Study on river-discharge measurements with a bottom-mounted ADCP

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ABSTRACT: To examine the accuracy of discharge measurements in rivers, continuous measurements of flood flows were conducted with a bottom-mounted ADCP. The observed data indicates that the vertical distribution of the velocity varied considerably in the rising and falling stages of a hydrologic event, in which the unsteadiness parameter α and H.W.L. were relatively larger. It should be noted from the observed data that the averaged coefficients of float were in good agreements with well-known empirical values, while the coefficients of float varied appreciably in each hydrologic event. The accuracy for evaluating river discharge is investigated by using the rating curves with *H*-*Q* and *V*-*Q*, showing that the rating curves with *H*-*Q* and *V*-*Q* are appropriate for the evaluation of discharge in the upper and lower reaches of the river, respectively.

1 INTRODUCTION

River discharge is essential for river planning and management. In measuring river discharge, rod-float measurements are widely adopted under flood-flow conditions. Using a rating curve between the observed discharge *Q* and water elevation *H* at a cross-section of a river, so called an *H*-*Q* curve, the continuous data for river discharge *Q* can be obtained from the observed water elevation *H*. Therefore a huge number of gauging stations recording water elevation have been developed.

However, under flood-flow conditions, the discharge in a rising stage tends to be higher than that in a falling stage at a same water elevation, producing a looped rating curve. Further the discharge monitoring with floats may have measuring errors due to various hydraulic phenomenon. From the above viewpoints, it is necessary to evaluate the accuracy and applicability of previous methods for discharge measurements. Moreover it is expected to develop a more accurate technique for measuring river discharge.

For this purpose, the continuous measurements of flood flows were conducted with a bottom-mounted ADCP (Acoustic Doppler Current Profiler) which can record a vertical distribution of velocity. An ADCP has already been used as a standard current meter of physical oceanography and coastal environments (*e.g.*, Pettigrew et al. 1986). The recent ADCP technology can realize to measure the three-dimensional velocity with fine vertical resolution in which the minimum cell size is 1cm. Then the potential for applying the ADCP into current measurements in shallow-water flow like river flow has been increasing. In the present paper, the field measurements were done in the Oohori River in Japan, an urban small river. The analysis of the observed data was employed to examine the vertical distribution of velocity in rising and falling stages and then evaluate a coefficient of float which is the ratio of depth-averaged velocity to velocity in surface layer. In addition, the accuracy of rating curves with *H*-*Q* and *V*-*Q* (Huang 2004) is discussed, in which *V* means a depth-averaged velocity.

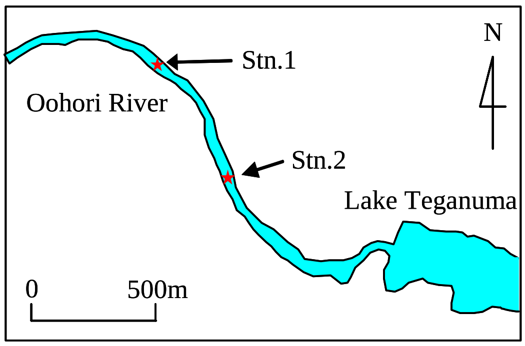
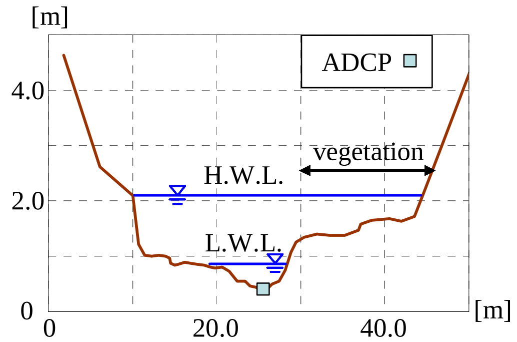


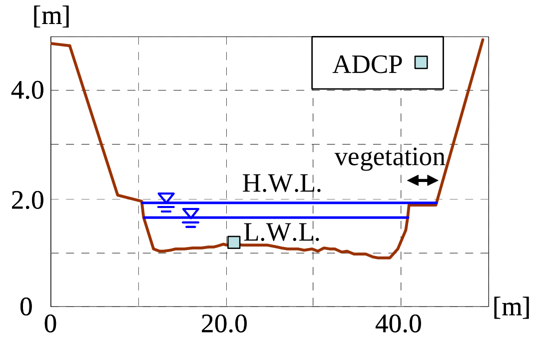
Figure 1. Field site and location of measuring stations.

