Uncertainties in the Methods of Flood Discharge Measurement

Yen-Chang Chen · Yung-Chia Hsu · Kuang-Ting Kuo

Abstract This study demonstrates an application of uncertainty analysis in evaluating methods of discharge measurement including: the velocity-area, rating curve and efficient methods based on the probabilistic velocity distribution equation. The measurement of river discharge plays a large part in the distribution of water resources. The conventional methods of discharge measurement are costly, time-consuming, and dangerous. Therefore the efficient method of discharge measurement which bases on the relationship between maximum and mean velocities being constant was employed to justify its alternative for the conventional methods: velocity-area and rating curve methods. Distribution test was applied to investigate the statistical properties of the uncertainties involved in the three methods of discharge measurement. Latin hypercube sampling (LHS) method was employed accordingly to assess the discharge features of the three methods of discharge measurement. The main purpose of this study is to quantify the uncertainty involved in several discharge measurement methods and justify the availability and reliability of using the efficient method as an alternative of the conventional methods. Results show that the correlation analysis also validates that the efficient method is a more reliable method than the rating curve method to yield accurate discharge measurements. Moreover, it also yielded comparably accurate measurements as those by the velocity-area method.

Keywords Efficient method of discharge measurement · Uncertainty analysis · Latin hypercube sampling method · Correlation analysis

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1 Introduction

River discharge measurement is the fundamental to water resources related engineering. The observation of river discharge has become more important nowadays due to Taiwan's water shortage. The velocity-area method which is considered as the most reliable approach to obtain accurate measurements is very time-consuming, costly, and dangerous during the flood events. In Taiwan, the heavy rainfalls and steep landforms cause the river stage to rise and recess rapidly. Discharge measurement which cannot be implemented in time would influence the measurement accuracy. Moreover, the hydrologists inevitably expose themselves in the dangerous environment to measure the flow velocity at various points and cross sections. Therefore, the most "reliable" method seems not the best alternative in Taiwan because of its distinctive river characteristics. The advantage of the rating curve method is that this method is very convenient to implement. With one observation in stage, the discharge measurement would come out accordingly from the rating curve equation or diagram. Sivapragasam and Mutill (2005) and Lee et al. (2010) have developed the modified rating curve methods for rating curve extension or observation improvement. However, the rating curve still has its shortcoming such as the controlling features that influences the discharge measurement accuracy (Herschy 2009). This indicates that ignoring the flow velocity would compromise the accuracy in discharge measurement.

The efficient method of discharge measurement developed by Chen (1998) takes the advantage of accuracy in the velocity-area method and convenience in the rating curve method. The efficient method applies the Acoustic Doppler Profiler (ADP) to the verticals of a river section. The maximum velocity of a section can be measured and located. The relationship of cross-sectional average velocity and maximum point velocity is derived from the maximum entropy method and probabilistic velocity distribution function. Multiplying the cross-sectional area from the stage-area relation, discharge may be estimated. The advantages of the efficient method are: (1) obtaining the discharge by a pair of observations on the maximum velocity and the stage, (2) reducing the observation time, and (3) lower hydrologists' risk in dangerous environment. This method has been implemented in several places including: Taiwan (Chen and Chiu 2002), US (Chiu and Chen 2003), Italy (Moramarco et al. 2004), and Algeria (Ammari and Remini 2010).

Discharge measurements usually involve in errors and are subjected to uncertainties. Generally, the measurement errors come from the following three sources (Bureau of Reclamation 1997): (1) spurious errors, (2) systematic errors, and (3) random errors. Spurious errors can be minimized through training and inspection. Systematic errors can be reduced through maintenance of system parts. Random errors are the irreproducibility in repeatedly measuring velocities and water stages and affect the precision of results. Therefore, all discharge measurement methods are all subjected to uncertainties in observation.

Uncertainty analysis has been conducted in engineering systems for years (Hsu and Rohmer 2010). The purpose of uncertainty analysis is to quantify statistical features of the system outputs and responses affected by uncertainty factors within the system. Tung and Mays (1981) applied the first-order second-moment (FOSM) method to flood levee design. Hsu et al. (2007) presented a solution by projecting FOSM results to obtain an equivalent most probable failure point in the material space as defined by the advanced first-order second-moment (AFOSM). Cheng et al. (1982) and Cheng (1993) applied the AFOSM method for dam overtopping assessment. Yeh and Tung (1993) applied the FOSM method to evaluate the uncertainty and sensitivity of a pit-migration model for sand and gravel mining from riverbed. Askew et al. (1971) used Monte Carlo sampling (MCS) technique to evaluate

the design of a multi-object reservoir system. McKay (1988) developed the LHS method, and it was proved to achieve a convergence in system performance more quickly with less samples than the MCS by various studies (Hall et al. 2005; Khanal et al. 2006; Manache and Melching 2004; Salas and Shin 1999; Smith and Goodrich 2000). Hsu et al. (2011) proposed the IS-LHS scheme, a combination of the importance sampling (IS) and LHS methods, to investigate the rare event of dam overtopping. Hsu and Rohmer (2010) employed LHS method to investigate the reliability of industrial synergy systems. Approximation methods (FOSM, AFOSM, or point estimation methods) have more restrictions in data distributional type or model linearity. The LHS method is therefore proposed to adopt in this study to reduce the computational burden in comparison with the MCS approach while preserving the accuracy of the solutions.

