Flood discharge measurement of a mountain river – Nanshih River in Taiwan

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Abstract

An efficient method that accounts for personal safety, accuracy and reliability for measuring flood discharge of the Nanshih River at the Lansheng Bridge is proposed. The method applying available tools which are adapted for flood conditions can be used to quickly and accurately measure flood discharge. Measuring flood discharge directly from mountain rivers by using conventional discharge measurement methods is costly, time-consuming, and dangerous. Thus previous discharge estimations for mountainous area in Taiwan were typically based on indirect methods, which alone cannot generate accurate measurements. This study applies a flood discharge measurement system composed of an Acoustic Doppler Profiler and crane system to accurately and quickly measure velocity distributions and water depths. Moreover, an efficient method for measuring discharge, which is based on the relationship between mean and maximum velocities and the relationship between cross-sectional area and gauge height, is applied to estimate flood discharge. Flood discharge of the Nanshih River at the Lansheng Bridge can be estimated easily and rapidly by measuring maximum velocity in the river cross-section and the gauge height. The measured flood discharges can be utilized to create a reliable stage-discharge relationship for continuous estimations of discharge using records of water stage. Results of measured discharges and estimated discharges of the Nahshih River at the Lansheng Bridge only slightly differed from each other, demonstrating the efficiency and accuracy of the proposed method.

1. Introduction

Discharge data enable populations to share and manage finite water supplies. Effective water management requires accurate discharge measurements. With an average annual precipitation of 2,471 mm, rainfall is abundant in Taiwan. Thundershowers and the typhoons bring heavy downpours in the summertime. Therefore, the distribution of rainfall is uneven, making the water available for use per capita low. As water shortages become increasingly apparent, accurate discharge measurements become crucial. Sources of all major rivers worldwide are located in mountains and a significant proportion of the earth's surface is mountainous. Mountain rivers supply a large share of the world's population with fresh water (Viviroli and Weingartner, 2004). A mountain river is a river located within a mountainous region and has a stream gradient greater than or equal to 0.2% (Jarrette, 1992) along the majority of its channel-length.Mountains cover about 27% of the world's land surface, but only 13% of mountainous rivers have data (Bandyopadhy et al., 1997). Although the World Meteorological Organization recommends using high-density instrument networks in mountainous areas, the number of stream-gauging stations is still far lower than the recommended number (WMO, 1988). With a total area of about 36,179 km^2, two-thirds of Taiwan is covered with forested peaks. Steep mountain terrain above 1,000 m elevation constitutes about 32 % of the island's land area; hills and terraces between 100 and 1,000 m above sea level make up 31 %. However only a few of gauging stations can be found in Taiwan's mountain area. The reasons accounting for the lack of data for mountain rivers discharges are lack of funding, limitations of conventional methods and instruments for discharge measurement, difficulties in accessing gauging stations, and harsh environments that hinder discharge measurements.

A mountain river is a river located within a mountainous region and has a stream gradient greater than or equal to 0.2% (Jarrette, 1992) along the majority of its channel-length. Understanding the temporal and spatial variability of mountain river hydrology requires measuring discharge directly, systematically, and periodically. The most popular conventional method (current-meter method) for directly measuring discharge first measures velocities and cross-sectional areas. The required velocity measurements are obtained by placing a current meter at a desired location. However, during rapid flows associated with floods, submerging a meter in water is almost impossible, even when an adequate sounding weight is utilized. Additionally, riverbed instability due to rapid scouring and deposition during flooding make sounding water depth impossible; thus, measuring a cross-sectional area is extremely difficult. Flow conditions during floods are highly unsteady and water stages and discharges vary dramatically. Thus, accurate discharge measurements must be completed quickly. Furthermore, the conditions when measuring mountain river discharge during floods are far from ideal, especially as floods often occur during thundershowers and typhoons in Taiwan. Heavy rains and rapid flows combined with threats to the safety of hydrologists and instruments add to the difficulties associated with accurate measurements. Consequently, discharge data for mountain rivers are lacking in Taiwan. Due to these unsuitable conditions, using a velocity meter to measure discharge is difficult at best. Some new monitoring systems apply fixed side-looking Doppler profilers (H-ADCP) to measure river discharge (Nihei and Kimizu, 2008; Le Coz et al., 2008). However the water depth of the mountain rivers is usually very shallow. Intense rainfall events are frequent enough to cause significant high concentrations of suspended sediment in rivers that can also limit the function of ADCP. Those expensive systems lie idle most of the time. However it is possible to install an H-ADCP at an ideal site to measure high flow. A non-contact method that uses such instruments as a float (ISO, 2007; Rantz, 1982), optical current meter (Bureau of Reclamation, 1997), radar (Costa et al., 2006), and satellites (Alsdorf et al., 2007) may be considered. These instruments are safe and quick enough for estimating river discharge. Fixed surface velocity, however, is difficult to measure since the velocity of the water surface is normally affected by waves, winds and weather; thus, water surface velocity is also problematic since studied areas and angles change in accordance with water stages.

