A new monitoring system for river discharge with horizontal acoustic Doppler current profiler measurements and river flow simulation

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[1] A new monitoring system using horizontal acoustic Doppler current profiler (H-ADCP) measurements and river flow simulation was developed to attain accurate and continuous monitoring for river discharge at a low cost. The H-ADCP can measure the velocity profile along a horizontal line. In the numerical simulation the measured velocities were interpolated and extrapolated for a river cross section. As part of the simulation, we developed a river flow model with a new approach for data assimilation to reflect rationally measured velocities in numerical simulations. The new computational method is referred to as the dynamic interpolation and extrapolation (DIEX) method. To confirm the fundamental performance of the present system, H-ADCP measurements were performed in the middle reach of the Edo River in Japan, and the river discharge was then evaluated using the DIEX method. The calculated velocity and discharge were compared with the results measured using an ADCP and a Price current meter. The vertical and lateral distributions of the calculated velocities are in good agreement with the measured results. The discharge calculated by the DIEX method is in good agreement with the observed data. The root mean squares of the relative error for the calculated discharge is 4.9%, showing that the accuracy of the DIEX method is the same as the conventional method using point sensors such as a Price current meter. The present monitoring system achieves accurate, automatic, and continuous monitoring of river discharge at a lower cost than direct measurement methods for discharge.


1. Introduction

[2] River discharge has been widely applied to hydrology and river engineering as well as limnology, oceanography, and other aquatic sciences. The performance of automatic, continuous and accurate river discharge evaluations under various flow conditions, including drought and flood conditions, is vital.

[3] Continuous and automatic monitoring of river discharge is often performed in an indirect approach that calculates discharge at all stream stages on the basis of the stage-discharge relationship or rating curve. Direct measurements of discharge used to develop the rating curve are made using a wide variety of current sensors including propellers, electromagnetic sensors, floats, image processing techniques, radio current meters and an acoustic Doppler current profiler (ADCP) [Rantz, 1982; Fujita et al., 1998; Oberg et al., 2005; Plant et al., 2005]. The direct measurements using current sensors are unreliable and unsafe under some flow conditions such as large floods [Costa et al., 2006]. In addition, the accuracy of the indirect approach on the basis of rating curves is generally less than that of the direct measurements, especially during floods in which the unique relationship between the discharge and water stage cannot always be obtained. The rating curve cannot be applied to the evaluation of discharge in tidal or backwater reaches of rivers.

[4] The accuracy and applicability issues of the indirect approach on the basis of the stage-discharge relationships may be avoided by utilizing flow measurements from the current sensors that can continuously measure stream velocity. Among existing sensors, a horizontal acoustic Doppler current profiler (H-ADCP), which measures the horizontal velocity profile across a channel [Wang and Huang, 2005], is one of the promising tools for continuous discharge measurements. This instrument transmits acoustic signals in a horizontal line and receives the signals reflected by suspended matter such as sediment. Then, the measured Doppler effects are used to calculate the water velocity. Although an H-ADCP used for flow monitoring collects a velocity profile along a horizontal line, it cannot measure the velocity distribution over the whole cross section directly, and, cannot determine the discharge. The H-ADCP data may also be adopted in an index-velocity method in which the discharge is evaluated by the relationship between the measured velocity and cross-sectional mean

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velocity [Ruhl and Simpson, 2005]. However, the unique relationship between the above velocities may not be obtained under flooding conditions. The issue in the index-
velocity method is similar to that in the indirect method on the basis of the stage-discharge relationship.

To resolve this issue, Daitoh et al. [2001] developed an automatic scanning system for an H-ADCP that can change the vertical position of the H-ADCP, collecting stream velocity data in the whole cross section. This system has already been applied to discharge measurement in several rivers in Japan. However, the system is very large and expensive and has not been widely used. Another approach to calculate the discharge using the horizontal velocity distribution measured by the H-ADCP is to simply interpolate and extrapolate the horizontal velocity profile over the whole cross section on the basis of the power law [Wang and Huang, 2005]. However, the above simple interpolation and extrapolation operations for the measured horizontal velocity cannot satisfy the dynamic principle for fluid motion, and hence the accuracy of this approach decreases markedly [Nihei and Kimizu, 2006].

The current promising method is to perform a river flow simulation by assimilating the H-ADCP field data to evaluate river discharge from the horizontal velocity profile at a lower cost. Although the data assimilations are widely adopted in meteorology and oceanography [Lorenc, 1986; Robinson et al., 1997], few assimilations of river flow data have been conducted [Sutzer et al., 2002]. However, the authors have recently developed a river flow model incorporating a new assimilated method, called the dynamic interpolation method, in which observed results for velocities are taken into account for river flow computations [Nihei and Kimizu, 2006]. Previously, we reported the fundamental applicability of the dynamic interpolation method to the evaluation of river discharge using depth-averaged velocities measured at discrete points in a cross section. It is therefore expected that this dynamic interpolation method can accurately interpolate and extrapolate the horizontal velocity profile measured by the H-ADCP over the whole cross section on the basis of a reliable physical background description.

In the present study, we designed an accurate, automatic and inexpensive monitoring system of river discharge with H-ADCP measurements and river flow simulation. In the field, the rigidly mounted H-ADCP measured the horizontal velocity profile at a fixed height. For the river flow simulation, the measured velocities across a horizontal line were interpolated and extrapolated over a cross section on the basis of a reliable physical background description. For this purpose, we developed a new river flow model with an assimilated technique that is based upon the dynamic interpolation method presented previously by the authors [Nihei and Kimizu, 2006]. The present computational method is referred to here as the dynamic interpolation and extrapolation (DIEX) method. To confirm the fundamental performance of the new discharge monitoring system, H-ADCP measurements were conducted in the middle reaches of the Edo River, Japan and the river discharge was evaluated using the present computational methods. The calculated velocity and discharge were compared with results measured by an ADCP and a Price current meter.