This article consists of three parts: (1) three methods of discharge measurement (velocity-area, rating curve, and efficient methods) and their application in the study site, (2) distribution test on the uncertainty factors associated with the three measurement methods, and (3) uncertainty analysis and model validation.

2 Methods of Discharge Measurement

Methods of discharge measurement generally can be categorized into three major methods: (1) velocity-area method, (2) rating curve method, (3) efficient method. The velocity-area method in this study is the control method, while the others are experimental methods. The discharge observations by the rating curve and efficient methods are compared with those estimated by the velocity-area method. Of the three methods, four uncertainty factors are considered in the uncertainty analysis detailed in Section 3.

The Lansheng Bridge Gauging Station is selected as the case study, which is located in midstream of the Nanshih River, Taipei County, Taiwan (see Fig. 1). Nanshih River has a mainstream of 45 kms in total length and a drainage area of 331.6 km². The annual rainfall in this watershed ranges between 3,000 and 4,400 mm. The watershed has no clear wet and dry seasons. However, the rainfall slightly concentrates in summer and autumn from June to October with the monthly average of more than 500 mm due to typhoons. Fig. 2 depicts the cross-sectional area which is divided into segments by a sufficient number of verticals across the channel. The velocity-area method was applied to observe 20 discharge rates at the Lansheng Bridge Gauging Station in the Years of 2007 and 2008. Meanwhile, the efficient method was also applied to locate and measure the maximum velocity. The details of the three discharge measurement methods for the application of the study site are given in the following three subsections.

2.1 Velocity-Area Method

The conventional flow velocity measurement generally applies propeller or acoustic Doppler velocimeters to measure the flow velocity at different vertical points of a river section. Once the velocity profile is obtained, the flow discharge rate can be estimated multiplying by the cross-sectional area:

$$Q = \sum_{i=1}^{n} \overline{u}_i \cdot A_i \tag{1}$$

where $\overline{u}_i$ and A_i represent the mean velocity and cross-sectional area of a segment, respectively. The details procedures for determining mean velocity can be referred to
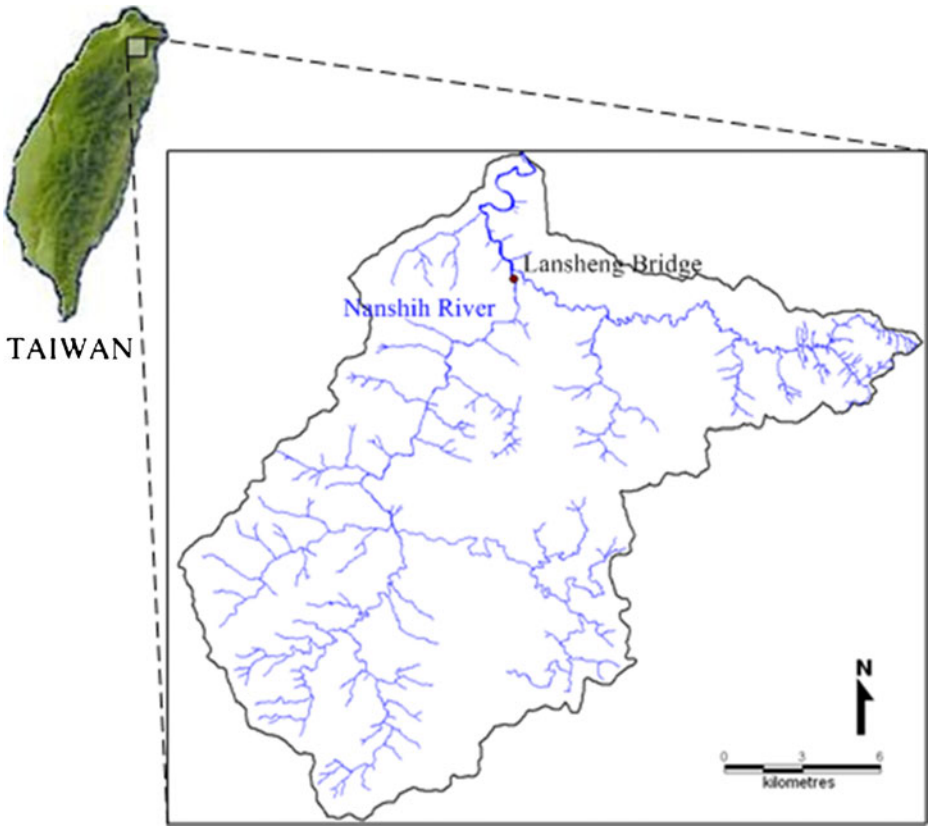
Fig. 1 Location of the Lansheng Bridge gauging station

Rantz (1982). Considering the flow discharge uncertainty in measurement, the mean velocity $\overline{u}_i$ and the cross-sectional area A_i of the ith segment will be further analyzed in the distribution test to obtain their distribution properties for the uncertainty analysis.