Measuring discharge levels using conventional methods and instruments during flooding is frequently impossible and very impractical. Thus, many discharges are determined after floods using indirect methods. Most indirect methods, such as the slope-area method (Chow, 1973), step-backwater method (O'Connor and Webb, 1988), contracted opening method (Benson and Dalrymple, 1967), and flow through culverts (Bodhaine, 1968), assume a steady and uniform flow. Mountainous floods, which typically move along steep river courses with debris, are generally unsteady and vary rapidly. Hence, using indirect methods to calculate estimated discharges frequently results in significant errors with accuracies rates of only 30% or greater (Bathurst, 1990). However, some rediscovered techniques such as dilution gauging (McGuier et al., 2007) and rising bubble method (Hilgersom and Luxemburg, 2012) can be used to measure discharge indirectly.

An accurate method and reliable equipment are needed to measure discharge from mountain rivers during high flows. This study applies a novel method and flood discharge measuring system that can be used to easily and accurately measure flood discharge of mountain rivers in Taiwan. Section 2 is devoted to the measuring system which is composed of an acoustic doppler current profiler, heavy sounding weight, wireless data transmission system, and crane for measuring velocity profile quickly. I introduce my measurement method for flood discharge that I refer to as "the efficient measurement method". The efficient method which makes use of maximum velocity and gauge height to estimate flood discharge is developed in Section 3. In section 4, the flood discharge measured by the proposed measurement system is used to illustrate the accuracy and reliability of the measurement method.

2. Flood discharge measuring system

The flood discharge measuring system must withstand the worst possible weather conditions and strong currents to observe and provide velocities and cross-sectional information for discharge calculations. Instruments can be selected according to the characteristics of each gauging station. Several different instruments are typically utilized to collect data during high flows. The measurement of swift streams with highly unsteady flow condition by current meter presents some problems such as impossible to sound and meter drift downstream. Therefore it would be better not to submerge an instrument in the water during high flow.

Based on Lu's work (Lu et al., 2006), the Acoustic Doppler Profiler (ADP) is placed in the C type sounding weight which is streamlined to offer minimum resistance to flow water. The height of the sounding weight is less than 0.3 m. When the sounding weight is lowered to the position under water surface 0.4 m, the sounding weight will be stationary in the water and submerged sufficiently to avoid air entrainment beneath the transducer. The advantage of the ADP is that it can immediately obtain velocity distribution and water-depth when ADP touches water (Chen et al., 2007). When adequate sounding weights are used, the ADP can stably measure velocity distribution in each of the selected verticals from water surface. The key instrument of the flood discharge measuring system is the ADP which is a 3-axis water current profiler. The resolution of velocity distribution and water depth depend on the frequency of ADP. High frequency pings yield more precise data, but low frequency pings travel father in the water. So a compromise between the distance that the profiler can measure and the precision of the measurements has to be made. Two ADPs with 3.0 and 1.5-MHz are tested at the beginning of the flood discharge measurement. However the 1.5-MHz ADP cannot be used near the right bank when water is too shallow. A 3.0-MHz ADP gives shorter profiling ranges but better spatial resolution. The water depth of the Nanshih River at the Lansheng Bridge is usually less than 6 m and the maximum profiling range of a 3.0-MHz ADP is 6 m. Thus a 3.0-MHz ADP, which is suited to the hydrological characteristics of the Nanshih River at the Lansheng Bridge, can collect velocity data.

The U.S. Geological Survey (USGS) has developed acoustic velocity meter systems for river discharge observations since the mid-80s (Laenen, 1985) and using ADCPs on moving boats for discharge measurements since the early 1990's (Oberg and Mueller, 1994), and recently has it been used in observations (ISO, 2005). The profiling range of an ADP is determined by its acoustic frequency. The performance of an ADP is also affected by sediment concentration, air bubbles and the hydraulic situation in which it is placed. Hence, an observer must first know the flow condition, concentration of suspended sediment, and water depth to select the appropriate acoustic frequency. The ADP measures water velocity using the Doppler shift, which is the shift of sound frequency reflected by a moving object (Brumley et al., 1991). The ADP transmits sound at a fixed frequency and obtains echoes returning from sound scatters in the water. These sound scatters are small particles, such as a suspended load, that reflect sound back to the ADP (Boiten, 2003). The ADP transmits a short pulse to measure relative water speed for many depth cells by range-gating the reflected signal as a velocity distribution on a vertical. It also transmits a series of bottom-track pings to determine water depth. Thus, during floods, an ADP can be placed on the water surface to measure the velocity distribution and water depth on a vertical. Although velocity distribution data can be obtained immediately, some areas were data is missing. Blanking distance is the distance the emitted sound travels while internal electronics prepare for data reception and the transducers stop vibrating from the transmission and become quiescent enough to accurately record the backscattered acoustic energy (Mueller et al., 2007). Fig. 1 shows transducer depth, blanking distance and bottom estimate, respectively. To obtain complete data for the velocity distribution using the ADP, water depth cannot be less than 1.5 m. At such depths, the current meter can be applied to measure the velocity distribution.

