Improvement of Uncertainty Assessment of Discharge Estimated by Velocity-Area Method

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Abstract. The present study was conducted to re-estimate the factors needed for the velocity-area method previously provided by ISO through precise actual scale experiments in order to verify the appropriateness of the errors of the individual factors presented by ISO 748 and ISO 1088. For this, a steady-state flow of a flow velocity of approximately 1 m/s, 7 m wide, and 1 m deep, was maintained in the mild slope channel located at the River Experiment Center (Andong) of the Korea Institute of Construction Technology. Under this condition, the objective was to measure the flow velocity very precisely with respect to the space by using a micro-ADV having a high accuracy of flow velocity measurement. The water depth was precisely measured before the generation of the flow by using Total Station. The ISO regulations and the results of the present experiment were applied to three different conditions. The uncertainty assessed by applying the results of the present experiment exceeded twice that of the uncertainty estimated by applying the uncertainty factors provided by ISO. The uncertainty of the lateral gap between measurement lines and the number of measurement points in the depth direction was dependent on the scale of rivers. However, ISO may have presented the uncertainty factors analyzed from the data obtained from a wide range of river scales. Therefore, the discharge estimated by the velocity-area method may be dependent on the scale of rivers. The errors of the individual factors of the velocity-area method derived from the present study may be applied to the estimation of the uncertainty of the discharge calculated by the velocity-area method in small rivers.

1. Introduction

Discharge measurements have shown their numerous applications in riverine analysis regarded as the design of irrigation and flood control, estimating design flood volume and height of rivers, developing streamflow rating curve, as well as used for practical design and research purposes as the input, verification, and correction data for hydrologic and hydraulic numerical models. Therefore, uncertainty estimation of in-situ discharge measurements driven by various field and flow conditions affects reliability of those applications, subsequently denoting its importance in hydrometric communities in these days. Since there

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could be a bunch of different ways to calculate streamflow uncertainty, there have been many efforts in the communities such that several theoretical frameworks (e.g., GUM) were seriously considered in terms of standardizing the methodology to assess uncertainty. Yet, ISO 748/1088 (ISO 748:2007, ISO 1088:2007) have been still widely accepted among agencies and practitioners before more advanced standards are valid. ISO 748 also has several drawbacks: 1) there have been critical reviews that ISO 748 was not on rigorous mathematical and statistical background; 2) not generic, but only dedicated to velocity area method, thereby not suitable for other methods like ADCPs, since all experimental data are based on current meters; 3) considering acoustic instruments are becoming dominant and rapidly replace conventional instruments, consistency issue in terms of applying theoretical framework and error sources can exist; 4) field data used for identifying error sources were actually collected in a couple of decades ago (i.e., 1960), and heavily relied on filed observations where unsteadiness might happen; 5) the values for error sources were too much averaged covering from small to large scale of rivers, so they are weak to be applied for a specific condition of rivers; 6) velocity area method relying on wading method is not usually used any more in large and deep rivers where ADCPs take the role, rather it is still good alternative in shallow stream where ADCPs cannot be applicable.

In this study, rather than scrutinizing theoretical limitations of ISO toward alternative frameworks like GUM, we mainly investigate the values of error sources addressed in ISO 748/1088 with newly measured experimental data, where the methodologies used in ISO were followed in exactly identical way. However, we stress that there were the following differences: 1) controlled real-scale natural river channel was used to maintain steady state, 2) only focused on relatively small size of stream to avoid scale issue appeared in ISO 748; 3) acoustic instrument was applied rather than conventional current meters; 4) we tried to get a reference velocity and discharge which is not available in field mostly. The results ended up with summarized in tables which had the same format with ISO 748 for each parameters: sampling time, number of verticals, and number of points in the verticals.