The conventional methods apply velocity measuring devices such as current meters to sample point velocity. Each point velocity is assigned to represent a meaningful part of the

Fig. 2 Cross section of the Lansheng Bridge gauging station
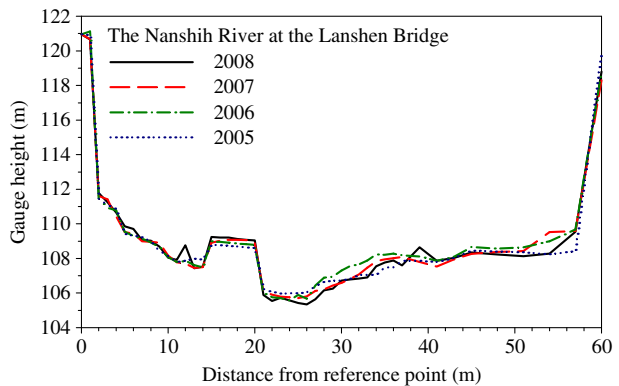
entire cross-section passing flow. The velocity-area principle is used to evaluate the discharge of the cross-section by those measured point velocities.

2.2 Rating Curve Method

Rating curve method develops a graphical figure of discharge versus stage at a gauging station of a stream, where the stage is measured by reading a gauge installed in the stream and later converted into flow discharge according to the rating curve. This method is a useful approach to the non-tidal waterway under the conditions that the stage and the cross section do not change rapidly. Once the relationship is developed, one just needs to observe the stage to obtain the flow discharge from the rating curve. If G represents gauge height (also known as stage) for flow discharge Q, the rating curve can be expressed as:

$$Q = a(G - e)^b \tag{2}$$

where a and b are constants; e is a constant representing the control elevation corresponding to zero discharge. The constants in Eq. (2) can be estimated by the standard methods given by Herschy (1999). Figure 3 indicates that the rating curve derived from the 20 discharge records collected from gauging station of the Lansheng Bridge is given as:

$$Q = 24.89(G - 107.80)^{2.089} \tag{3}$$

in which, the stage G is the gauge height which involves measurement and natural environment uncertainties. Its distributional properties will be obtained in the distribution test in Section 3.

2.3 Efficient Method

The efficient method can be seen as a combination of velocity-area and rating curve methods. The velocity term is based on the hypothesis that the mean velocity is constant proportional to the maximum velocity in the same stream (Chen1998; Chen and Chiu 2002). Moreover, this method also develops a direct relationship between stage and cross-sectional
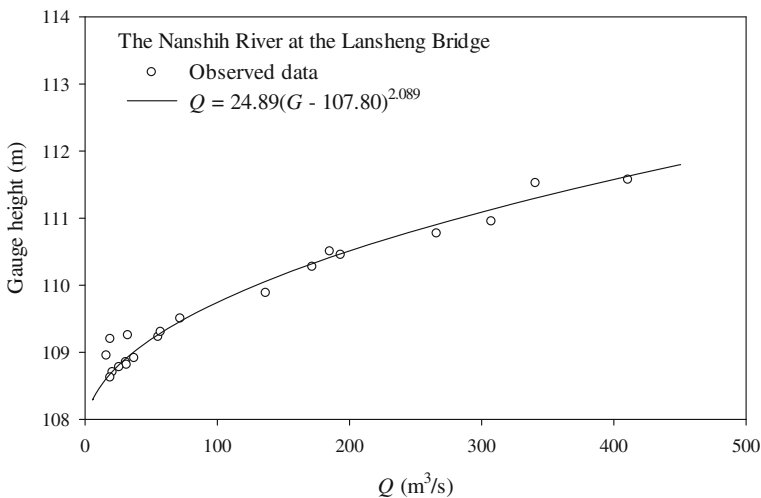

Fig. 3 Stage-discharge rating curve of the Lansheng Bridge

area like the rating curve method does for stage-discharge relationship. Therefore, one discharge rate by the efficient method can be estimated from one pair of maximum velocity and stage observation at the gauging station without the burdens arising from the time-consuming procedures by the conventional methods. The discharge Q estimated by the efficient method can be expressed as:

$$Q = \phi u_{\max} A_{est} \tag{4}$$

where ϕ is a constant which represents the relationship between the mean velocity $\overline{u}$ and maximum velocity $u_{\max}$; $u_{\max}$ and A_{est} are the maximum velocity and cross-sectional area, respectively. The procedure of developing an efficient discharge formula involves the following two steps: (a) developing the relationship between the mean velocity and maximum velocity, and (b) developing the relationship between stage and cross-sectional area. Once the maximum velocity is located and measured at the gauging station, the flow discharge is obtained accordingly. The details for developing the two relationships are given as:

2.3.1 Mean Velocity and Maximum Velocity

The relationship between mean and maximum velocities is based on (Chiu 1988):

$$\frac{\overline{u}}{u_{\max}} = \frac{e^M}{e^M - 1} - \frac{1}{M} = \phi \tag{5}$$

where $u_{\max}$ is the maximum velocity in the cross-section in m/s; ϕ is a constant ratio of the mean and maximum velocities; and M is the parameter of the probabilistic velocity distribution:

$$\frac{u}{u_{\max}} = \frac{1}{M} \ln \left[l + \left(e^M - 1 \right) \frac{\xi - \xi_0}{\xi_{\max} - \xi_0} \right] \tag{6}$$

where u is velocity on an isovel of a ξ; ξ is constant value on an isovel as shown in Fig. 4 (Chiu 1988). $\xi_{\max}$ and ξ_0 are the values of ξ when u is the maximum velocity and at the channel bed,
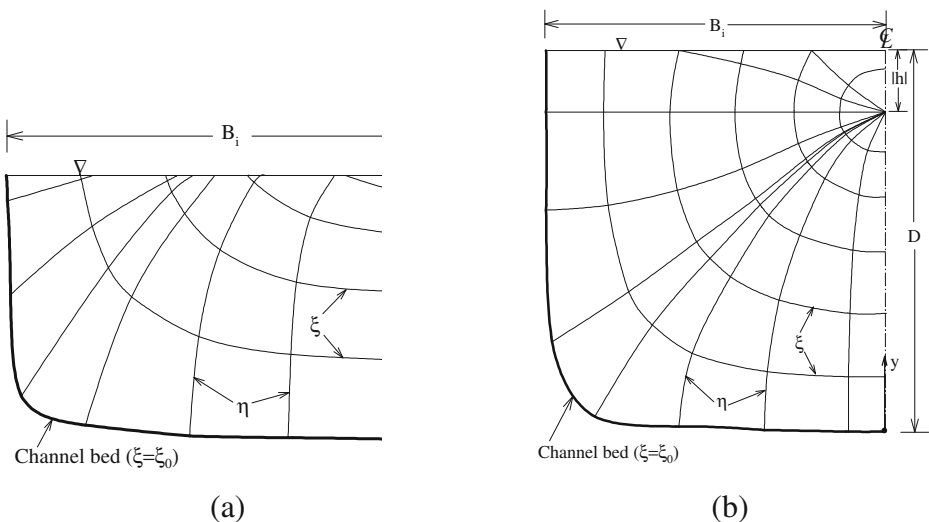

Fig. 4 Patterns of velocity distribution and isovels; **a** $h=0$; **b** $h \geq 0$.

respectively. ξ can be expressed as function of y on y-axis, which is the vertical passing through the point where the maximum velocity of the cross section occurs.

$$\xi = \frac{y}{D-h} \exp\left(1 - \frac{y}{D-h}\right) \qquad (7)$$

where y is the vertical distance from the channel bed; D is the water depth; h is a parameter with the value dependent on the location of maximum velocity. If u_{max} occurs on the water surface, $h \leq 0$ which describes the slope of the velocity profile in the vicinity of the water surface. If u_{max} occurs below the water surface, $h > 0$ which is regarded as the depth where u_{max} occurs.

   If the channel is free of scouring or depositing and does not change drastically, the location of y-axis is fairly stable and invariant with time and discharge (Chen and Chiu 2002). Therefore u_{max} can be determined from velocity samples on the y-axis. If many velocity samples on y-axis are available by new instruments such as Acoustic Doppler Current Profiler (ADCP), u_{max} can be obtained along with M and h by regression using (6) with ξ represented by (7). Therefore the mean velocity can be obtained by the product of u_{max} multiplied by ϕ, according to (5).

   The linear relationship between mean and maximum velocities indicates that ϕ value at a channel section is constant and stable for a wide range of discharge, water stage and sediment concentration, regardless the flow being steady or unsteady. This method was used in US (Chiu and Chen 2003), Taiwan (Chen and Chiu 2002), Italy (Moramarco et al. 2004), and Algeria (Ammari and Remini 2010) to estimate the mean velocity at a channel section. Figure 5 shows the excellent linear relationship between $\bar{u}$ and u_{max} from the Nanshih River at the Lansheng Bridge during a flood event. u_{max} was determined from velocity distribution measured by ADCP; and $\bar{u}$ was obtained as Q/A.