2. Outline of the New Discharge-Monitoring System

2.1. H-ADCP

The ADCP, which can measure simultaneous vertical velocity distributions, is the most commonly used among the acoustic Doppler instruments. In previous studies, the ADCP successfully measured ocean velocity structures [e.g., Pinkel, 1979; Pettigrew et al., 1986], and river flow structures [Gordon, 1989; Lipscomb, 1995; Mueller, 2002; Oberg et al., 2005]. Further developments in ADCP technology produced the H-ADCP, which can transmit and receive acoustic signals horizontally and can then generate a horizontal velocity profile [e.g., Wang and Huang, 2005].

Depending on the transducer, the H-ADCP emits 300, 600 or 1200 kHz acoustic frequencies. Under normal conditions, the profiling ranges of 300, 600 and 1200 kHz H-ADCPs are approximately 300, 100 and 20 m, respectively. In the present study, we used the 600 kHz H-ADCP with a 3-beam head (Workhorse 600 kHz, Teledyne RDI) to accommodate the 70 m river width at the field site (Figure 1). Minimum cell size and the maximum number of cells in the H-ADCP are 0.25 m and 128, respectively. The H-ADCP can typically measure flow velocity up to 10 m/s.

Figure 2 illustrates a schematic view of the velocity measurement by the H-ADCP with three transducers, named T1, T2 and T3. The H-ADCP was mounted horizontally to measure the velocity profile at a fixed height. The three transducers transmitted acoustic beams in different directions to obtain radial velocities V1, V2 and V3, where subscripts 1–3 refer to the transducers T1–T3 (Figure 2a). The velocity vectors in a horizontally two-dimensional flow were calculated using V1 and V2, as follows [Lemmin and Rolland, 1997]

\[
\begin{align*}
    u &= \frac{V_1 - V_2}{2 \sin \theta_H}, \\
    v &= -\frac{V_1 - V_2}{2 \cos \theta_H},
\end{align*}
\]

where u and v are the streamwise and spanwise velocities, respectively, and \( \theta_H \) is the internal angle between beam 1 (or beam 2) and beam 3, as shown in Figure 2a. The above equations are based on the assumption that the velocity vectors of suspended matter S1 along the acoustic beam from T1 correspond to that of the S2 along the beam from T2, in which the distances of S1 and S2 from the H-ADCP are identical. It is unclear whether the assumption is valid at a larger distance from the H-ADCP where the distance between S1 and S2 also becomes larger. The width of the transmitted acoustic beam expands with the distance from the transducer, \( \gamma \), and its angle \( \theta_L \) is about 1 degree for the 600 kHz H-ADCP used in the present study. The vertical range of the measurement therefore increases with the distance \( \gamma \). When the range includes the water surface or the
bottom boundary, the measured data contains significant errors.

2.2. Fundamental Structure

[11] The new monitoring system for river discharge consists of two combined subsystems, as shown in Figure 3. One system is the field observations for the horizontal velocity profile by using H-ADCP, and the other is numerical simulations, in which the observed velocities at a horizontal line are interpolated and extrapolated over a cross section with the DIEX method.

[12] For the field measurements, the H-ADCP is mounted near the bank in the main channel, as depicted in Figure 3, to measure the horizontal velocity profile at a fixed height. The numerical simulations compute the velocity distribution over the whole section, interpolating and extrapolating the measured horizontal velocity profile by applying dynamic principles and evaluating discharge. To attain real-time discharge monitoring under the new system, a telemetry system transmits the horizontal velocities measured by the H-ADCP. Because the velocity measured by the H-ADCP is limited at a fixed height, the present system is an indirect approach for discharge measurement.

3. Outline of the DIEX Method

3.1. Fundamental Concept

[13] We performed the river flow simulation to evaluate the river discharge from the measured horizontal velocity profile. The numerical model adopted here included (1) a new data assimilation approach that incorporated the measured velocities into the numerical simulation, and (2) an effective algorithm that required less CPU time and less memory to perform real-time discharge monitoring. We selected the necessary terms in a 3-D momentum equation for discharge evaluation and simplified the momentum equation to reduce the heavy computational load inherent in 3-D computations. In addition, one of the general methods used for data assimilation is a nudging scheme that allowed the measured data to replace the velocity calculated by the numerical simulations [Anthes, 1974]. However, the numerical accuracy of the nudging scheme with fewer measured data may be appreciably lower [Robinson et al., 1998]. Consequently, the development of a new method for data assimilation in river flow simulations is critical for an accurate evaluation of discharge using measured velocity.

[14] A new data assimilation technique, previously presented by the authors [Nihei and Kimizu, 2006], is the dynamic interpolation method which is based on the data assimilation method using a simplified momentum equation for computational efficiency. The dynamic interpolation method completes the lateral interpolation of the depth-averaged velocities measured at discrete points in the cross section and then evaluates the river discharge. An additional term representing the measured data in the numerical simulation was introduced into the simplified momentum equation. Previously, we demonstrated the fundamental performance of the dynamic interpolation method through a test case using simulation data for a river flow computation [Nihei and Kimizu, 2006]. However, although the dynamic interpolation method evaluates the lateral distribution of the depth-averaged velocity, it cannot calculate the vertical velocity distribution. Furthermore, the measured data generally contain errors that become assimilated into the numerical simulation in the dynamic interpolation method. Consequently, it is difficult to use the dynamic interpolation method as the numerical model of the present discharge monitoring system.