2. Assessment of Uncertainty Discharge Measurement in ISO

ISO 748 (2007) basically provides the methodology for estimating river discharge by using a point-based current meter or a floating device. The procedure includes guidelines about the collection of fundamental data for discharge calculation, such as the method of determining sampling time, number of points in the verticals, and the distance between the verticals or number of verticals. The discharge computation in ISO 748 stems from “velocity area method”, the mean-section method as shown in below is most popular.

$$Q_{Total} = \sum_{n=3}^{25}(\overline{v_n} \times \frac{b_{n+1}-b_{n-1}}{2} \times d_n) \qquad (1)$$

ISO 1088 (2007) provides the methodologies of estimating the measurement errors with respect to the individual uncertainty sources defined in ISO 748 (2007). ISO 1088 (2007) also showed the analysis, and values of the individual uncertainty sources on the basis of the data measured by using point propeller current meters between 1963 and 1970, where flow discharge ranged from 0.7 ~ 7,550 m3/s, channel width was between 6 ~ 685 m, depth ranged from 0.44 ~ 10.5m (IOS 1088, 2007). Overall the number of datasets were 62. Note that the field conditions applied in the present study was 2.1 m3/s of discharge, 6 m of channel width, depth range of 0.2 ~ 0.8 m. ISO 1088 provides those error sources in the case of different field, flow, and measurement conditions, which has been applied for field operators with no doubt when there are no further information.

Considering the velocity area method, ISO 748 (2007) divided the factors affecting the discharge estimated by the velocity-area method into the channel width, the depth, and the velocity measurements, and presented the following as the equation for assessing the uncertainty of discharge:

$$\mathrm{u}(Q)^2 = u_m{}^2 + u_s{}^2 + \frac{\sum_{i=1}^{m}[(b_i d_i \bar{v}_i)^2 (u_{b,i}{}^2 + u_{d,i}{}^2 + u_{\bar{v},i}{}^2)]}{(\sum_{i=1}^{m} b_i d_i \bar{v}_i)^2} \quad (2)$$

where $\mathrm{u}(\mathrm{Q})$ is the combined standard uncertainty (%) of the discharge measurements, $u_{b,i}$, $u_{d,i}$, $u_{\bar{v},i}$ are the relative standard uncertainties in the channel width, depth, and mean velocity measured at vertical i^{th}, u_s is the relative uncertainty of the measurement device due to calibration errors in the flow velocity, width, and depth measurement instruments (practical value of 1%), u_m is the relative uncertainty due to the limited number of verticals (%), and m is the number of verticals. Among velocity, depth, width measurements, while measurement errors relevant to depth and width are regarded to be trivial, ISO separated errors relevant to velocity stem from number of vertical ($\mathrm{u_m}$), and relative error of mean velocity ($u_{\bar{v},i}$) depth-averaged from at least one or more point-measurement for each individual vertical, i, with a designated exposure time to stabilize velocity fluctuations in the stream for obtaining time-averaged mean velocity at the point. Given that the measurement of length scale of the verticals (i.e., width and depth) is relatively straightforward meaning that no in-situ decisions are conventional needed, velocity measurement for field operators routinely requires 3 main judgements: number of verticals and points for each vertical as well as the duration of velocity measurement, which should consider spatial and dynamic scale of the given cross-section. In this context, ISO 1088 categorized and named above three major sources of error as type i, ii, iii errors, respectively, where ISO 1088 demonstrated the details of mathematical definition and procedure to calculate them. We do not provide the detailed procedure of error type i, ii, iii step by step in this paper (see reference ISO 1088), rather explicitly denoting their definitions when comparing outputs derived from the present experiments with the original version of table of ISO 1088.

$$u_{\bar{v},i}{}^2 = u_{p,i}^2 + \left(\frac{1}{n_i}\right)\left(u_{c,i}^2 + u_{e,i}^2\right) \quad (3)$$

where, $u_{p,i}$, $u_{c,i}$, $u_{e,i}$ are exposure time, number of points in the verticals, and error of instrument.