The suspended sounding weight is supported by the crane, the ADP is placed inside the sounding weight, and the electronic assembly is placed inside a metal box located above the sounding weight. The velocity distribution can be monitor on a laptop real time. The electronics assembly supplies power for ADP and processes the signal sent from ADP. To avoid damaging the flood discharge measurement system, application-specific carrying tools and supports are required for the worst conditions. Thus, a 136 kg C type sounding weight that is streamlined to offer minimum resistance to flowing water is used as the carrying device for the ADP. This sounding weight stabilizes the ADP and avoids damage from being struck by floating branches, junk and debris. The heavy weight of the sounding weight and ADP makes it impossible to operate without the help of machinery. A mobile crane is used to suspend the measuring system. This crane can be moved quickly among different locations. Because strong currents can overturn sounding weights and destroy the cable between ADP and the laptop, a wireless data transmission system is installed. The signals obtained by ADP are first transmitted through a probe cable to an electronics assembly and then the data is then sent to the radio telemetry system to transmit serial data to a wireless processing device - a laptop. The velocity distribution and water depth can be measured instantaneously and then calculated via data analyses. These data can be stored and saved on a computer for further study.

Measurements are usually made from a bridge; the flood discharge measurement is best carried out downstream of the bridge so the sounding weight does not collide with piers. However the discharge measurement is made at upstream of the bridge. The reason of making discharge at upstream of bridge is that the flow conditions are not affected by pier, less bubbles are found to block signal, and is more stable. Additionally, the crane arm must be long enough to suspend the sounding weight and position it far away from piers for avoiding the sounding weight colliding piers.

3. Computation of Flood Discharge

The discharge equations for open channels are based on the velocity area method (Herschy, 1999):

$$Q = \bar{u}A \tag{1}$$

where Q is discharge; $\bar{u}$ is mean velocity across a channel; and A is the cross-sectional area. Flood discharge measurement of mountain rivers can be estimated directly using mean velocity and cross-sectional area. The estimation of mean velocity is based on the relationship between mean and maximum velocities, and the cross-sectional area can be estimated by gauge height. Therefore estimating mean velocity of the cross-section from maximum velocity is unique to the proposed method.

The relationship between mean and maximum velocities (Chiu, 1987) is

$$\frac{\bar{u}_{obs}}{u_{\max}} = \phi \tag{2}$$

where $u_{\max}$ is the maximum velocity in a channel cross-section; $\bar{u}_{obs} = Q_{obs}/A_{obs}$; Q_{obs} is the observed discharge; and A_{obs} is the observed cross-sectional area. The ratio of $\bar{u}_{obs}$ to $u_{\max}$ in a given cross-section, ϕ, approaches a constant (Chiu and Said, 1995; Chiu, 1996). It is a linear relationship passing through the origin. The ϕ ratio characterizes the flow pattern at a given channel cross-section, and can be applied to steady or unsteady flows and is unaffected by discharge or the water stage (Chen and Chiu, 2002). Different cross-sections of an open channel have different ratios (Chen and Chiu, 2004). Using ϕ ratio to estimate discharge of rivers 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). To determine flood discharge using Eq. (2), one must obtain many sets of $\bar{u}$ and $u_{\max}$ to establish the relationship between maximum and mean velocities—the ϕ ratio. Once ϕ is determined, the flood discharge can be estimated quickly using maximum velocity and gauge height.

3.1 Estimation of maximum velocity to determine ϕ

To determine maximum velocity, an alternative velocity distribution model is needed that can describe the velocity distribution when maximum velocity is below the water surface. Chiu (1987) derived the following probabilistic velocity distribution equation:

$$\frac{u}{u_{\max}} = \frac{1}{M}\ln\left[1+\left(e^M-1\right)\frac{\xi-\xi_0}{\xi_{\max}-\xi_0}\right] \tag{3}$$

