A NEW MONITORING SYSTEM FOR SEDIMENT TRANSPORT WITH H-ADCP MEASUREMENT AND NUMERICAL SIMULATION

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Abstract. Monitoring sediment transport in rivers is indispensable for integrated watershed management. A horizontal acoustic Doppler current profiler (H-ADCP) can measure the lateral profiles of velocity and echo intensity along a horizontal line. Since the echo intensity is closely related to turbidity in water, the H-ADCP may be a promising tool to monitor the sediment transport. However, the H-ADCP cannot directly collect the turbidity distribution over the entire cross section and so cannot measure sediment transport. In order to realize accurate and continuous monitoring for suspended-sediment transport in rivers, we develop a new monitoring system with H-ADCP measurement and sediment-transport simulation. In the field measurement, the H-ADCP measures the lateral profile of echo intensity at a horizontal line and the echo intensity is converted to the turbidity and suspended sediment concentration (SSC). In the numerical simulation, the measured SSC at the horizontal line is interpolated and extrapolated over a cross section using a dynamic interpolation and extrapolation (DIEX) method that was recently developed by the present authors. In order to validate the fundamental performance of the present system, it is applied to evaluate the river discharge and suspended-sediment transport in the Edo River in Japan. The simulated suspended-sediment transport was compared with observed data, revealing the high performance of the present monitoring system for suspended-sediment transport.

1. Introduction

Continuous and automatic monitoring of suspended-sediment transports in rivers and coasts is indispensable for integrated watershed management [1]. In order to measure the suspended-sediment transport in rivers, we need to grasp appreciable variations in velocity and suspended solid concentration (SSC) over the entire cross section of the river. However, an appropriate technique to simultaneously monitor the spatial distribution of the velocity and SSC has not yet been reported.

One possible technique for sediment-transport measurements that might satisfy the above-described requirement is to adopt an horizontal acoustic Doppler current profiler (H-ADCP), which can measure the lateral profiles of velocity and echo intensity along a horizontal line [2], [3]. Since echo intensity is closely related to turbidity in water [4], the H-ADCP may indirectly estimate the turbidity, and hence the SSC, which is significantly correlated with the turbidity. Although turbidity measurements have been performed widely using an ADCP (e.g., [4]), which transmits acoustic signals in the vertical direction, the echo intensity of the H-ADCP has not yet been applied to turbidity measurements. Furthermore, the H-ADCP cannot directly measure the velocity and echo intensity distributions over a entire cross section, and hence cannot measure discharge and sediment transport. Therefore, for the measurements of discharge and sediment transport using the H-ADCP, it is crucial to provide a new technique which can evaluate the discharge and sediment transport from the velocity and SSC observed along a horizontal line.

We previously reported a new monitoring system of river discharge using H-ADCP measurement and river-flow simulation [3]. In the present study, in order to realize accurate and continuous monitoring for suspended-sediment transport in rivers, we attempt to develop a new real-time monitoring system with H-ADCP measurement and sediment-transport simulation. In the field measurement, the H-ADCP measures the turbidity profile along a horizontal line from the measured echo intensity, and the turbidity is then converted to the SSC using an in-situ relationship between the turbidity and the SSC. In the numerical simulation, the measured SSC along the horizontal line is interpolated and extrapolated over a cross section using a new model for sediment-transport simulation, which is based on a dynamic interpolation and extrapolation (DIEX) method recently developed by the present authors [3]. In order to validate the fundamental performance of the present system, it is used to evaluate the river discharge and suspended-sediment transport in the Edo River in Japan. The simulated suspended-sediment transport is compared with the observed data, revealing the high performance of the present monitoring system for suspended-sediment transport.