[15] We therefore introduced a numerical method that resolves the shortcomings of the dynamic interpolation method. A simplified three-dimensional momentum equa-
tion was adopted and an additional term was also introduced into the simplified momentum equation. In addition, to resolve the issue of the measurement errors, a numerical procedure that minimizes the velocity measurement errors obtained by the H-ADCP was incorporated. As a result, the numerical procedure interpolated and extrapolated the line velocity measured by the H-ADCP over the entire cross section and accurately evaluated the discharge. This numerical method is referred to as the DIEX method, to distinguish it from the dynamic interpolation method. The fundamental equation and numerical procedures of the DIEX method are outlined below.

3.2. Fundamental Equation

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = gI + \frac{\partial}{\partial y} \left( A_H \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( A_V \frac{\partial u}{\partial z} \right) + \frac{1}{D^2 \frac{\partial}{\partial \sigma} \left( A_V \frac{\partial u}{\partial \sigma} \right)}, \]  

(2)

where \( t \) is time, \( u, v \) and \( w \) are velocities in the \( x, y \) and \( z \) directions, respectively, \( D \) 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. The definition of the \( \sigma \) coordinate using a relative depth is expressed as

\[ \sigma = \frac{z - \eta}{D}, \]  

(3)

where \( z \) represents the vertical coordinate and \( \eta \) is water elevation. The diffusion terms on the right-hand side of equation (2) omit the cross terms derived in the transformation from the Cartesian to the \( \sigma \) coordinates in accordance with Blumberg and Mellor [1983].

\[ \text{[17]} \] The advection and diffusion terms in equation (2) are difficult to estimate using only a horizontal velocity profile at a fixed height. Therefore, the simplified momentum equation, from which these terms are omitted, is given as

\[ gI + \frac{\partial}{\partial y} \left( A_H \frac{\partial u}{\partial y} \right) + \frac{1}{D^2 \frac{\partial}{\partial \sigma} \left( A_V \frac{\partial u}{\partial \sigma} \right)} = 0. \]  

(4)

We omitted the advection terms and diffusion term in the \( x \) direction as well as the unsteady term, which is much smaller than the other terms in equation (4) such as \( gI \). To replace the omitted terms, we introduced an additional term \( F_a \) in accordance with the dynamic interpolation method, expressed as

\[ gI + \frac{\partial}{\partial y} \left( A_H \frac{\partial u}{\partial y} \right) + \frac{1}{D^2 \frac{\partial}{\partial \sigma} \left( A_V \frac{\partial u}{\partial \sigma} \right)} + F_a = 0, \]  

(5)

where the additional term \( F_a \) compensates for the effects of the omitted terms in equation (4), and is determined from the measured velocities to assimilate the field data into the numerical simulation. In the river flow simulation on the basis of the DIEX method, we adopt equation (5) as the fundamental equation.
To solve equation (5), we need a turbulence model to give the horizontal and vertical eddy viscosities. The vertical eddy viscosity $A_V$ involved in equation (5) is given as a zero-equation turbulence model,

$$A_V = \kappa U_a z^* \left(1 - \frac{z^*}{D}\right),$$

(6)

where $\kappa$ is the Karman constant ($= 0.41$), $U_a$ is a friction velocity and $z^*$ is the height from the riverbed. The horizontal eddy viscosity $A_H$ is modeled to be proportional to the vertical eddy viscosity, i.e.,

$$A_H = \beta A_V,$$

(7)

where $\beta$ is the constant that describes the effect of anisotropy turbulence generally occurring in river flows and is set to be $1 - 10$ [Nihei et al., 2007]. Although we choose the zero-equation turbulence model in the present paper for simplicity, we shall improve the turbulence model in the near future for further progress of the DIEX method.

### 3.3. Evaluation of the Additional Term $F_a$

In solving equation (5), we incorporated the horizontal velocities measured by the H-ADCP as assimilated data. As mentioned above, calculating the additional term $F_a$ from the measured velocities is an assimilation procedure in the DIEX method. However, it is difficult to calculate the additional term $F_a$ using equation (5) because the field measurements only provide measured velocities at a fixed height. The calculation of equation (5) requires the evaluation of the vertical profile of the additional term, which depends markedly on the treatment of the boundary conditions at the water surface and on the riverbed, complicating the determination of the vertical distribution of $F_a$. Assuming in the present method that the vertical profile of $F_a$ is uniform, the depth-averaged additional term $F_a$ is based on the depth-averaged momentum equation derived from equation (5), expressed as

$$gl + \frac{\partial}{\partial y} \left( \frac{\overline{A_H} \partial \overline{p}}{\partial y} \right) - \frac{C_f}{D} \overline{u}^2 + F_a = 0,$$

(8)

where $\overline{u}$ is the depth-averaged streamwise velocity and $\overline{A_H}$ and $C_f$ are the depth-averaged horizontal eddy viscosity and coefficient of bottom friction, respectively. $\overline{A_H}$ and $C_f$ in equation (8) are given as

$$\overline{A_H} = \beta \kappa U_a \frac{D}{6},$$

(9a)

$$C_f = \frac{g n^2}{D^{1/2}},$$

(9b)

where $n$ is the Manning’s roughness coefficient. Although the validity for the assumption of the uniform distribution of $F_a$ in the vertical should be confirmed, this validation requires the collection of horizontal velocity distributions at several heights, for which field measurements have not been conducted. In a future study, we plan to measure horizontal velocity distributions using several H-ADCPs and evaluate directly the horizontal and vertical distributions of $F_a$. When we calculated the depth-averaged additional term $F_a$ at each observational point, the lateral distributions of calculated $F_a$ and horizontal velocity were scattered owing to errors in the measured horizontal velocity, as shown in Figure 5a. As a more accurate method for data assimilation, the DIEX method introduced a numerical procedure that minimized the measuring errors for velocity obtained by the H-ADCP, and satisfied the momentum equation. The measuring errors are primarily caused by instrument noise and flow uncertainty mainly owing to turbulence. To reduce the scattering of the lateral distribution of $F_a$ owing to measuring errors, as illustrated in Figure 5b, we minimized the measuring errors using an approximation for $F_a$ evaluated at each observational point. Using the least squares method, we obtained a cubic expression as the approximation. The resulting assimilated approach was expected to be able to accurately convert the line velocity into the cross-sectional velocity using the appropriate interpolation and extrapolation on the basis of fluid dynamics.