2 OUTLINE OF FIELD MEASUREMENTS

The Oohori River chosen as a field site inflows into the western part of Lake Teganuma, one of typical eutrophied lakes in Japan. As shown in Fig.1, the measuring stations were in lower reach of the Oohori River at Stns.1 and 2 which were located at 1.5 km and 0.9 km upstream from the river mouth, respec-



(a) Stn.1



(b) Stn.2

Figure 2. Cross-sectional view at both the measuring stations.

tively. The backwater from the lake was known to affect time variations of the water elevation at both the stations. The influence from the lake appeared more appreciably at Stn.2 than at Stn.1. Figure 2 describes the cross-sectional view at both the stations. The Oohori River is a compound channel and the width of the flood plane with vegetation layer at Stn.1 is much larger than that at Stn.2. The ADCP is bottom-mounted in the center of the main channel.

The instrument used in the present study was a 1200 kHz WorkHorse Sentinel ADCP (RD Instruments, Inc.). The ADCP was installed on the river bed looking upward, to give the vertical profile of velocity, as indicated in Fig.3. The configuration pa-

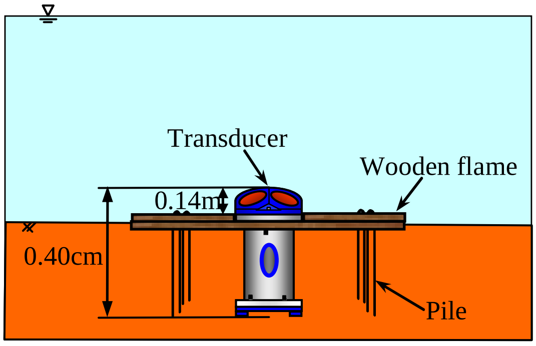


Figure 3. Schematic view of the bottom-mounted ADCP in the field measurements.

Table 1. Configuration of the ADCP used in the field measurements.

Cell size	0.02m
Cell number	150
Sampling interval	5 minutes
Blank zone	0.14m

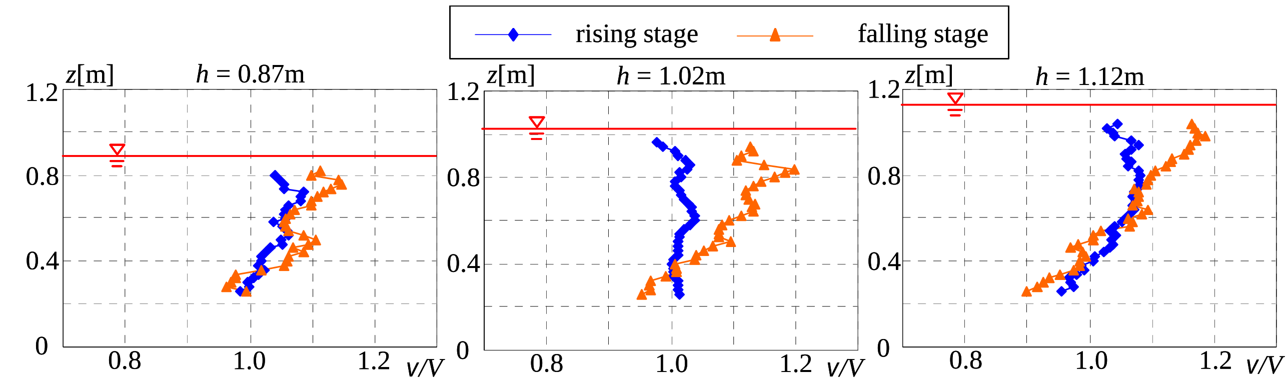
rameters of the ADCP are summarized in Table 1. In the configuration, the blank zone, in which no measurements were taken near the head of the ADCP, was 0.14 m. The measurements of water elevation were also conducted with the pressure gauge (Diver, Eijikelkamp Co.).