2. Outline of a New Monitoring System for Sediment Transport

2.1. *Fundamental Structure*

As shown in Fig. 1, the present system for sediment-transport monitoring combines the H-ADCP measurements of velocity and turbidity with the river-flow and sediment-transport simulations. This system is based on the discharge monitoring system with the H-ADCP measurement and numerical simulation, which was recently developed by the

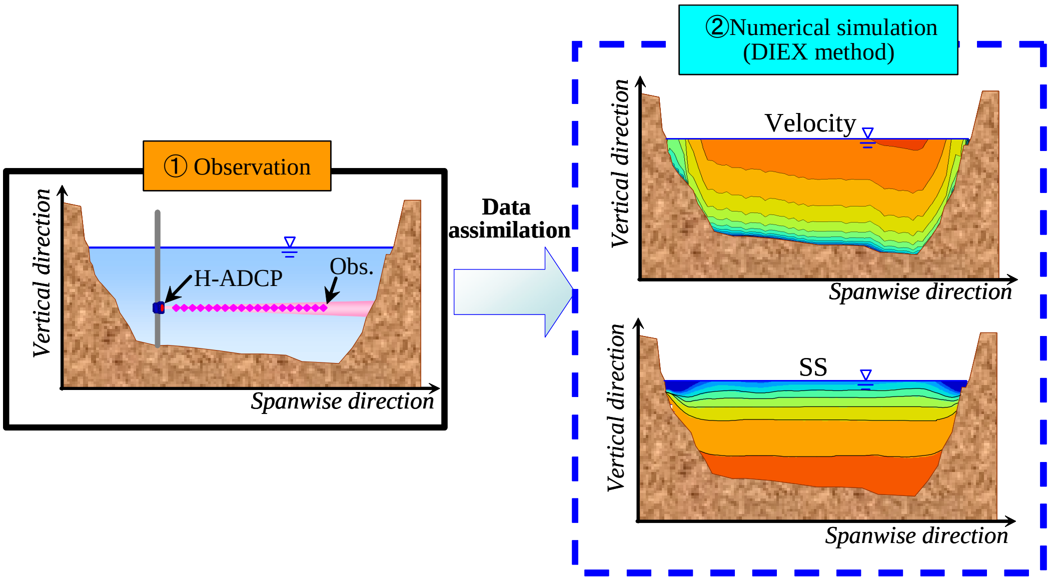


Fig. 1 Fundamental structure of the present monitoring system.

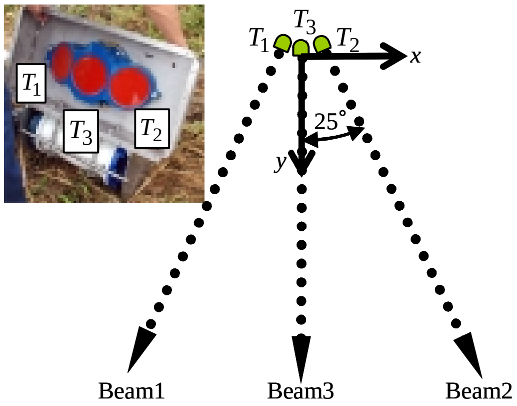


Fig. 2 Schematic view of acoustic signals of three beams from the H-ADCP.

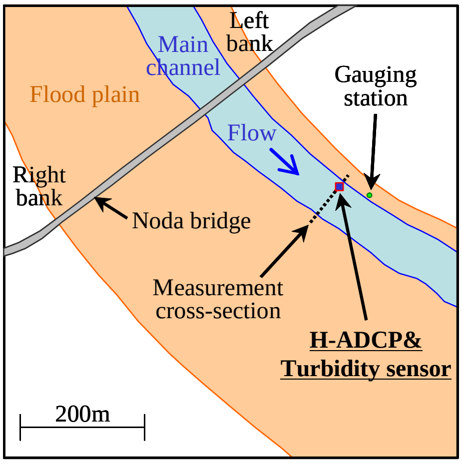
present authors [3]. Furthermore, evaluation of the turbidity and SSC from the acoustic technique is incorporated into the H-ADCP measurement. In the numerical simulations, we introduce a new model for sediment transport in which a new approach for data assimilation is incorporated in order to reflect the measured SSC. The numerical simulations indicate that the observed results at a horizontal line are interpolated and extrapolated over a cross section satisfying a dynamic principle.