### 3.4. Finite Difference Scheme

The current study adopted a finite difference solution to obtain the solution of the velocity $u$ using equation (5). The DIEX method used a collocation grid in which the variables were located in the center of each grid. Using a second-order central difference scheme for the horizontal and vertical diffusion terms in equation (5), the finite difference equation is given as

$$A_{H,i+j/2}(u_{i+j/2} - u_{i,j}) - A_{H,j+i/2}(u_{i,j} - u_{i-1,j}) = \frac{(\Delta y)^2}{g l + F_a}$$

$$+ A_{V,j+i/2}(u_{i,j+1} - u_{i,j}) + A_{V,j+i/2}(u_{i,j} - u_{i,j-1})$$

$$+ \frac{(D_i \Delta \sigma)^2}{g l + F_a} = 0$$

(10)

where the subscripts $i$ and $j$ refer to the grid number in the lateral and vertical directions, respectively, and $\Delta y$ and $\Delta \sigma$ are the grid intervals in the lateral and vertical directions, respectively. The gradient of water elevation $I$ is assumed to be uniform in the lateral direction. The horizontal and vertical eddy viscosities in the above equation are expressed as

$$A_{H,i+j/2} = \frac{A_{H,i} + A_{H,i+1}}{2},$$

(11a)

$$A_{V,j+i/2} = \frac{A_{V,j} + A_{V,j+1}}{2}.$$  

(11b)

In accordance with equation (10), the finite difference equation for the depth-averaged momentum equation represented in equation (8) is also given as

$$gl + \frac{\overline{A_{H,i+j/2}}(\overline{u}_{i,j} - \overline{u}_{i+1,j}) - \overline{A_{H,i-1+j/2}}(\overline{u}_{i,j} - \overline{u}_{i-1,j})}{(\Delta y)^2}$$

$$- \frac{C_f}{D_i} \overline{u}_{i,j}^2 + F_a = 0.$$ 

(12)
Although we assumed a uniform profile of $F_a$ in the vertical direction (i.e., $F_a = F_a^0$), $F_a$ and $F_a^0$ are separately described in equations (10) and (12), respectively. To calculate $F_a^i$ from equation (12), we employed the data assimilation method by introducing the measured velocity at grid $i$, $u_{oi}$, into equation (12), given as

$$F_a^i = \frac{C_f}{D_y} u_{oi}^2$$

(13)

where the measured data are provided only for grid $i$. In the case that there are measured data for the neighboring grids, $i - 1$ and $i + 1$, these measured data are substituted into equation (13).

### 3.5. Initial and Boundary Conditions

[23] To impose the initial conditions of the streamwise velocity, we determined the vertical distribution of the velocity from the measured velocity at a fixed height. The logarithmic velocity profile was shown in natural flood flows through ADCP measurements [e.g., Nihei and Sakai, 2007]. The initial conditions of velocity were given using this logarithmic profile, expressed as

$$\frac{u}{U_*} = \frac{1}{\kappa} \ln \frac{z}{z_0} + A_r,$$

(14)

where $A_r$ is a universal constant ($= 8.5$) and $k_s$ is the equivalent roughness parameter, which is related to Manning’s roughness coefficient, $n$, given as

$$k_s = \left( \frac{n}{0.0417} \right)^6$$

(15)

We substituted the measured velocity $u_{oi}$ and its measuring height from the riverbed $z_{oi}$ into equation (14), and then calculated the friction velocity $U_*$. Using the friction velocity and equation (14), we finally obtained the vertical velocity profile and the depth-averaged velocity $\overline{u_{oi}}$. At lateral positions without measured velocity, the depth-averaged velocity $\overline{u_{oi}}$ was interpolated in the lateral direction and the vertical velocity profile was given by the logarithmic profile expressed in equation (14) and the interpolated $\overline{u_{oi}}$. We imposed the initial condition of the streamwise velocity throughout these procedures.

[24] To simplify the boundary conditions, we set a no-slip condition at the side and bottom boundaries, and employed a slip-wall condition at the surface boundary.

### 3.6. Sequential Procedures

[25] We summarized the sequential procedures of the DIEX method, which is composed of establishing the initial condition and performing the main calculation, and are illustrated in Figure 6. Establishing the initial conditions and the main conclusions are steps 1–3 and 4–9, respectively.

[26] 1. The depth-averaged velocity $\overline{u_{oi}}$ at grid $i$ corresponding to an observational point was calculated from the measured velocity $u_{oi}$ and the logarithmic profile expressed in equation (14).

[27] 2. The depth-averaged velocity $\overline{u_{oi}}$ was interpolated and extrapolated in the lateral direction and the lateral distribution of the depth-averaged velocity $\overline{u_{oi}}$ was obtained.

[28] 3. The vertical velocity profile was calculated from the $\overline{u_{oi}}$ obtained in step 2 using the logarithmic profile, and the velocity $u_{ij}$ at grid $(i,j)$ as the initial condition was imposed.

[29] 4. The depth-averaged velocity $\overline{u_{oi}}$ or $\overline{u_{oi}}$ was calculated through the averaging operation of $u_{ij}$ in the vertical direction.

[30] 5. $\overline{F_{ai}}$ at grid $i$ corresponding to an observational point was evaluated by substituting velocities $\overline{u_{i}}$ and $\overline{u_{oi}}$ obtained in step 4 into equation (13).