3. Experimental Methods and Conditions

An in-situ experiemnt to apply ISO 1088 procedure to estimate type i, ii, and iii errors was carried out in a small scale of river channel in KICT River Experiemtn Center located at Andong, South Korea([4]). The facility has a mile slope channel of 1/800 with approximately 6 meter of water surface width in a nearly trapezoidal shape of cross-section, where mean flow speed and depth are around 0.8 m/s, 0.8 meter, respectively. The channel is straight with the total lenght of 490 m and the experimental cross-section is located at 300 m from pumps to minimize the disturbance driven by them. The channel bed is mostly sany but partially vegetated. So, this can be a typical small scale of mimicking natural stream that coressponded to near miminum scale of river channel that ISO 1088 engaged with. This outdoor river channel was designed to control the flow scale up to 10 m^3/s, but 2.1 m^3/s of flowrate was applied in the present experiment, where it was possible to main the flow steadiness for 8 hours at the given flowrate. Before conducting the experiment, approximately 9 hours were secured to get rid of infilteration toward channel bed, since bed material is sandy.

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Rather than using conventional currernt-meters in ISO 748/1088, an acoustic instrument of 10 MHz micro-ADV with 50 Hz of sampling frequency was applied to continousely measure velocity at a location, which provided three components of velocity vector (i.e., u, v, and w). Here, u component was regarded to be streamwise velocity, for which the alignment of ADV was carefully checked out. In order to avoid flow disturbance due to conventional wading process driven by intrusion of operators, the instrument was mounted at a bridge, where . For measureemnt campaign basically to obtain true streamflow discharge, where 23 verticals with 25 cm of lateral spacing by following the minimum size represented in ISO 1088 for acquiring zero uncertainty in this scale of rivers. The alignment was purposed to identify the difference in terms of changing number of verticals. Vertical spacing for a given vertical was basically 5 cm sufficient enough to capture whole verstical velocity profile, whereas 10 cm spacing was used in the middle area assuming similarity in the velocity in this region. At each location, temporal scale of the micro-ADV was designed to exposured to continously measure flow velocity for 90 seconds, meaning that 5400 velocity measurement was temporary averaged to come up with mean velocity. Practical recommendation from the manufactures for the exposure time of wading is 30~40 seconds, so that 90 seconds of duration was assumed to be sufficient enough to derive mean characteristics. Moreover, 300 seconds of duration was applied for a vertical located in the middle of the cross-section to estimate

We considered this amount of spatially and temporily dense velcoty measurements in both lateral and vertial domain enabling to capture flow field precisely thereby gurnateeing calcuated flow discharge to be possible used as a reference discharge of 2.1 m^3/s which accounted for summation of cell-based discharge without applying any theoretical law. An important aspect of the experiment compared with prior measurements accounted for ISO 748 was to whethere the flow ensured the steady state during the experiment of about 10 hours. Accoridng to the measurements of stages per every 30 minutes, we confirmed that steady state was maintained, so that the flow was stable without water level fluctuation during the measurement time.