2.2. *Field Measurement with the H-ADCP*

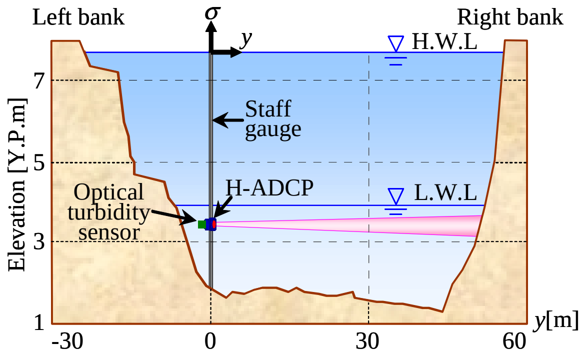
In the field measurement, an H-ADCP is mounted near the bank in a main channel, as depicted in Fig. 1, to measure the horizontal profiles of velocity and echo intensity at a fixed height. The 600-kHz H-ADCP (Teledyne RDI) used in the present study can collect the profiles of velocity and echo intensity at a horizontal range of between 70–100 meters. Since the river width in the field site of the present study is approximately 70 m, the H-ADCP may obtain the velocity profile near the opposite bank. In the H-ADCP, there are three transducers that transmit acoustic signals, as shown in Fig. 2. In the present study, the velocities are calculated using the data observed by both sides of the transducers, T_1 and T_2, and the echo intensity measured by T_3 is adopted. Absorption of the acoustic beam in water should be treated in order to accurately evaluate the turbidity from the echo intensity [5]. Since the water absorption remains unclear at this stage, the evaluation of the turbidity is conducted using the values of the echo intensity with the gradient of the echo intensity in the lateral direction. The estimated turbidity is converted to the SSC.

2.3. *Numerical Simulation with the DIEX Method*

To evaluate the river discharge and sediment transport, we perform numerical simulations into which the velocities and SSC measured using the H-ADCP are incorporated via a new data assimilation approach. We apply the recently developed DIEX method for evaluation of the river discharge into the sediment-transport simulation. The DIEX method



(a) Plane view



(b) Cross-sectional view

Fig. 3 Measurement station in the present study.

consists of the river-flow and sediment-transport simulations, as depicted in Fig. 1. In the river-flow simulation, we adopt a previously presented fundamental equation and numerical procedure to accurately evaluate the river discharge with a lower computational load [3]. To appreciably reduce the heavy computational load inherent for a general three-dimensional (3D) river-flow simulation, the simplified fundamental equation for fluid motion is adopted as

$$gI + \frac{\partial}{\partial y}\left(A_H \frac{\partial u}{\partial y} \right) + \frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(A_V \frac{\partial u}{\partial \sigma} \right) + F_{a,u} = 0\,, \tag{1}$$

where y and σ are the spanwise and vertical directions, respectively, u is velocity in the streamwise (x) direction, D is water depth, g is the gravitational acceleration, I is the slope of the water elevation, and A_H and A_V are the horizontal and vertical eddy viscosities, respectively. In the above equation, an additional term $F_{a,u}$ is introduced, which compensates for the effects of the neglected terms. The new term is determined from the measured horizontal velocities to assimilate the field data into the numerical simulation [6].

On the other hand, the fundamental equation and numerical procedure in the sediment-transport simulation are in line with the concept of the river-flow simulation described above. The fundamental equation for sediment transport is derived by simplifying terms in a general 3D sediment-transport equation, expressed as

$$-\frac{w_0}{D}\frac{\partial c}{\partial \sigma} = \frac{\partial}{\partial y}\left(A_H \frac{\partial c}{\partial y} \right) + \frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(A_V \frac{\partial c}{\partial \sigma} \right) + F_{a,c}\,, \tag{2}$$

where c denotes the SSC, and w_0 is the settling velocity of a soil particle in still water. Instead of the neglected terms in Eq. 2, we also introduce the added term for sediment-transport simulation, $F_{a,c}$, which is determined using the observed SSC. The numerical procedure in the sediment-transport simulation is composed of the following three steps:

1. The added term $F_{a,c}$ is evaluated with Eq. 2 and the measured SSC.
2. The SSCs over the entire cross section are determined using Eq. 2 and the value of $F_{a,c}$ obtained in step 1.
3. The calculation of steps 1 and 2 is repeated until the solution of Eq. 2 converges.