Fig. 5 $\bar{u} - u_{max}$ relation of the Nanshih River at the Lansheng Bridge
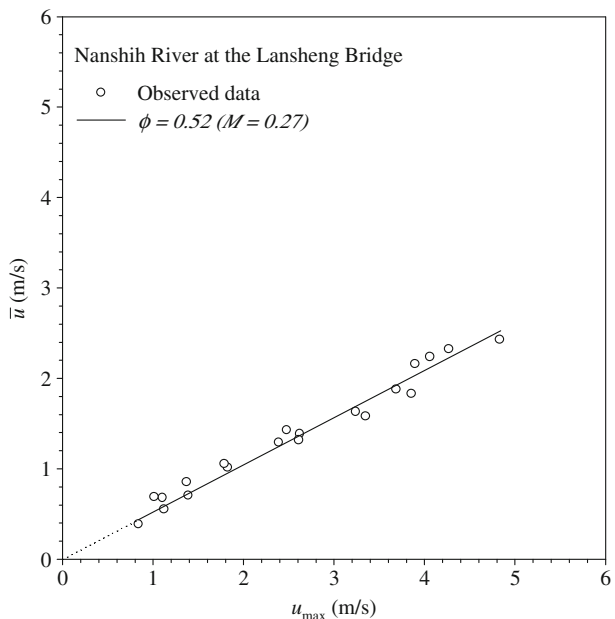
2.3.2 Stage and Cross-Sectional Area

In order to describe the bed shape and cross-sectional area, the cross-section is divided into segments by a sufficient number of verticals across the channel. The depths of successive verticals are averaged, the segment cross-sectional area being the product of the average depth and the segment width. Then the cross-sectional area is the sum of all segment areas. Those cross-sectional areas and water stages sampled by the conventional methods can be used to establish the stage - area relation as:

$$A = a(G - b)^c \tag{8}$$

where G is gauge height; a, b, and c are coefficients.

The efficient method of discharge measurement applies the relation of mean and maximum velocities being constant to obtain the mean velocity. The location of y-axis at the Lansheng Bridge occurs at 22 m from the reference point and is quite stable. Therefore the maximum velocity of the cross-section can be estimated from y-axis. Figure 5 indicates that the constant value of ϕ for the Lansheng Bridge is 0.52. Therefore the mean velocity of the cross section can be obtained as $\bar{u} = 0.52u_{max}$. Figure 6 shows that the stage-area relation of the Lansheng Bridge is $A=27.99(G-107.80)^{1.34}$. Thus, the discharge of the Lansheng Bridge can be estimated by using the efficient method of discharge as:

$$Q = 14.56u_{max}(G - 107.80)^{1.34} \tag{9}$$

Both, the stage and the discharge of a channel vary over the time. It is impossible to measure discharge continuously by the conventional methods. In Eq. (4), u_{max} and G effecting A are subjected to measurement and natural environment uncertainties. Their distributional properties will be obtained in the distribution test in Section 3.

3 Distribution Test on the Parameters of the Three Methods

The purpose of distribution test is to investigate the occurrence probability of different events. The commonly used distribution test methods, such as Kolmogorov-Smirnov (K-S) and Chi-square tests, are applied to investigate whether the observed data (including mean velocity, cross-sectional area, maximum velocity and water stage) have passed or failed the

Fig. 6 Stage-area relation of the Nanshih River at the Lansheng Bridge
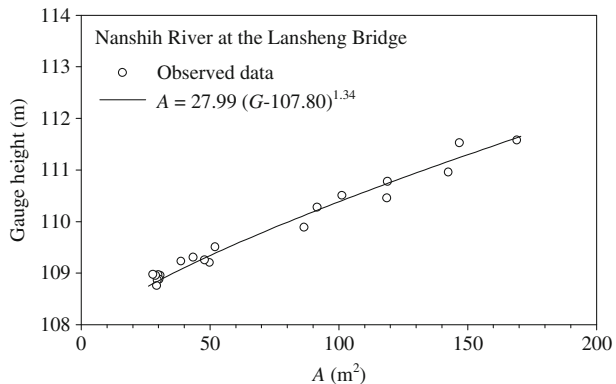
hypothesis of the fitted distributions. The distributions fitted in this study include the following distributions: normal, log-normal, Gumbel, Pearson III, and log-Pearson III. The observed data fitted in a distribution should both pass K-S and Chi-square tests. The best fitted distribution is selected according to the minimum sum of square errors (SSE). Once the best fitted distribution is selected, the distributional properties can also be obtained accordingly, which will be later applied in the uncertainty analysis as input.

As mentioned in the previous section, each of the discharge measurement methods has one or two variables for distribution tests: (1) velocity-area method: mean velocity and cross-sectional area, (2) rating curve method: stage, (3) efficient method: maximum velocity and stage. Table 1 demonstrates the key information of best fitted distributions for the four uncertainty factors, in which the mean velocity is Pearson III distributed, cross-sectional area is log-normally distributed, the stage is Gumbel distributed, and the maximum velocity is Pearson III distributed. Furthermore,

4 Uncertainty Analysis and Model Validation

Uncertainty analysis is employed to quantify statistical features of the system outputs and responses affected by uncertainty factors within the system. The commonly used methods are categorized into two methods: (1) Approximation methods: mean-value first-order second-moment (MFOSM), advanced first-order second-moment (AFOSM), Rosenblueth's point estimation (RPE) and Harr's point estimation (HPE) methods; and (2) Simulation methods: Monte Carlo sampling, Latin hypercube sampling, importance sampling and their variation methods (Hsu et al. 2011). The selection of appropriate method depends on the problem under investigation, including the availability of information, the complexity of the model, the type of results, and the level of accuracy required (Tung and Yen 2005).