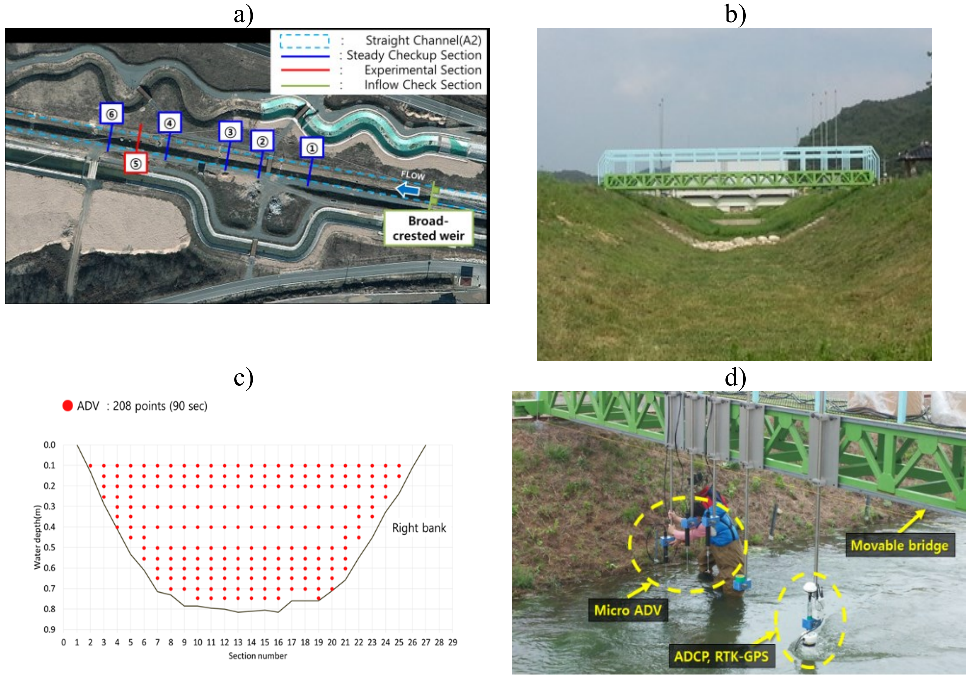

Figure 1. Site and measurement conditions : a) plan view of river channel in KICT River Experiemnt Center ; b) cross-sectional view of the straight channel ; c) ADV measurement points in the given cross-section ; d) micro-ADV (SonTek) mounted on a bridge.

4. Experimental Methods and Conditions

4.1. Type – i error : Assessment of Measurement Time Error

A ISO 1088 assessed the uncertainty of the average flow velocity within a designated time by using an autocorrelation coefficient on the basis of the measurement data obtained by using propeller current meters. But this mehtod may not be appropriately applied to the measurement data obtained by using the acoutic current meter that yields approximately 50 measurement values per second. Therefore, in the present study, the moving average data for each measurement time were used to assess the uncertainty.

$$\sigma_{F,rel} = \sqrt{\frac{\sum e^2}{n-1}} \tag{4}$$

Here, $\sigma_{F,rel}$ is the assessment uncertainty, e is the error of the velocity measured for time and the velocity measured for 300 seconds (%), and n is the number of measurement data.

To assess the uncertainty by using Equation (4), the ADV measurement in a channel center (i.e., No. 14 in Figure 1a) was conducted for 300 seconds at each 14 vertical locations. The average of the velocity measurement data for the 300 seconds was compared with the moving average of the velocity measurement data for each time interval. Table 1 showes velocity errors due to sampling time for 2 represnetative duration : 30s and 90s for conventional wading and this study covering of entire cross-section, where difference was computed with respect to the values derived from 300 s duration. These values of uncertainty were aproximately 1/3 compared with ISO 748/1088, which addresses the difference of acoustic and mechanical meters.

Table 1. Percentage uncertainties in mean velocity for selected duration of sampling times

30s			**90s**		
Depth (cm)	**Mean velocity (m/s)**	$\sigma_{F,rel}$	**Depth (cm)**	**Mean velocity (m/s)**	$\sigma_{F,rel}$
10	0.852	0.019	10	0.861	0.016
15	0.853	0.018	15	0.854	0.001
20	0.831	0.129	20	0.838	0.012
25	0.815	0.051	25	0.803	0.022
30	0.809	0.017	30	0.803	0.011

4.2. Type – ii error : Number of points in the verticls

The methods of estimating the depth-average velocity provided by ISO 1088 (2007) were analyzed in the present study Table 2. The data of the present study missed some measurement values in comparison with the ten-point method provided by ISO 1088. This is because the measurement was performed in an interval of 5 cm to 10 cm in the depth direction in the present study. Therefore, the velocity at each relative position (e.g., surface, 10%, 20%, ..., 90%) was interpolated by the log-law, which is considered to closely simulate the velocity distribution in the depth direction, to compensate the data for the missing points.

The depth-average velocity data estimated by the methods of Rules 1 to 10 were compared with the depth-average velocity data estimated by the ten-point method at a total of 21 measurement lines to calculate the errors. The errors were used to assess the uncertainty of the depth-average velocity estimation methods by using ISO standard.