[31] 6. The lateral distribution of $\overline{F_{ai}}$ in the cross section was determined from the approximation obtained by the least squares method for $\overline{F_{ai}}$ evaluated in step 5.

Figure 5. Lateral profiles of the additional term $F_a$ evaluated with and without measuring errors for the velocity obtained by the H-ADCP.

Although we assumed a uniform profile of $F_a$ in the vertical direction (i.e., $F_a = F_a^0$), $F_a$ and $F_a^0$ are separately described in equations (10) and (12), respectively. To calculate $F_a^0$ from equation (12), we employed the data assimilation method by introducing the measured velocity at grid $i$, $u_{oi}$, into equation (12), given as

$$F_a^0 = -gL + \frac{C_f}{D_y} u_{oi}^2$$

$$= \frac{\overline{A_{i+1/2}(u_{oi} - u_{oi})} - \overline{A_{i-1/2}(u_{oi} - u_{oi})}}{(\Delta y)^2},$$

where the measured data are provided only for grid $i$. In the case that there are measured data for the neighboring grids, $i - 1$ and $i + 1$, these measured data are substituted into equation (13).
7. The velocity in the streamwise direction $u_{i,j}$ was calculated using equation (10) and the value of $\bar{F_{ai}}$ obtained in step 6.

8. The calculation of steps 4–7 was repeated until the solutions for velocity $u_{i,j}$ and the additional term $\bar{F_{ai}}$ converge.

9. The discharge value was determined through the integration of $u_{i,j}$ over the cross section after the convergence of the numerical solution in the above steps.

The DIEX method developed in the present study used the simplified momentum equation as the fundamental equation and the simple sequential procedure described above. Consequently, the computational load of the DIEX method is expected to be markedly less than that of traditional three-dimensional river flow models.

4. Field Tests of the Present Monitoring System

4.1. Field Site

[36] We conducted continuous monitoring of river discharge using the present system to evaluate fundamental system performance and its accuracy as a discharge monitoring system. The field site selected in the current study was the middle reach of the Edo River, which diverges from the Tone River and flows into Tokyo Bay. As depicted in Figure 7, the measurement point is near the Noda gauging station, located 39 km upstream from the river mouth. The main channel is weakly curved at the measurement point. Figure 8a shows a cross-sectional view of the field site. The Edo River has a compound cross section with a total floodplain and channel width of 400 m and a main channel width of 70 m.

4.2. Field Measurements

4.2.1. Outline of the H-ADCP Measurements

[37] H-ADCP measurements were conducted during two observational periods, from 5 September to 6 December 2005, and from 6 June to 16 July 2006, hereafter referred to as periods 1 and 2, respectively. The diagram of the high water level (HWL) and low water level (LWL) during the monitoring periods is depicted in Figure 8a. Although the floodplain was wet at the time of HWL, there were no dominant currents on the floodplain. We mounted a 600 kHz H-ADCP onto the staff gauge located near the left bank of the main channel. The height of the mounted H-ADCP was 3.4 m above Y. P. (Yedogawa Peil) 0 m, which is the base level in the Edo River. The measuring height was lower than

![Figure 6. Sequential procedures of the DIEX method.](image)

![Figure 7. Map of the study site on the Edo River, Japan.](image)
the ground level of the floodplains and the measurements were limited to the main channel, as depicted in Figure 8a. In addition, point \( y = 0 \) m in Figure 8a corresponds to the location of the H-ADCP transducer. The angle of the transmitted acoustic beam \( \theta_v \) is approximately 1 degree in the 600 kHz H-ADCP as described above, resulting in an acoustic beam vertical width of approximately 0.8 m near the opposite bank. The H-ADCP emitted three acoustic signals into the water column, as depicted in Figure 8b, and two of the three signals, beam 1 and beam 2, were used to calculate the streamwise and spanwise velocities. As shown in Figure 9, the H-ADCP was mounted with slight horizontal rotation owing to the direction of the staff gauge with the H-ADCP. Therefore, the distance from the H-ADCP to the opposite bank in beam 1 was larger than that in beam 2.

The H-ADCP was set at a 10-min sampling interval, the blank distance was 1.0 m, and the cell size and number of cells were 1.0 m and 80, respectively. At each interval, 100 samples were averaged to obtain the velocities. Under these conditions, the instrument noise was about 1 cm/s. To sustain real-time monitoring of river discharge, the H-ADCP was connected to a telemetry system (Watch-ADCP Jr, Hydro System Develop, Inc.), which transmitted the H-ADCP data at a constant interval via email.

**4.2.2. Measurements for Validation of the Present System**

We confirmed the fundamental performance and measuring accuracy of the present monitoring system using the velocity distributions and discharge measured by two different direct methods. The first was an ADCP (Workhorse 1200 kHz, Teledyne RDI), which measured the velocity distribution and discharge. At the time of conducting field measurements, we set a downward looking ADCP near the water surface. In the discharge measurements, the ADCP was transected across the channel. Data from two transects were averaged to obtain a mean discharge. These transects were completed by the authors under low- and high-flow conditions. For the velocity measurements, the ADCP was fixed at each observational point in the cross section for one minute, and then we moved the ADCP to the next observational point. We obtained the velocities averaged over a minute. Discharge measurements obtained by the ADCP were previously reported to be accurate [e.g., Gordon, 1989; Oberg et al., 2005].

We also compared the discharge data measured by a Price current meter, a conventional point-velocity sensor, with the present monitoring system. The Edogawa River Office of the Ministry of Land, Infrastructure and Transport, Japan, conducted the field measurements three times per month only under low-flow conditions in the field.
measurements using the Price current meter, a two-point method was utilized to sample the river discharge, except in the shallower regions where a one-point method was applied. The velocity measurements were conducted at eight vertical lines in the cross section.