The ADCP was installed at Stn.1 in 2004 and at Stn.2 in 2005, respectively. From these field measurements, the observed data in five hydrologic events were selected to perform the analysis of observed data. The information for the events are detailed in Table 2, in which the unsteadiness parameter α proposed by Nezu et al. (1997) is defined as

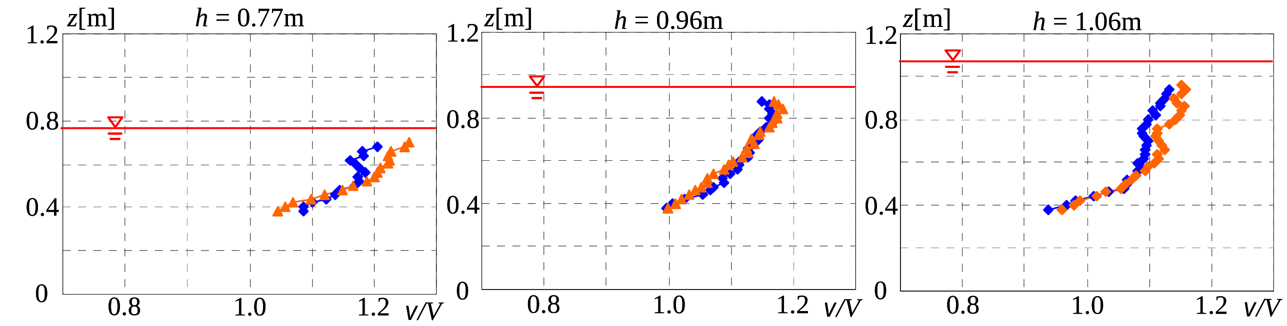
$$\alpha = \frac{\Delta h}{T_d} \frac{1}{U_c}, \qquad (1)$$

Table 2. Outline of the hydrologic events.

Event	Station	Period		T_d [s]	h [m]	U_c [m/s]	
A	Stn.1	May 20 to 21, 2004	Rising stage	14100	0.938	0.748	8.9×10^{-5}
			Falling stage	37800	0.815	0.612	3.5×10^{-5}
B		June 11 to 12, 2004	Rising stage	7200	0.248	0.497	6.9×10^{-5}
			Falling stage	15600	0.246	0.455	3.5×10^{-5}
C-1		November 12, 2004	Rising stage	6900	0.335	0.552	8.8×10^{-5}
			Falling stage	6300	0.171	0.677	4.0×10^{-5}
C-2		November 12, 2004	Rising stage	13500	0.363	0.697	3.9×10^{-5}
			Falling stage	29100	0.513	0.638	2.8×10^{-5}
D		November 15, 2004	Rising stage	20700	0.681	0.609	5.4×10^{-5}
			Falling stage	20100	0.557	0.682	4.1×10^{-5}
E	Stn.2	July 3 to 4, 2005	Rising stage	10500	0.217	0.446	4.6×10^{-5}
			Falling stage	10500	0.129	0.455	2.7×10^{-5}



(a) Event A (Peak depth=1.66m)



(b) Event D (Peak depth=1.20m)

Figure 4. Vertical distribution of streamwise velocity in the rising and falling stages (*h*: water depth).

where Δh is the difference of maximum flow depth and the base flow depth, T_d means the time duration of the rising or falling stage in the hydrograph and U_c represents the average of peak flow and base flow depth-averaged velocity. In Table 2, these parameters are displayed in the rising and falling stages of each event. Since two peaks of the hydrograph appeared in the event C, the period of the event is separately denoted as event C-1 and C-2 in Table 2.