3. Application of the Present System to Sediment-Transport Monitoring in the Edo River

3.1. *Outlines of Field Measurement and Numerical Simulation*

To examine the fundamental performance and validity of the present monitoring system for sediment transport, we have conducted the field measurement with the H-ADCP. The field site chosen for the present study is the middle reach of the Edo River, which flows into Tokyo Bay, as shown in Fig. 3. The 600-kHz H-ADCP was mounted in the staff gauge located near the left bank of the main channel. The field measurement has been performed since June 6, 2006 until the present. In the present paper, we evaluated the river discharge and sediment transport from June 6, 2006 to June 30, 2006. During this period, a small hydrologic event occurred from June 16, 2006 to 19, 2006. For the settings of the H-ADCP, the cell size and number were 1.0 m and 80, respectively. In addition, the sampling interval was 10 minutes, and the blank distance was 2.0 m.

To examine the relationship between the echo intensity measured by the H-ADCP and the turbidity, we have conducted the turbidity measurement using an optical turbidity sensor (Compact-CLW; Alec Electronics Co., Ltd.,

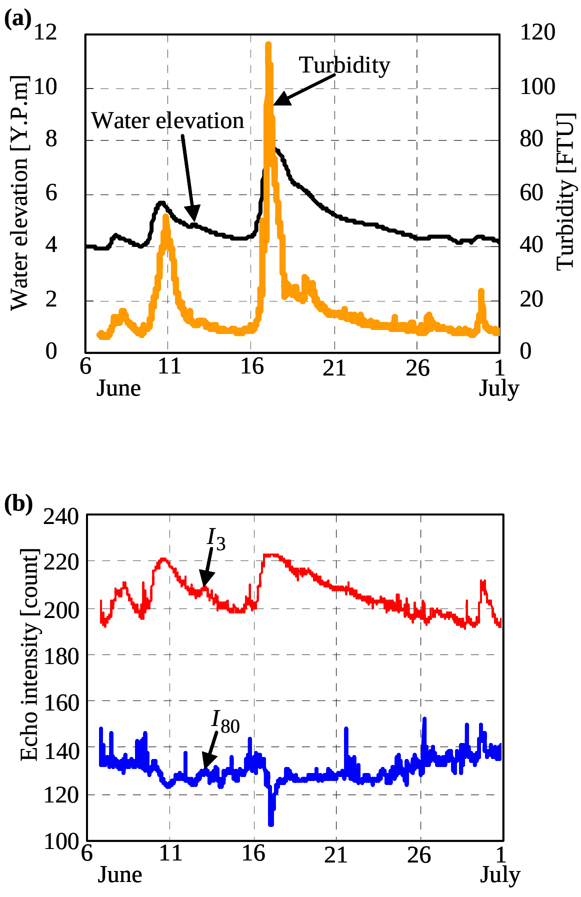


Fig. 4 Temporal variations of water elevation and optical turbidity (a) and echo intensities (b).