4.1 Uncertainty Analysis Considering Correlated Field Data

As indicated by many investigators (Hall et al. 2005; Khanal et al. 2006; Kuo et al. 2008; Manache and Melching 2004; Salas and Shin 1999; Smith and Goodrich 2000) that the LHS method was proved to achieve convergence in a system performance more quickly with less samples than the MCS by various studies, this study adopts the LHS method to produce the

Table 1 Statistical properties of the uncertainty factors involved in the three discharge measurement methods	Uncertainty factors	Distribution	Parameters
	Mean velocity	Pearson 3	Location: −0.002
			Scale: 0.338
			Shape: 4.021
	Cross-sectional area	Log-Normal	Mean: 70.781
			Std Dev: 46.915
	Maximum velocity	Pearson 3	Location: 0.821
			Scale: 0.822
			Shape: 1.488
	Water stage	Gumbel	Mode: 109.73
			Scale: 0.73

input samples for the three discharge models. The LHS algorithm can be implemented, for k independent random variables, as follows (Tung and Yen 2005):

(1) Select the number of subinterval M for each random variable and divide the plausible range into M equal-probability intervals according to:

$$F_i(x_{im}) = \int_{\underline{x}_i}^{x_{im}} f_i(x_i)dx_i = \frac{m}{M} \tag{10}$$

where $F_i(\cdot)$ is the CDF of the random variable X_k; x_{im} and $\underline{x}_i$ are the upper and lower bounds of $F_i(\cdot)$, respectively.

(2) Generate M standard uniform random variates from $U\left(0, \frac{1}{M}\right)$.

(3) Determine a sequence of probability values p_{im} for $i=1, 2,...,k$; $m=1, 2,...,M$ using

$$p_{im} = \frac{m-1}{M} + \xi_{im} \tag{11}$$

where $\xi_{im} = \{\xi_{i1}, \xi_{i2}, ..., \xi_{iM}\}$ are the independent uniform random numbers from $\xi \sim U(0, 1/M)$.

(4) Generate random variates for each of the random variables using an appropriate method, such as: $x_{im} = F_i^{-1}(p_{im})$.

(5) Randomly permutate generated random sequences for all random variables.

(6) Compute the value of the performance function $Z = g(X) = g(X_{1m}, X_{2m}, ..., X_{im})$ corresponding to each set of generated random variables and estimate the statistical moments of the performance function Z.

Because of correlation among the field data collected at the Lansheng Bridge gauging station, the correlation of input samples should be taken into account. Figure 7 demonstrates that the correlation coefficient between the mean velocity and the cross-sectional area is estimated as -0.009, while it is estimated as 0.915 for the correlation between the maximum velocity and stage (see Fig. 8). Considering the two correlation factors, as mentioned in Section 3, the correlated input samples can be produced by following the standard procedures of Cholesky or eigenvetor decomposition methods given in Hasofer and Lind (1974), Der Kiureghian and Liu (1985), Chang et al. (1994), and Hsu et al. (2007).

Table 1 presents the four uncertainty factors and their distributional properties considered in the three discharge methods. The LHS and Cholesky decomposition methods are

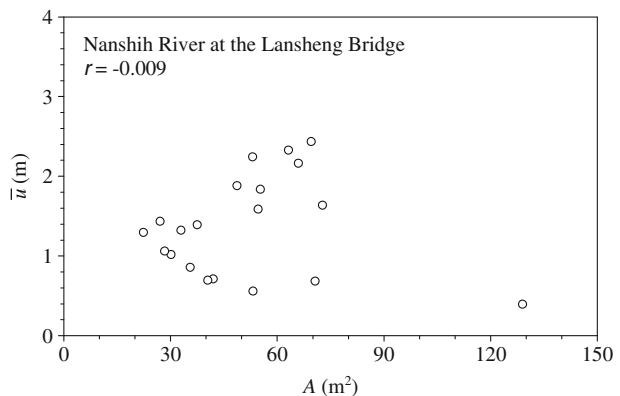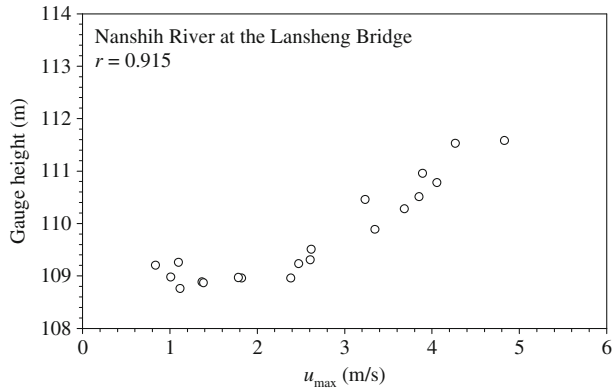Fig. 7 Correlation between mean velocity and cross sectional area