3 VERTICAL FLOW STRUCTURE IN FLOOD EVENTS

3.1 *Vertical distribution of streamwise velocity*

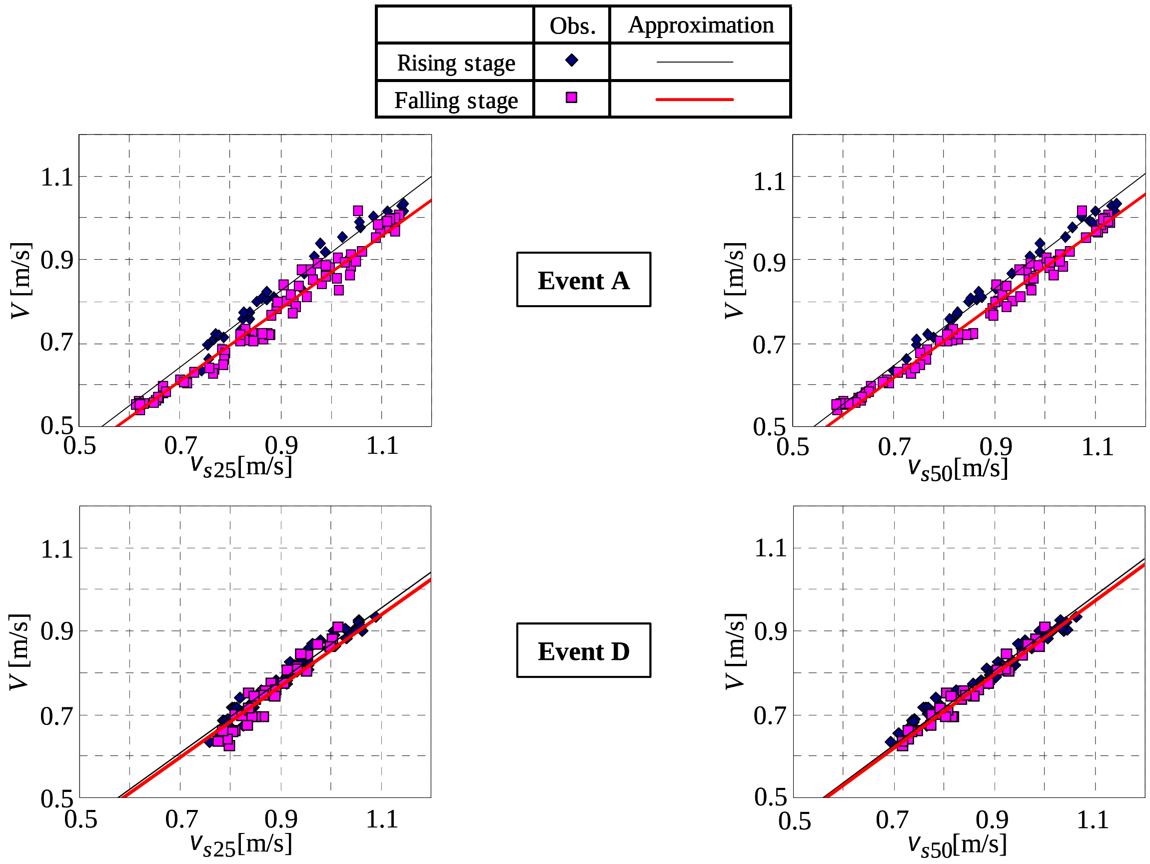
To examine the fundamental vertical flow structure in the rising and falling stages, Fig.4 indicates the vertical distribution of streamwise velocity in the events A and D. The horizontal axis in the figure means the streamwise velocity v normalized by the depth-averaged velocity *V*. For evaluating the depth-averaged velocity *V*, the velocity in the blank zone near the riverbed are estimated with the approximation described as $v = az^b$ (*z*: the height from the riverbed; *a*, *b*: constants).

The observed results in the event A shows that, in shallower water depth (*h*=0.87 m), the velocity distributions in the rising and falling stages almost coincided with each other. However, in deeper depth (*h*=1.02 m and 1.12 m), the velocity in the rising stage tended to be uniform vertically, while the velocity distribution in the falling stage was inclined in the vertical direction. The results in the event A demonstrate that the vertical distribution of the velocity varied considerably in the rising and falling stages of the hydrologic event. On the other hand, the observed results in the event D reveal that the velocity distributions in the rising stage were almost agreements with those in the falling stage at three depth conditions.