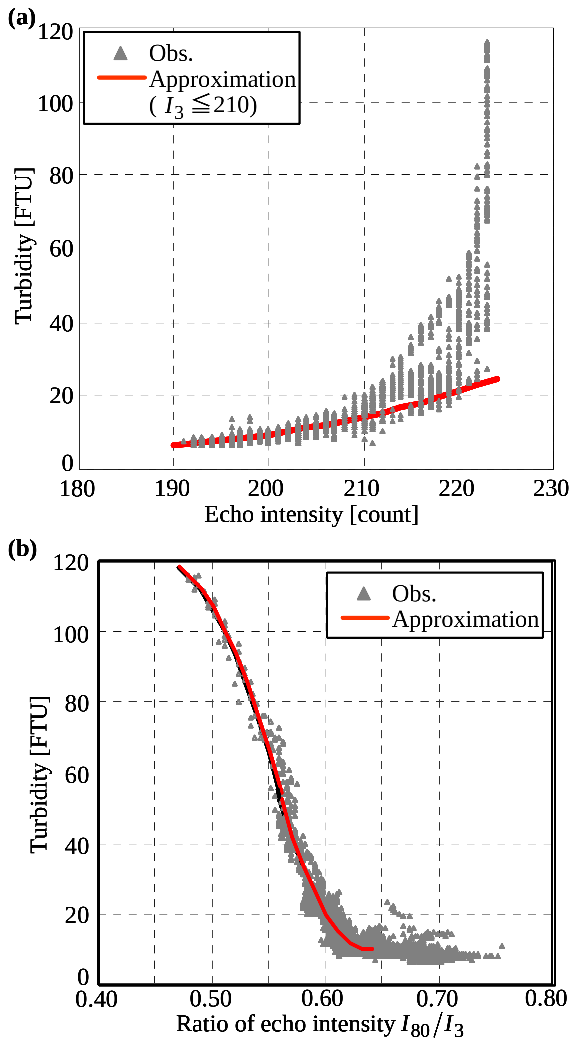


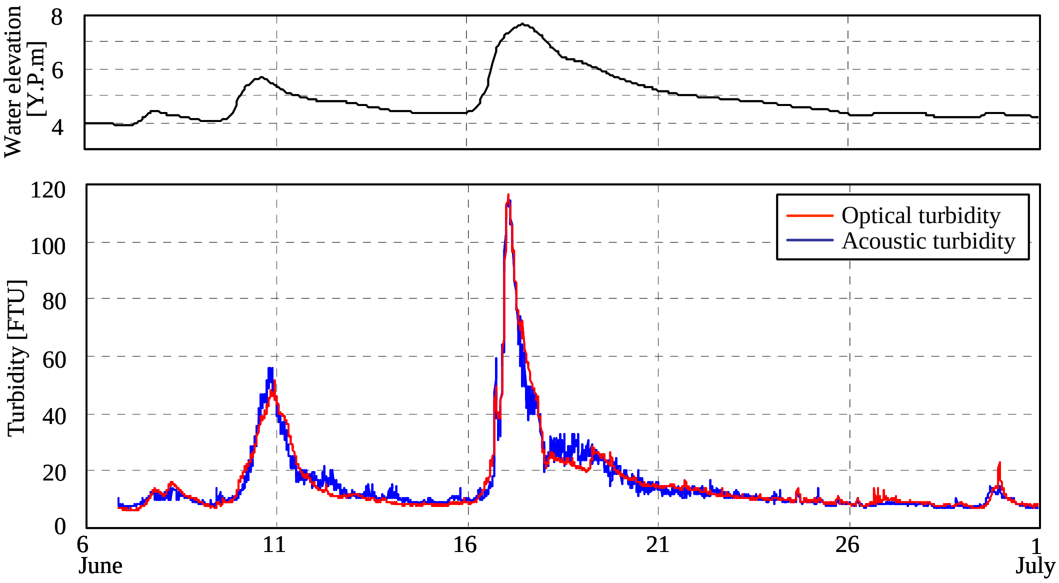
Fig. 5 Correlations between the optical turbidity and echo intensity (a) and ratio of echo intensity (b).