4.2.3. Results of the H-ADCP Measurements

Figure 10 shows the temporal sequences of the water elevation and the lateral distributions of the streamwise velocity at the field site during period 1. Temporal variation in the streamwise velocity was somewhat similar to that of the water elevation. The velocity near the right bank was higher than near the left bank owing to the curved geometry of the main channel. Note that there was no missing velocity data from the H-ADCP during period 1 and period 2 (not shown).

To check the accuracy of the velocity measured by the H-ADCP, the present study compared the lateral distributions of the streamwise velocity obtained with the H-ADCP and ADCP on 13 October 2005, illustrated in Figure 11. The ADCP-measured velocity depicted in the figure was averaged vertically over the measuring range of the H-ADCP, which increased with the distance from the H-ADCP. These results in the figure were obtained at the measuring height of the H-ADCP. The result indicated that appreciable differences in the overall pattern of the streamwise velocity between the ADCP and H-ADCP were not detected, and the bias of the velocities between ADCP and H-ADCP was 2.0–4.0 cm/s. Note that the ADCP data was slightly higher than the H-ADCP data at \( y > 36 \) m near the right bank of the main channel. We also confirmed this discrepancy in other observed results. The reason for this discrepancy is the horizontal rotation of the H-ADCP, as mentioned above, which leads to the invalidation of the assumption that the velocities of the suspended matter on beam 1 and beam 2, \( u \) and \( v \), agree precisely near the opposite bank. In contrast, the velocity measured by the H-ADCP at \( y = 1 \) m was lower near the gauge owing to the fluid drag of the staff gauge. These observations suggest that the installation of the H-ADCP affected the velocity measured by the H-ADCP, resulting in certain errors and necessitating the careful selection of H-ADCP data for the evaluation of the discharge.

4.3. Computational Conditions

The horizontal velocities measured by the H-ADCP were adopted to determine the discharge using the DIEX method. The computational domain was the main channel

![Figure 10](image1.png)  
**Figure 10.** Time sequences of (a) the water elevations and (b) the lateral profile of the streamwise velocity in period 1 (the number on the lower diagram indicates the velocity on each contour line).

![Figure 11](image2.png)  
**Figure 11.** Comparison of the lateral distributions of the streamwise velocities measured by the ADCP and H-ADCP at the measuring height of the H-ADCP.
of the cross section, since a flood flow did not occur on the floodplains, as mentioned above. Table 1 displays the detailed computational conditions. The grid numbers in the lateral and vertical directions are 73 and 100, respectively. The grid interval is 1.0 m in the lateral direction. We regarded case A-1 as a reference case and, in the other cases, changed the values of various numerical parameters, such as \( n \), \( b \) and \( Y_{\text{max}} \), which is the range of data assimilation. In the present study, to remove the influence of the staff gauge, we assimilated the H-ADCP data for \( 2 \text{ m} / C_20 \) as shown in Figure 8a. When the acoustic beam passes through the water surface or bottom, the measurement accuracy decreases significantly. To avoid this situation, we calculate the lateral distance, \( Y_s \), that the acoustic beam passes through the water surface. If the distance \( Y_s \) is smaller than the range of the data assimilation \( Y_{\text{max}} \), \( Y_{\text{max}} \) is set to be \( Y_s \).

In case A-1, parameters \( n \), \( b \) and \( Y_{\text{max}} \) are selected to be \( n = 0.035 \text{ m}^{-1/3} \text{ s} \), \( b = 1 \) and \( Y_{\text{max}} = 36 \). On the basis of the lower accuracy of the H-ADCP measurements near the opposite bank as discussed above, we assigned \( Y_{\text{max}} = 36 \). The Manning’s roughness coefficient \( n \) was selected in accordance with the river flow simulation for the Edo River [Nihei et al., 2007]. The influence of the above parameters on the discharge evaluation of the DIEX method was examined by assigning varying values to \( n \), \( b \) and \( Y_{\text{max}} \) for case A-2, case A-3 and case A-4, respectively. To evaluate the water elevation gradient \( I \) in equation (5), we used the data measured at the Noda gauging station and at Gyokuyou, located 39 km and 35 km upstream from the river mouth, respectively.

The procedures simply conducting the interpolation and extrapolation of the velocity measured by the H-ADCP without satisfying the dynamic principles were proposed by Wang and Huang [2005], based upon which the vertical velocity profile is given by the power law,

\[
u = az^b,
\]

where \( b \) is given as \( b = 1/6 \) in accordance with Chen [1991]. This method was also evaluated for comparison and is referred to as the simplified method. Coefficient \( a \) in equation (16) varies in the lateral direction. Within the measuring range \( (2 \text{ m} \leq y \leq Y_{\text{max}}) \), we calculated coefficient \( a \) by substituting measured velocity \( u_o \) and its measuring height \( z_o \) into equation (16), expressed as

\[
a = \frac{u_o}{z_o^{b}}.
\]

For the remaining lateral position, we evaluated coefficient \( a \) using a linear interpolation. In the simplified method, the grid number and interval correspond with those in the DIEX method, and values of \( Y_{\text{max}} \) varying from 10 to 46 m are given. The computational condition in the simplified method is referred to here as case B.

### 4.4. Computational Results and Discussion

#### 4.4.1. CPU Time

The computational load of the DIEX method was calculated to reflect the CPU time needed for each computational step of the DIEX method. When we used a personal computer with a 2.8 GHz CPU (Pentium 4) and 1 GB memory, the CPU time per each time step for the simulation was approximately 0.3 s, indicating that the CPU time in the DIEX method was appreciably shorter than that of traditional three-dimensional river flow models. These results suggest that the DIEX method has a sufficiently low computational load to support real-time discharge monitoring.