The observed results for the vertical flow structure indicate that the appreciable differences of the vertical distribution of the velocity were found only in the event A. It is noted from Table 2 that the unsteadiness parameter α and depth difference Δh in the event A were larger than those in the other events. These parameters may be closely related to the difference of the vertical flow structure in the hydrograph. In near future, hence, it is necessary to collect further ADCP data to clarify the vertical flow structure under various flow conditions. It is also noteworthy that $\alpha = 8.9\times10^{-5}$ in the event A may be regarded as a weak unsteadiness condition in the laboratory experiments done by Nezu et al. (1997).

3.2 *Coefficient of float*

In discharge measurements with rod floats flowing near water surface, it is necessary to convert measured surface velocity with rod floats into a depth-averaged velocity *V*. In the evaluation for the river discharge, one needs to use a coefficient of floats



(a) V and v_{s25}

(b) V and v_{s50}

Figure 5. Comparison between the depth-averaged velocity V and the surface velocity v_{s25} and v_{s50}.

which is a ratio of the depth-averaged velocity to the surface velocity. The ADCP can monitor the vertical distribution of velocity. It is therefore possible to confirm the validity of well-known coefficients of float by using the vertical distribution of velocity obtained by the bottom-mounted ADCP. In general float measurements, a surface float and a 0.5 m long rod are adopted in h < 0.7 m and 0.7 m < h < 1.3 m, where h is water depth, respectively. The relationship between the depth-averaged velocity and surface velocity in the events A and D are illustrated in Fig.5. Here two surface velocities v_{s25} and v_{s50} are introduced as the velocity averaged in the surface layer with the thickness of 25 cm and 50 cm, respectively. The surface velocities v_{s25} and v_{s50} corresponds to the velocities measured by surface float and a 0.5 m long rod, respectively. The observed results are separately depicted in the rising and falling stages in the figure.

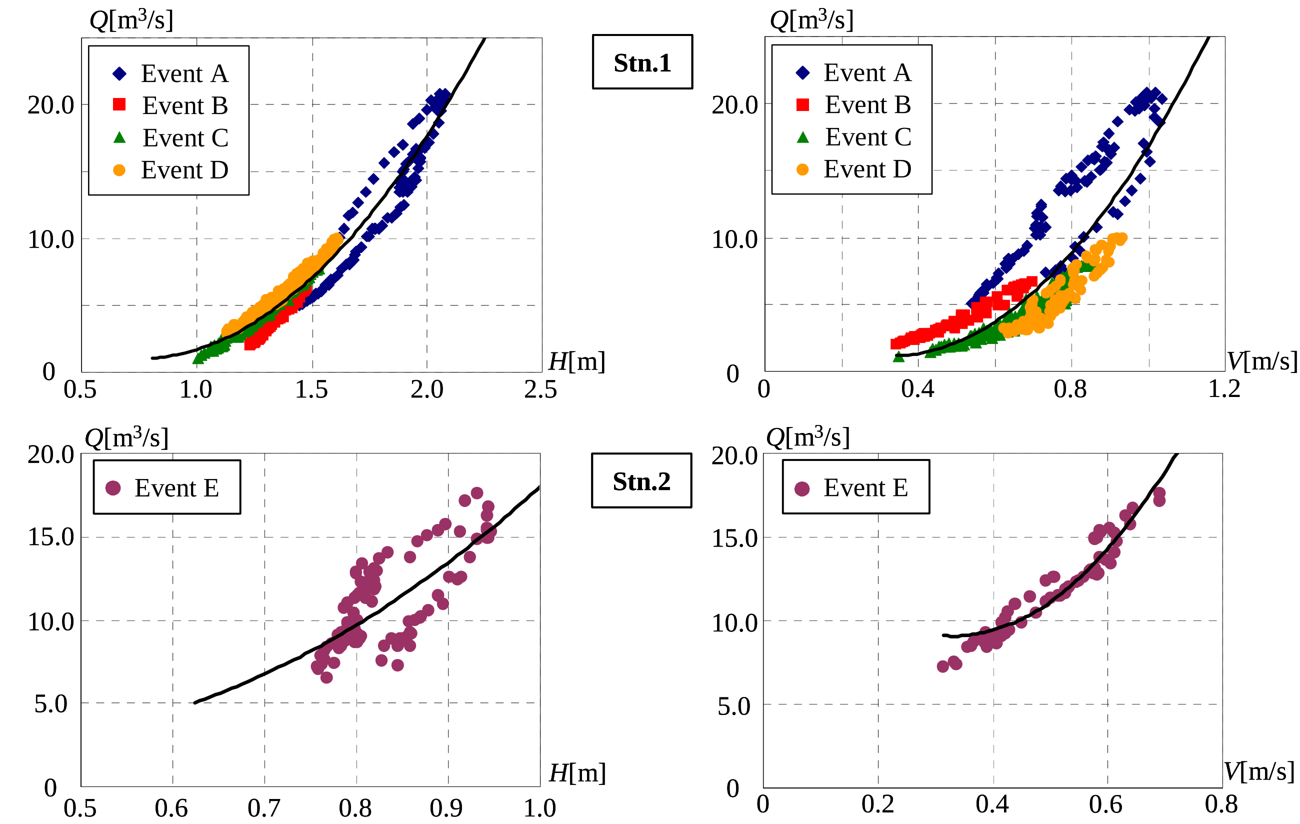
The correlations between the depth-averaged velocity V and the surface velocities v_{s25} and v_{s50} in the event A indicate that, under the same surface velocity, the depth-averaged velocity V in the rising stage was larger than that in the falling stage. These tendencies were found in both the surface velocities. On the other hand, the difference of the depth-averaged velocity in the rising and falling stages was not observed in the event D. The relations between the depth-averaged and surface velocities are almost similar to the vertical flow structure mentioned in the above.