Japan), which was mounted near the H-ADCP shown in Fig. 3(b). An automatic water sampler (6712 full-size portable sampler; Teledyne ISCO) is installed next to the H-ADCP to collect water samples under hydrologic events. The water samples are used to analyze the SSC and particle-size distribution using a laser diffraction particle-size analyzer (SALD-3100; Shimadzu Co., Ltd., Japan). The calibration line between the turbidity and SS is $SS = 2.77Turb$, where $turb$ denotes the turbidity. The units of the turbidity and SS are FTU and mg/l, respectively. To validate the fundamental performance of the new monitoring system, a 1,200-kHz ADCP (Teledyne RDI) and a Conductivity, Temperature and Depth (CTD) sensor with the optical turbidity sensor (Compact-CTD; Alec Electronics Co., Ltd.) were used to measure the velocity and turbidity distributions at the field site under the above-described hydrologic event. From these data, we calculated the discharge and sediment transport as reference data for the present monitoring system.

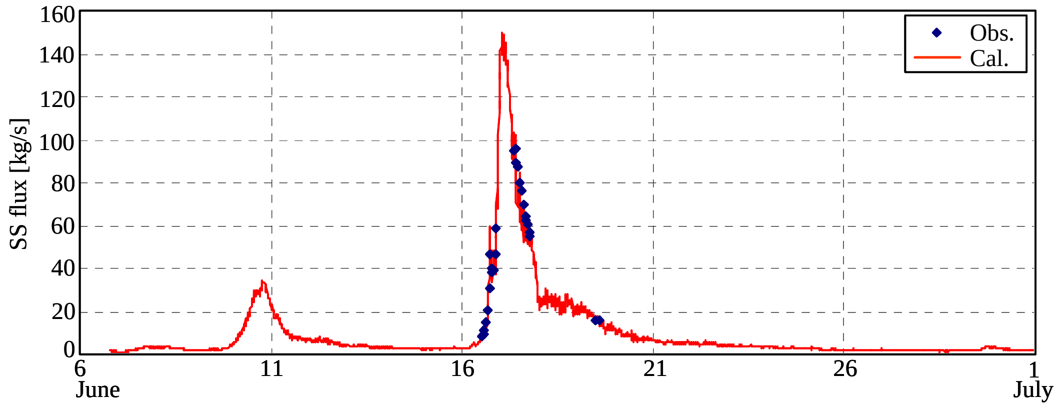
The numerical simulations with the DIEX method were performed using the observed data from June 6, 2006 to June 30, 2006 to evaluate the river discharge and sediment transport. The computational domain is the main channel of the cross section because flood during this period did not flow on the flood plain. The settling velocity of a soil particle w_0 is set at that of diameter of 10 μm and 20 μm in low- and high-flow conditions, respectively.

3.2. *Measured Results and Discussion*

To grasp the fundamental features of the echo intensity and turbidity, Fig. 4 indicates the temporal variations of water elevation, turbidity measured by the optical sensor (optical turbidity), and echo intensity. A unit of count is used for the echo intensity. To examine the echo intensities in the vicinity and far from the H-ADCP, the echo intensity in the 3rd and 80th layers, I_3 and I_{80}, in which the lateral distances from the H-ADCP are equal to 3.25 and 41.75 m, respectively, are depicted here. Although the temporal variations of the echo intensity in the 3rd layer, I_3, are similar to those of the optical turbidity in lower turbidity, the upper limitation of I_3 appears in flood conditions with higher turbidity. In contrast, the



(a) Turbidity



(b) Sediment transport

Fig. 6 Comparison of measured and calculated results.

echo intensity in the 80th layer, I_{80}, decreases when the optical turbidity increases due to the acoustic attenuation. These results indicate that the dependence of the turbidity on the echo intensity is different in the distance from the H-ADCP. To elucidate the relationship between the echo intensity and turbidity, Fig. 5(a) indicates the correlation between the optical turbidity and echo intensity in the 3rd layer I_3. The positive correlation between them is established in lower turbidity, given as

$$Turb = 0.0034 * \exp(0.0397 * I_3), \tag{4}$$

where the units of *turb* and I_3 are FTU and counts, respectively. The above correlation is obtained for values of I_3 of less than 210 counts. On the other hand, the echo intensity in higher turbidity is scattered widely, and hence it is quite difficult to evaluate the turbidity using the echo intensity in higher turbidity conditions.

