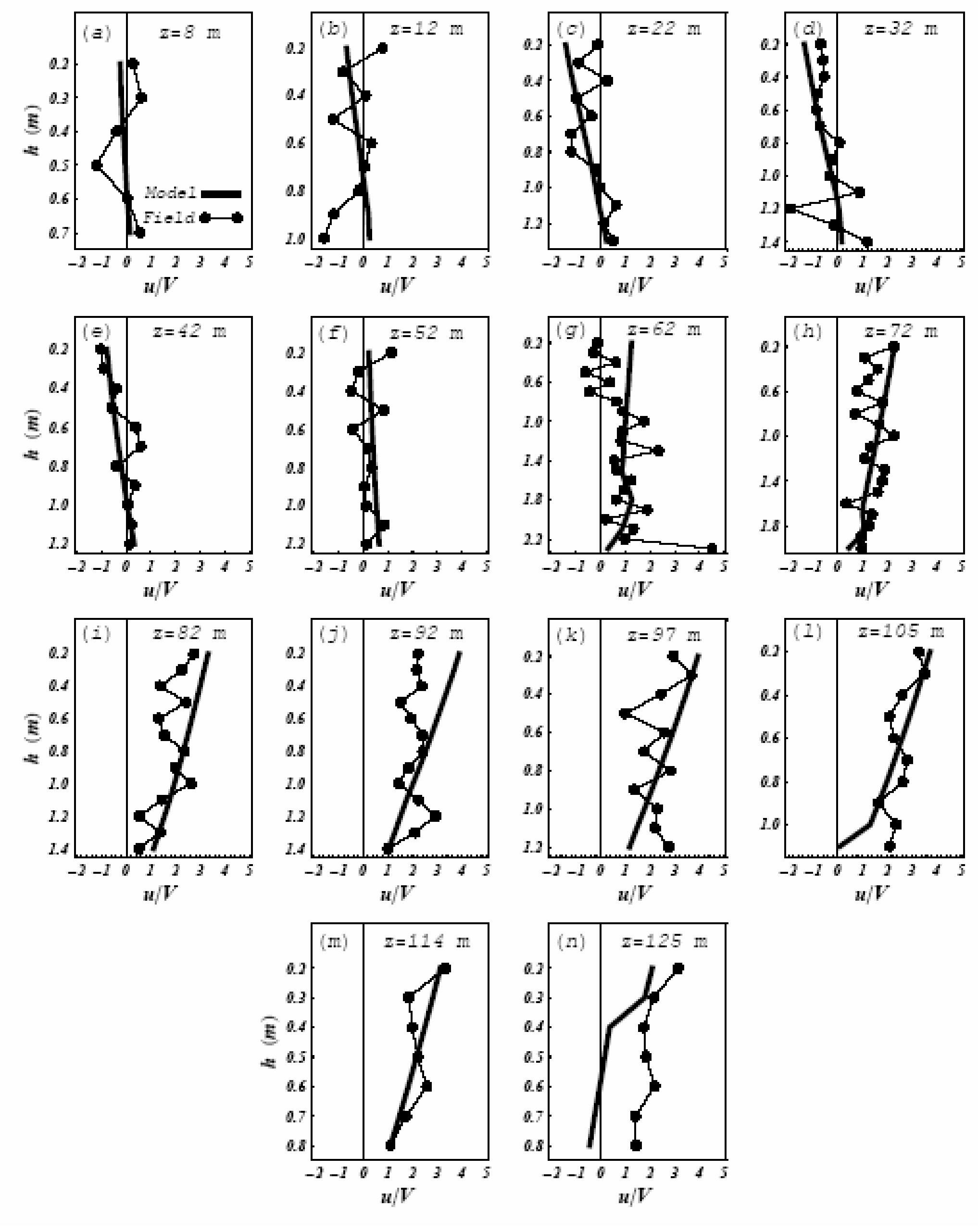

Fig.4 The measured velocity profiles using aDcp in comparison with the results provided by the proposed model at different transverse verticals of the observation section.

Then, the relative percentage of error in discharge estimation is calculated by:

$$Error\ \% = \frac{Q_a - Q_c}{Q_a} \times 100 \tag{5}$$

Due to the velocity fluctuations in a vertical, if the discharge is estimated based on a single point of velocity measurement, the result would be far from the actual discharge. This leads to larger errors. To minimize the uncertainty, it is recommended to estimate the discharge using a number of measured velocity points. Although any combination of the measured points can be used for the estimation of discharge, two ways of grouping were chosen. The first one, which is shown in Fig. 5(a), seems to be a natural grouping technique, because the points in a vertical are measured simultaneously. Therefore, the expected magnitude of error would be smaller. Based on each point in a group an estimated discharge is obtained. In this case, the best expected value of discharge will be the mean value.