Fig. 8 Correlation between stage and maximum velocity

Nanshih River at the Lansheng Bridge
$r = 0.915$

employed to produce the input samples that follow the probabilistic properties assigned for the uncertainty factors of the three discharge models. 100,000 sample sets are produced as the inputs for the three discharge models. The discharges estimated by the three models statistically follow the log-normal distribution. As demonstrated in Table 2, the results by the efficient method all tend to approximate those by the velocity-area method, while the results by the rating curve method demonstrate a larger discrepancy from those obtained by the velocity-area method. The mean discharge by the efficient method is 95.81 m³/s, slightly smaller than 95.90 m³/s by the velocity-area method. Comparing the discharge measurements (Figs. 9, 10 and 11) by the three models, the efficient method shows that the discharge ranges from 11.76 m³/s to 334.20 m³/s within the 95 % confidence interval; while it ranges from 13.33 m³/s to 323.19 by the velocity-area method and 7.99 m³/s to 479.24 m³/s by the rating curve method. With little differences in the mean value, standard deviation, skewness, and kurtosis between the results of the velocity-area and efficient methods, the efficient method is proved to yield highly accurate solutions in discharge measurement similar to those of the conventional velocity-area method. Ignoring the flow velocity, the rating curve method has caused greater loss in accuracy by the hysteresis effect.

4.2 Model Validation

The aim of model validation is to prove the reliability of estimated discharges by the efficient method. In this study, the correlation coefficient is used to validate the reliability of the efficient method by comparing the discharge observations by the

Table 2 Results of uncertainty analysis on the three discharge measurement methods

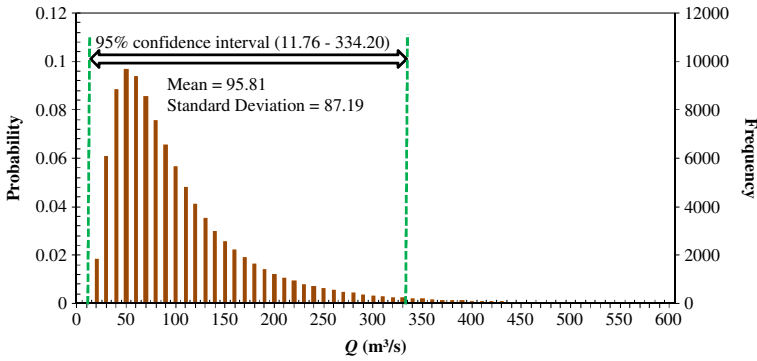| Method	Velocity-area	Rating curve	Efficient
Distribution	Log-Normal	Log-Normal	Log-Normal
Mean	95.9	122.28	95.81
Standard Deviation	83.74	125.15	87.19
Skewness	2.55	2.44	2.48
Kurtosis	12.97	11.13	12.97
Coeff. of Variability	0.87	1.02	0.91
95 % confidence interval	13.33–323.19	7.99–479.24	11.76–334.20

Fig. 9 Distribution of discharge measurements by the efficient method with 95 % confidence interval

conventional method with the discharges estimated by the efficient method. The correlation coefficient ρ is given as:

$$\rho = \frac{\sum \left(Q_{obs} - \overline{Q}_{obs}\right)\left(Q_{est} - \overline{Q}_{est}\right)}{\sqrt{\sum \left(Q_{obs} - \overline{Q}_{obs}\right)^2 \sum \left(Q_{est} - \overline{Q}_{est}\right)^2}} \tag{12}$$

Where Q_{obs} and Q_{est} are the discharge observations by the velocity-area method and the estimated discharges by the efficient method, respectively. $\overline{Q}_{obs}$ and $\overline{Q}_{est}$ are the mean values of the discharge observations and the estimated discharges, respectively. The correlation coefficient between the observed and estimated discharge data is 0.993 (Fig. 12) which assures the validity of the efficient method in discharge estimation. This also indicates that the efficient method is capable of yielding highly accurate discharge measurements, and is as reliable as the velocity-area method.