Taking into account the results in Fig. 4(b), the correlation between the optical turbidity and the ratio of the echo intensities I_{80}/I_3 is depicted in Fig. 5(b). Although I_{80}/I_3 varies widely in lower turbidity conditions, good correlation between the turbidity and I_{80}/I_3 is established in higher turbidity conditions. This is because the acoustic absorption is significantly dependent on the turbidity in higher turbidity conditions. The approximations between them are expressed as

$$Turb = -5516(I_{80}/I_3)^2 + 4973(I_{80}/I_3) - 1001 \qquad \text{at } I_{80}/I_3 \leqq 0.56 \tag{5a}$$

$$Turb = 7334(I_{80}/I_3)^2 - 9333(I_{80}/I_3) + 2979 \qquad \text{at } 0.56 < I_{80}/I_3 \leqq 0.64 \tag{5b}$$

where the two approximations are obtained because a quadratic function is applied to the above correlation. From these results, in the present study, we can evaluate the turbidity using Eqs. 4 and 5 in lower and higher turbidity conditions, respectively. The estimated turbidity from the above procedure, referred to as *acoustic turbidity*, is depicted in Fig. 6(a). The optical turbidity is also shown in the figure. The result indicates that the temporal variation of the acoustic turbidity has good agreement with that of the optical turbidity.

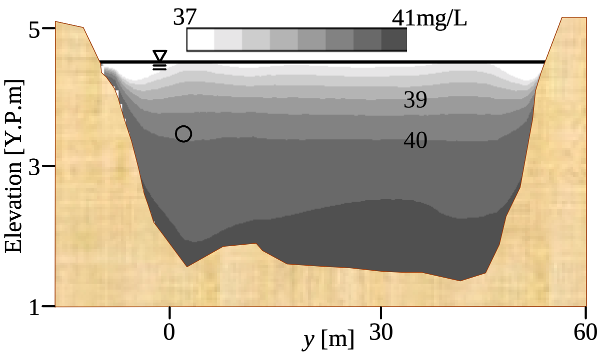


Fig. 7 Contour of the calculated SSC in the cross section at 0:00 on June 14, 2006. The circle means the measurement station used for data assimilation.

3.3. *Evaluation of sediment transport*

An example of the contour of the SSC at 0:00 on July 14, 2006, evaluated with the acoustic turbidity and the DIEX method, is shown in Fig. 7. The results reveal that the spatial pattern of the SSC varies smoothly near the measurement station, indicating that the present method can reflect rationally the measured data over the entire cross section. Figure 6(b) illustrates the temporal variations of the sediment transport evaluated in the present monitoring system. The sediment transport observed with the ADCP and CTD sensor is also depicted in the figure. The present system can evaluate the sediment transport during the entire period. Comparison of the observed and calculated sediment transports indicates that the calculated sediment transport agrees well with the observed data, demonstrating the fundamental validity of the present monitoring system for accurately and continuously evaluating the sediment transport in the river.

4. Conclusions

The main conclusions in the present study are as follows:

1) A new monitoring system is developed to realize continuous and accurate monitoring for sediment transport by H-ADCP measurement and sediment-transport simulation. The SSC measured by the H-ADCP is interpolated and extrapolated over the entire cross section of the river using the numerical simulation based on the DIEX method that was recently developed by the present authors [3].
2) The acoustic turbidity can be accurately evaluated using the echo intensity I_3 near the H-ADCP and the ratio of the echo intensities I_{80}/I_3 in lower and higher turbidity conditions, respectively.
3) We applied the present system to monitor the sediment transport in the middle reach of the Edo River. The results indicate that the calculated sediment transport agrees well with the observed results, showing the high performance of the present monitoring system for the accurate and continuous evaluation of the sediment transport.

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