#### 4.4.2. Lateral and Vertical Velocity Distributions

The DIEX method was replicated for the lateral and vertical velocity distributions, and the observed results were compared with the calculated results in the reference case (case A-1) to confirm this application. Figure 12a presents the lateral distributions of the streamwise velocities measured by the ADCP and H-ADCP and calculated by the DIEX method at the measuring height of the H-ADCP. As

**Table 1. Computational Conditions of the DIEX Method**

<table>
<thead>
<tr>
<th>Case</th>
<th>( n ) ((\text{m}^{-1/3} \text{ s}))</th>
<th>( b )</th>
<th>( Y_{\text{max}} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>0.035</td>
<td>1</td>
<td>36</td>
</tr>
<tr>
<td>A-2</td>
<td>0.010 ~ 0.050</td>
<td>1</td>
<td>36</td>
</tr>
<tr>
<td>A-3</td>
<td>0.035</td>
<td>1 ~ 10</td>
<td>36</td>
</tr>
<tr>
<td>A-4</td>
<td>0.035</td>
<td>1</td>
<td>10 ~ 46</td>
</tr>
</tbody>
</table>

**Figure 12.** Lateral distributions of the streamwise velocities at 1120 LT on 13 October 2005. The calculated results were obtained using the DIEX method (case A-1) and the simplified method (case B).
an example, we selected the results from 1120 LT on 13 October 2005, under a low-flow condition. The comparison indicated that the calculated results fully incorporated the results measured by the H-ADCP over the whole cross section, and inadequately assimilated results, frequently observed in the nudging scheme, were not found. Figure 12a shows that the calculated velocity is in good agreement with the results measured by the ADCP, except near the riverbanks. This discrepancy is due to the inadequate evaluation of horizontal mixing by turbulence. The DIEX method could be further improved by adopting a more accurate turbulence model for horizontal eddy viscosity.

Figure 12b depicts the lateral distribution of the depth-averaged streamwise velocities, which were measured by the ADCP and calculated by the DIEX method (case A-1) and the simplified method (case B, \( Y_{\text{max}} = 36 \) m), for the same measurement time, shown in Figure 12a. Although the results calculated using the DIEX method agree well with the measured results inside and outside the range of the data assimilation, the results calculated using the simplified method and the measured results are well reproduced only within the range of data assimilation. Consequently, the calculated velocity in the simplified method is lower than the measured velocity outside the range, suggesting that the accuracy of the DIEX method is appreciably better than that of the simplified method.

Figure 13 shows the contours of the streamwise velocity observed by the ADCP and calculated by the DIEX method over the whole cross section. Figure 14 shows the vertical distributions of the streamwise velocity at \( y = (a) 3 \) m, (b) 19 m, and (c) 41 m at 1120 LT on 13 October 2005 (case A-1).
method (case A-1) at 1120 LT on 13 October 2005. The calculated results demonstrate that the line velocity measured by the H-ADCP is well translated into the cross-sectional velocity over the domain using the DIEX method. A comparison of the measured and calculated contours reveals similar patterns for the calculated and measured velocities. As a detailed comparison, Figure 14 indicates the vertical distributions of the measured and calculated streamwise velocities at \( y = 3 \) m, 19 m and 41 m. In the figure, the velocities measured by the H-ADCP are also shown at \( y = 3 \) m and 19 m, within the assimilation range. The calculated results are in good agreement with the measured results both inside and outside the assimilation range except for the surface layer, in which the velocity may be disturbed by the ADCP [Mueller et al., 2007]. Thus, the interpolation and extrapolation procedures in the DIEX method can reproduce the lateral and vertical velocity distributions accurately.

### 4.4.3. Discharge

To validate the evaluation of the discharge by the present monitoring system, Figure 15 displays the temporal variations of the measured and calculated discharges during two observational periods. The observed discharges were obtained with the ADCP and the Price current meter. In addition, the calculated results for case A-1 are depicted in Figure 15. The results for both periods indicate that the calculated discharge is in good agreement with the observed results.

To validate the numerical accuracy of the present system in detail, the observed and calculated discharges, \( Q_{\text{obs}} \) and \( Q_{\text{cal}} \), during the two periods were correlated and are represented in Figure 16. The calculated results were obtained for case A-1 and case B, used by the DIEX and simplified methods, respectively. In both methods, the assimilation range \( Y_{\text{max}} \) is set to be 36 m. The difference between \( Q_{\text{obs}} \) and \( Q_{\text{cal}} \) is specified by the 0% and 10% relative errors, displayed with solid and broken lines, respectively. The similarity between the results calculated by the DIEX method and the observed data is illustrated in the figure, with a relative error of less than 10% for all simulated results. In contrast, relatively larger differences were observed between the calculated and measured discharges in case B used in the simplified method. Note that the calculated results in case B are slightly lower than the observed results owing to the underestimation of the interpolated velocity near the banks, as drawn in Figure 12b.

The accuracy of the discharge evaluated by the present system can be quantified using root mean square (RMS) value of the relative error, \( Err \), defined as

\[
Err = \frac{|Q_{\text{cal}} - Q_{\text{obs}}|}{Q_{\text{obs}}}.
\]

The RMS values of the relative error, \( Err \), for all results are 4.9% and 8.1% in the DIEX and simplified methods, respectively, showing the higher accuracy of the DIEX method than the simplified method. The accuracy of the present monitoring system is less than 5%, indicating a good discharge measurement [Sauer and Meyer, 1992].
Figure 17 shows the relationship between the water elevation and discharge under a flood condition, which occurred from 16 to 20 June 2006. The results observed by the ADCP and calculated for case A-1 are drawn separately for the rising and falling stages of the flood. The calculated results indicate the well-known clockwise loop of the stage-discharge relationship, for which the discharge in the rising stage is larger than in the falling stage at the same water elevation. The calculated results show excellent agreement with the observed results. The stage-discharge relationship mentioned above cannot reproduce the unsteady variation of the discharge as effectively as the clockwise loop. These facts demonstrate that the present monitoring system was more effective at continuously evaluating discharge under flood conditions than the stage-discharge relationship.