Discharge estimation based on groupings shown in Fig. 5(a) implies that for the vertical groups on the left region of the section the errors are relatively large. The best result is related to C6 with 32.4% of error. However, as going towards the right bank of the river, velocity is increased. It has been mentioned that as the corresponding values of the contour lines are increased, errors in discharge estimation would be decreased (Maghrebi, 2006). The errors associated with C8, C10, C11 and C13 are -0.5, 6.6, -2.7 and -2.1%, respectively (Table 1).

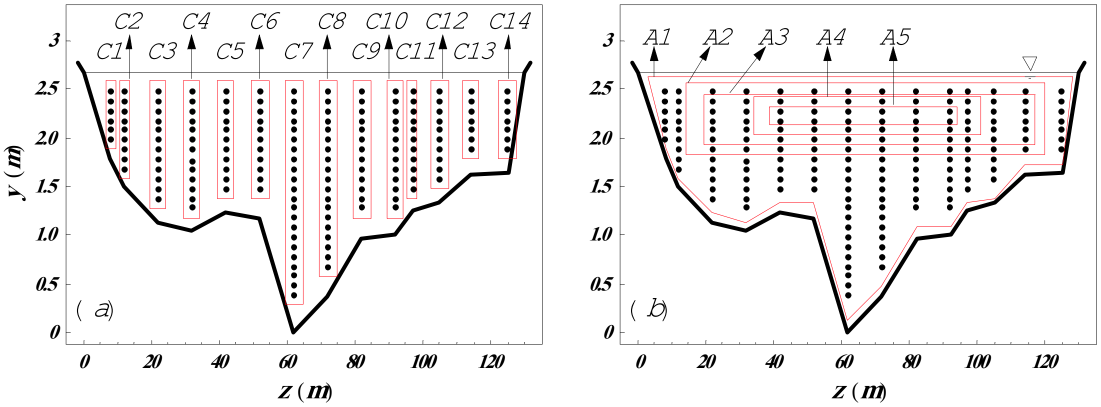

Fig.5 Definition areas for calculation of average percentage of error in discharge estimation (a) vertical groups and (b) horizontal groups

Table 1 Average error in discharge estimation using data grouping of Fig. 5(a)

Vertical Groups	z (m)	No. of points	Average Error %	Vertical Groups	z (m)	No. of points	Average Error %
C1	8	6	-381.7	C8	72	19	-0.5
C2	12	9	239.9	C9	82	13	23.5
C3	22	12	179.5	C10	92	13	6.6
C4	32	13	374.6	C11	97	11	-2.7
C5	42	11	89.1	C12	105	10	-199.3
C6	52	11	32.4	C13	114	7	-2.1
C7	62	22	-40.8	C14	125	7	578.5

The second considered grouping technique for the measured points are shown in Fig. 5(b). These are essentially horizontal arrangements. From this sketch, it is not expected to get a better estimation with smaller errors. As a matter of fact, the sign of isovel contours is changed when moving horizontally. This means that isovel contours with small values will be contributed in discharge estimation. As previously mentioned, this will lead to a larger magnitude of error. In Table 2, the average calculated errors for this type of grouping is presented.

Table 2 Average error in discharge estimation using data grouping of Fig. 5(b)

Horizontal Groups	No. of points	Average Error %
A1	164	53.8
A2	77	30.9
A3	55	45.6
A4	28	59.2
A5	12	44.6

5 CONCLUSIONS

In large tidal rivers with partially reverse flow the task of velocity measurement should be completed quickly. This is due to high unsteadiness of the flow. This maybe fulfilled using an aDcp. The other task is the use of a theoretical approach for estimation of discharge based on the minimum number of points of velocity measurements. The proposed method for estimation of discharge using a single point of velocimetry can be considered as a great help. Due to the fluctuations of the measured velocities in a vertical, it is understood that discharge estimation based on a number of measured points would lead to more appropriate results.

The results of this study have revealed that the proposed model can be considered as an appropriate, fast and easy model for the production of isovel contours in natural rivers with partially reverse flow. When using a single point of velocity measurement for estimation of discharge, if the related normalized contour values are small, the corresponded errors will be large. Therefore, it is generally proposed to select the measured points from the regions with the corresponding high values of isovels. In the present study, selection of the measured points on a vertical especially those with high corresponded values of isovels lead to a better estimation of discharge. The results obtained for the verticals C8, C10, C11 and C13 are provided the best results with corresponded errors limited to less than $\pm 7\%$. On the other hand, the measured points on a vertical close to the solid boundaries or close to the dividing boundary of two adjacent regions with opposite flow directions, leads to poor discharge estimations.

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