Table 2. Percentage uncertainties in computation methods of depth averaged velocity

Rule	Number of points	Mean sampling error (%)	Standard deviation of sampling error (%)	RMS sampling error (%)
1	1	11.8 (1.6)	1.2 (7.5)	11.8 (7.7)
2	1	7.3 (3.3)	1.2 (4.8)	7.4 (5.9)
3	2	-4.3 (2.2)	1.7 (3.4)	4.6 (4.0)
4	3	3.8 (1.9)	0.4 (4.4)	3.8 (4.8)
5	3	-8.3 (-0.8)	1.5 (3.3)	8.5 (3.4)
6	3	1.1 (2.0)	0.8 (3.7)	1.3 (4.2)
7	4	1.2 (-0.9)	0.7 (2.2)	1.4 (2.4)
8	5	-8.2 (0.2)	0.5 (2.2)	8.2 (2.2)
9	6	-11.6 (-1.6)	0.3 (2.5)	11.6 (3.0)
10	6	-7.1 (0.9)	0.4 (2.1)	7.1 (2.3)

In Table 2, the numerical values in the parenthesis are the values suggested by ISO 1088, which were significantly different from the values obtained in the present study. The difference may be because the uncertainty was measured by using the data obtained from deep rivers as well as from shallow rivers. While the error of the depth-average velocity was greater than the standard deviation of the average error in the present study, the error of the depth-average velocity was smaller than the standard deviation of the average error in the ISO 1088 data. Therefore, the measurement error depending on the depth-average velocity measurement method may be appropriately analyzed for small-scale rivers to which the velocity-area method is mainly applied.

4.3. Type – iii error ; Number of Verticals

ISO 1088 assessed the error depending on the number of verticals in rivers by calculating the error for each individual measurement line, averaging the errors, and calculating the standard deviation of the errors. In the velocity-area method, as the number of measurement lines is decreased, the measurement area is increased in some parts or decreased in others, reducing the rate of error. On the contrary, if the method suggested by ISO 1088 is applied without modification, the absolute values of the errors resulting from the increased and decreased calculation areas are added, resulting in an increase of the total error rate. In the present study, to reduce the effect on the error rate, the errors were analyzed in comparison with the total discharge measurement results when the number of lateral measurement lines was changed.

In addition, as mentioned above, because the measurement error is significantly dependent on the number of verticals, which is determined by the channel width also in the method provided by ISO 1088, the error was assessed in the present study depending on the gap between measurement lines rather than the number of lateral measurement lines. Assuming the measurement line gap of 0.25 m, provided by ISO 1088, to be a reference, the gap of the lateral measurement lines was varied to 0.5 m, 0.75 m, and 1.0 m to estimate the sectional discharge. The results were then compared in table 3.

Table 3. Percentage uncertainties in terms of the distance between verticals

Distance of verticals (m)	Mean sampling error (%)	Standard deviation of sampling error (%)	RMS sampling error (%)
0.5	0.64	0.382	0.745
0.75	0.494	1.183	1.282
0.1	0.053	2.080	2.080

5. Conclusions

The present study described the method of assessing the uncertainty of river discharge estimated by the velocity-area method on the basis of ISO 748 (2007) and ISO 1088 (2007). On-site experiments and analyses were carried out to improve the uncertainty of the factors that were provided in the past. In the present study, the errors of the individual uncertainty factors were computed in a small-scale of river, where acoustic instrument was applied, reference velocity and discharge are known, and steady state was maintained.

The uncertainty depending on the number of measurement points in the depth direction was predominantly affected by the standard deviation of the errors rather than the measurement error values in ISO 1088. This was because the measured data used by ISO 1088 were obtained from a wide range of average water depths from 0.44 m to 10.5 m. The velocity profile in the depth direction was similar to an exponential distribution in deep channels, whereas that of shallower channels was more similar to a logarithmic distribution. Therefore, the uncertainty should be assessed separately for different depths of channels. Thus, the uncertainty assessed altogether by the previous studies may not be appropriately applied to actual sites without modification. The assessment showed that the discharge estimation uncertainty based on factors provided by the present study was smaller than that of ISO 1088. The difference in the uncertainty is most attributed to the error depending on the number of lateral measurement lines.

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