4.4.4. Influence of Numerical Parameters on the Accuracy of the DIEX Method

We compared the sensitivity of the numerical parameters used in the DIEX method to the accuracy of the present monitoring system. Figures 18a and 18b show the RMS values of the relative error for the calculated discharge, $\text{Err}_{\text{RMS}}$, under various conditions of $n$ and $\beta$, obtained in cases A-2 and A-3, respectively. The results for period 1 are depicted in the figure. In case A-2, $\text{Err}_{\text{RMS}}$ varies from 3.9% to 10.2% and the minimum value of $\text{Err}_{\text{RMS}}$ appears at $n = 0.035 \text{ m}^{-1/3} \text{s}$, indicating that an appropriate value of $n$ should be tuned for specific river flows for a more accurate evaluation of discharge. For the simulations presented, the appropriate value of $n$ was given to be $0.035 \text{ m}^{-1/3} \text{s}$, which almost corresponded with the values adopted in the river flow simulation of the Edo River [Nihei et al., 2007]. The calculated discharge maintains a higher accuracy (<5.5%) for values of $n$ from 0.02 to 0.04 m $^{-1/3}$ s. This means that general values of Manning’s coefficient $n$ may give appropriate numerical results of the present model. The variation in $\beta$ evaluated in case A-3 reveal that the relative errors, $\text{Err}_{\text{RMS}}$, are almost constant (equal to 3.9–4.0%). These evaluations suggest that the present system can maintain higher accuracy (<5.5%) under the general values of $n$ and $\beta$.

Figure 18c shows the dependence of the assimilation range $Y_{\text{max}}$ on the relative error $\text{Err}_{\text{RMS}}$. The results were obtained using the DIEX and simplified methods, which are the conditions in case A-4 and case B, respectively, during period 1. The results for the DIEX method implied that $\text{Err}_{\text{RMS}}$ range from 3.9 to 8.2%, the minimum for which is found at $Y_{\text{max}} = 36$ m. The increased $\text{Err}_{\text{RMS}}$ with $Y_{\text{max}} > 36$ m is caused by the H-ADCP velocity measurement error, which increases near the right bank of the main channel as displayed in Figure 11. In the narrower range of $Y_{\text{max}},$
and extrapolated in a cross section using a dynamic interpolation and extrapolation (DIEX) method, which incorporates a new approach to data assimilation to reflect rationally measured velocities in numerical simulations. For computational efficiency and numerical accuracy, we used a simplified momentum equation with a new additional term $F_a$, which compensates for the effects of omitted terms in the momentum equation and is determined from the measured velocity to assimilate the field data into the numerical simulation. Furthermore, the DIEX method introduces a numerical procedure that minimizes the measurement errors of the velocity by satisfying the momentum equation.

[58] The fundamental performance of the present monitoring system was confirmed by the H-ADCP measurements conducted in the middle reach of the Edo River in Japan. The velocity distributions and discharge obtained by the present system were compared with the results measured by an ADCP and a Price current meter. The vertical and lateral distributions of the calculated velocities in the DIEX method were in good agreement with the measured results inside and outside of the data assimilation range. The discharge calculated by the DIEX method was in good agreement with the observed data. The present monitoring system also reproduced a well-known clockwise loop of the stage-discharge relationship, which cannot be described by the methods on the basis of a rating curve. The RMS value of the relative error for the discharge in the DIEX method was 4.9%, showing that the accuracy of the DIEX method was the same as for conventional methods using a Price current meter and higher than that for the simplified method. These facts demonstrate that the present monitoring system provided accurate, automatic and continuous monitoring of river discharge.

[59] High discharge is an important target of the present monitoring system. Unfortunately, we did not have the opportunity to carry out measurements in high-flow conditions in which flood flows occurred in both the main channel and the floodplains, during periods 1 and 2. The high turbidity observed under high-flow conditions caused strong attenuation of the acoustic beam. In the future, we need to confirm the applicability of the present system to high-flow conditions with high turbidity.

5. Conclusions

[57] To attain an accurate, automatic and inexpensive monitoring system of river discharge, a new discharge monitoring system was developed using H-ADCP measurements and river flow simulation. In the field measurements, the H-ADCP continuously measured the horizontal velocity profiles at a fixed height. In the numerical simulation, the measured velocities along a horizontal line are interpolated and extrapolated because the fraction of the velocity calculated by the DIEX method increased relatively. In contrast, all of the error values $Err_{RMS}$ in the simplified method are larger than in the DIEX method. Although the accuracy for both methods decreased in the narrow range of $Y_{max}$, this tendency becomes more dominant in the simplified method because the DIEX method appropriately satisfies the dynamic principle in river flows for the interpolation and extrapolation procedure of the velocity over the cross section. These results imply that for field sites where river width exceeds the measurement ranges of the H-ADCP, the interpolation and extrapolation procedures by the DIEX method become more effective than the simplified method.

Figure 18. Relative error $Err_{RMS}$ under various conditions of (a) $n$, (b) $\beta$, and (c) $Y_{max}$.

Err$_{RMS}$ increased because the fraction of the velocity calculated by the DIEX method increased relatively. In contrast, all of the error values $Err_{RMS}$ in the simplified method are larger than in the DIEX method. Although the accuracy for both methods decreased in the narrow range of $Y_{max}$, this tendency becomes more dominant in the simplified method because the DIEX method appropriately satisfies the dynamic principle in river flows for the interpolation and extrapolation procedure of the velocity over the cross section. These results imply that for field sites where river width exceeds the measurement ranges of the H-ADCP, the interpolation and extrapolation procedures by the DIEX method become more effective than the simplified method.

References


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