5 Summaries and Conclusions

This study investigates the reliability of the discharge measurements by the efficient method. By comparing the measurements obtained by the velocity-area and rating curve methods, the efficient method was proved to yield highly accurate discharge measurements. Moreover, it is as time-efficient as the rating curve method with just one extra observation—flow
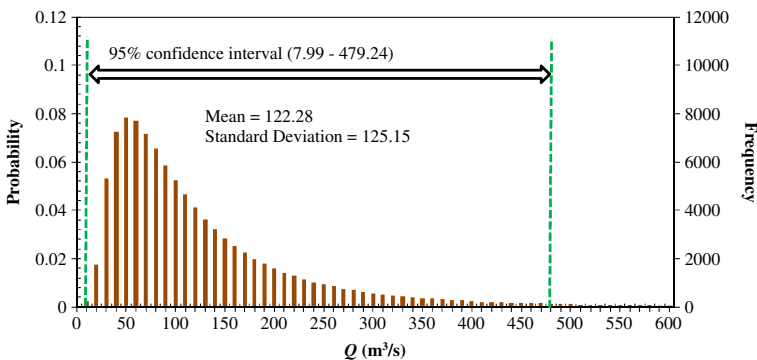

Fig. 10 Distribution of discharge measurements by the rating curve method with 95 % confidence interval
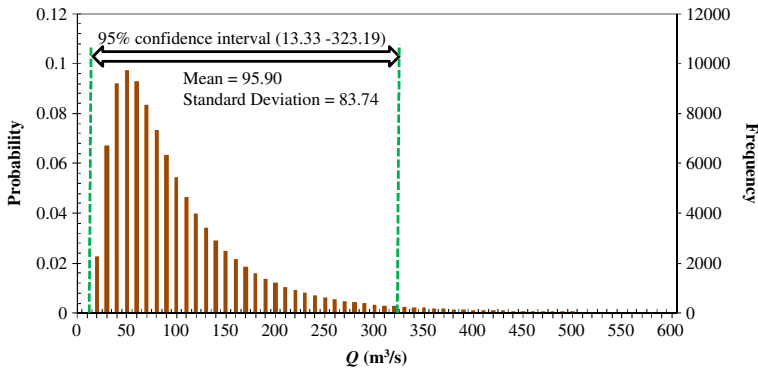
Fig. 11 Distribution of discharge measurements by the velocity-area method with 95 % confidence interval

velocity. The velocity-area method which requires both time and money is considered as the most reliable method for discharge measurements. The efficient method has been shown to perform as reliable as the velocity-area method and as efficient as the rating curve method.

To employ the uncertainty analysis on the three discharge measurement methods, the distribution type of the four parameters involved in the three methods were found: (1) mean velocity is Pearson III distributed, (2) cross-sectional area is log-normally distributed, (3) water stage is Gumbel distributed, and (4) maximum velocity is Pearson III distributed. The LHS method was employed to produce 100,000 sample sets of inputs for the three discharge models to illustrate the outputs of discharges. Results show that the discharge measurements by the three methods were all found log-normally distributed: (1) velocity-area method: mean value of 95.90 m^3/s, variability of 0.87, and 95 % confidence interval from 13.33 m^3/s–323.19 m^3/s; (2) rating curve method: mean value of 122.28 m^3/s, variability of 1.02, and 95 % confidence interval from 7.99 m^3/s–479.24 m^3/s; (3) efficient method: mean value of

Fig. 12 Correlation of discharge measurements by the velocity-area and the efficient methods
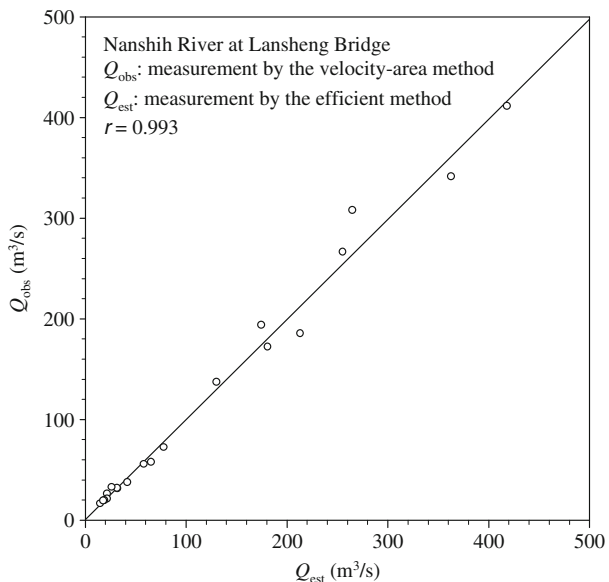
95.81 m^3/s, variability of 0.91, and 95 % confidence interval from 11.76 m^3/s–334.20 m^3/s. This indicates that the efficient method performs as well as the velocity-area method. With little difference in statistics, the efficient method can be considered as the better alternative to the conventional methods.

Moreover, the efficient method was also validated by evaluating the coefficient of correlation between its results and the results of the conventional method. The coefficient of correlation shows a very high relationship (0.993) between the discharge measurements obtained by the velocity-area and the efficient methods. This also proves that the efficient method is as respectably reliable as the velocity-area method.

Flow discharge not only acts as a vital piece of evidence to the national resources database, but also becomes an indispensable source to water resources planning and development. Good water management is founded on reliable discharge information that relies on the initial discharge measurements. The efficient method of discharge measurement can spare hydrographers from exposure to hazardous environments and sharply reduce the measurement time and cost. This study identifies that the efficient method of discharge measurement is as reliable as the conventional method and can accurately and quickly be applied to measure the flow discharge.

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