Table 3. Coefficients of float in each hydrologic event.

Event				
	Rising stage	Falling stage	Rising stage	Falling stage
A	0.916	0.867	0.925	0.883
B	0.746	0.759	0.779	0.778
C	0.826	0.811	0.876	0.878
D	0.866	0.851	0.900	0.883
E	0.812	0.805	0.902	0.885
Average	0.830		0.874	

In Fig.5, linear approximations for the correlations between the depth-averaged and surface velocities are also exhibited. The slopes of the linear approximations correspond to the coefficients of float (=V/v_{s25} or V/v_{s50}). The evaluated coefficients of float in each hydrologic event are summarized in Table 3. In the event A, the difference of the coefficients of float in the rising and falling stages was 0.04-0.05, while, in the other events, the coefficient in the rising stage was comparable to that in the falling stage. The results are also similar to those shown in Figs.4 & 5.

The averaged coefficients for v_{s25} and v_{s50} were 0.83 and 0.87, respectively, almost corresponding to well-known empirical values for the coeffi-



(a) *H-Q* (b) *V-Q*

Figure 6. *H-Q* and *V-Q* curves at Stns.1 and 2.

cients of float (=0.85 and 0.88, respectively). In each hydrologic event, however, the coefficients of float for the surface velocities v_{s25} and v_{s50} varied appreciably. The coefficients for v_{s25} and v_{s50} were from 0.75 to 0.92 and from 0.78 to 0.93, respectively.

4 ACCURACY OF DISCHARGE EVALUATION WITH H-Q AND V-Q CURVES

4.1 *Procedure of discharge evaluation*

Accuracy of discharge evaluation with rating curves is examined using the observed data with the ADCP. For this purpose, it is necessary to evaluate river discharge with the depth-averaged velocity obtained by the ADCP mounted at a point in a cross section. To obtain the transverse distribution of velocity in a cross section from the ADCP data, a dynamic interpolation method presented by Nihei & Kimizu (2006) is introduced, in which observed velocities can be spatially interpolated in the cross section with satisfying the fundamental dynamic principle of fluid motion. With the dynamic interpolation method, the time sequence of the discharge can be calculated from the depth-averaged velocity and water elevation.

4.2 *H-Q and V-Q curves*

The correlations of *H-Q* and *V-Q* at Stns.1 and 2 are displayed in Fig.6. Approximations for the correlations are also depicted in the figures. At Stn.1, both the rating curves of *H-Q* and *V-Q* were looped in the hydrograph. The loop of the *V-Q* curve was larger than that of the *H-Q* curve.

In contrast, at Stn.2, the *H-Q* rating curve was looped more largely than the *V-Q* curve. The influences of the backwater from Lake Teganuma appeared more appreciably for water elevation at Stn.2 than that at Stn.1 due to the difference of the distance from the river mouth. Therefore larger loop of the *H-Q* curve was found at Stn.2.

4.3 *Results and discussion*

The discharge can be evaluated by using the approximations for *H-Q* and *V-Q* as shown in Fig.6. Table 4 reveals the observed and evaluated discharges averaged during a hydrologic event. In the table, the observed discharge $\overline{Q}_{obs}$ and the ratio of the evaluated discharge $\overline{Q}_{cal}$ to $\overline{Q}_{obs}$ are separately expressed in the rising and falling stages and total period of each event. The results for the total periods of events A, B, C and D at Stn.1 illustrate that the ratio $\overline{Q}_{cal}/\overline{Q}_{obs}$ with the *H-Q* curve was from 89 to 124%, while $\overline{Q}_{cal}/\overline{Q}_{obs}$ with the *V-Q* curve was from 67 to 143 %. This fact exhibits that

Table 4. Comparison of the observed and evaluated discharge in each hydrologic event.

Event		[m^3/s]	H-Q	V-Q
A	Total	8.4	101.5	78.8
	Rising stage	9.4	88.9	103.7
	Falling stage	8.0	107.0	67.9
B	Total	3.4	123.6	67.1
	Rising stage	4.5	115.3	75.4
	Falling stage	2.9	129.4	61.3
C	Total	3.8	96.6	123.9
	Rising stage	5.0	93.6	130.4
	Falling stage	3.1	99.3	117.7
D	Total	3.9	88.9	142.6
	Rising stage	4.5	86.1	151.9
	Falling stage	3.2	93.0	129.1
E	Total	12.4	100.0	103.7
	Rising stage	13.8	93.1	104.6
	Falling stage	11.0	107.1	102.8

the accuracy of the *V-Q* curve was lower than that of the *H-Q* curve due to larger loop of the *V-Q* curve at Stn.1 as mentioned in Fig. 6. Furthermore the accuracy of the *H-Q* and *V-Q* curves was lower in the rising stage or falling stage because of the existence of the loop of the rating curves. Then the temporal variations of discharge may not be accurately evaluated with *H-Q* and *V-Q* curves.

On the other hand, $\overline{Q}_{cal}/\overline{Q}_{obs}$ in the event E at Stn.2 suggests that the accuracy of the *H-Q* curve was lower than that of the *V-Q* curve. It should be noted from the result that at measuring stations with significant backwater influences from lakes like Stn.2, a *V-Q* curve is more appropriate to accurately evaluate river discharge than an *H-Q* curve.

5 CONCLUSIONS

The flood-flow measurements were done with the bottom-mounted ADCP. With the observed data, the vertical flow structure and the evaluation of the discharge with the *H-Q* and *V-Q* curves are discussed. Main conclusions in the present study are as follows:

1) In the event A with relatively larger unsteadiness parameter α and stage variation Δh, the vertical flow structure and the coefficient of floats were found to be different appreciably in the rising and falling stages.
2) The averaged values of the float coefficients for v_{s25} and v_{s50} were 0.83 and 0.87, respectively, almost corresponding to the well-known empirical values. In each hydrologic event, however, the coefficients of float varied considerably. The coefficients for the surface velocities v_{s25} and v_{s50} were from 0.75 to 0.92 and from 0.78 to 0.93, respectively.
3) The *H-Q* and *V-Q* curves are appropriate for the evaluation of discharge in the upper and lower reaches of the river, respectively, due to the difference of the backwater effect from the lake.
4) The temporal variations of discharge may not be accurately evaluated with the *H-Q* and *V-Q* curves.

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