where ξ is the isovel in the $\xi-\eta$ coordinate system (Chiu and Chiou, 1988); *u* is velocity at ξ; *M* is the entropy parameter; ξ_0 and $\xi_{\max}$ are the maximum and minimum values of ξ at which $u = u_{\max}$ and *u*=0, respectively. *y*-axis is defined as the vertical on which $u_{\max}$ occurs. One of the advantages of Eq. (3) is that it is capable of describing the velocity distribution whether maximum velocity occurs on or below water surface. Thus Eq. (3) can be used to determine the maximum velocity from the velocity distribution data measured by ADP, especially maximum velocity occurring under water surface. Since isovels are intercepted by the *y*-axis, where both $\xi_{\max}$ and $u_{\max}$ occur, the ξ values of the isovels can be expressed as a function of *y* on the *y*-axis

$$\xi = \frac{y}{D-h}\exp\left(1-\frac{y}{D-h}\right) \tag{4}$$

where *D* is water depth on the *y*-axis; *y* is vertical distance from the channel bed; and *h* is the parameter indicating the location of $u_{\max}$. If $u_{\max}$ occurs on the water surface, $h \le 0$, and Eq. (3) becomes

$$\frac{u}{u_{\max}} = \frac{1}{M}\ln\left[1+\left(e^M-1\right)\frac{y}{D}\exp\left(\frac{D-y}{D-h}\right)\right] \tag{5}$$

If $u_{\max}$ occurs below the water surface, *h*>0 and *h* is the actual depth of $u_{\max}$ below the water surface, and Eq. (3) becomes

$$\frac{u}{u_{\max}} = \frac{1}{M}\ln\left[1+\left(e^{M}-1\right)\frac{y}{D-h}\exp\left(1-\frac{y}{D-h}\right)\right] \tag{6}$$

Although the location of $u_{\max}$ in an open-channel is not determined easily, it can be obtained using the isovels created with velocity data collected previously. In natural rivers, the *y*-axis can occur anywhere around the cross-section. If the cross-section of a relatively straight open channel does not change drastically, the location of *y*-axis is extremely steady and does not vary according to changes in time, water level, and discharge (Chiu and Chen, 2003). Restated, the likely location of the *y*-axis can be identified using historical data, and the maximum velocity of a cross-section can be obtained using the *y*-axis. Statistically, one standard deviation of distance from the *y*-axis can be used to identify the stability of the *y*-axis (Chiu and Chen, 1999). The maximum velocity obtained by data from around the *y*-axis and the actual value are very close; thus, a slight shift in the *y*-axis will not cause significant error in the estimated maximum velocity (Chiu and Chen, 2003). However ADP cannot sample the velocity near water surface and the velocity distribution is not continue. Hence, the nonlinear regression model can be fitted to velocity distribution data on the *y*-axis measured by the ADP to Eq. (3) for determining maximum velocity in the cross-section.

3.2 Estimation of mean velocity to determine ϕ

The mean velocity of the channel used to establish the relationship between mean and maximum velocities is determined by Q_{obs}/A_{obs}. Thus, measuring flood discharge using the conventional method becomes a very important but difficult task. The conventional method divides the cross-section into segments by spacing verticals at an appropriate number of locations across the channel. USGS suggests using 6 to 10 observation verticals in the measurement cross section for a small stream. Reduce the number of sections taken to about 15-18 during periods of rapidly changing stage on large streams (Rantz, 1982). Distance between verticals, depth, and velocities are measured at the verticals. A sounding weight or ADP is utilized to measure water depths at the verticals. The velocities at the verticals are measured using a current meter or ADP. Segment discharges are computed between successive verticals; therefore, total discharge may be computed as

$$Q_{obs} = \sum q_i \tag{7}$$

$$q_i = \bar{v}_i a_i \tag{8}$$

where q_i is the i^{th} segment discharge; $\bar{v}_i$ is the individual segment mean velocity normal to the segment; and a_i is the corresponding area of the segment. Notably, a_i can be determined using the midsection method.

3.3 Estimation of cross-sectional area

The cross-sectional area and gauge height data are collected during discharge measurement. The segment areas are summed to obtain the cross-sectional area of the open channel. If the streambed is stable and free of scouring and deposits, it is normally reliable to estimate cross-sectional area with gauge height. The relationship between cross-sectional area and gauge height (Chen and Chiu, 2002) can be expressed as

$$A_{est} = a(G-b)^c \tag{9}$$

where A_{est} is the estimated cross-sectional area; G is gauge height. a, b, and c are coefficients determined by nonlinear regression. Compared to the cross-sectional area during flood, when the area caused by scouring or depositing is small. Eq. (10) can also be applied to estimate cross-sectional area. If the relation of G and A_{obs} is not good enough, it could be a large source of uncertainty in the final discharge.

3.4 Estimation of the discharge by the efficient measurement method

Before the discharge estimation method, referred to as the efficient measurement method, is developed in a stream, obtaining $\bar{u}_{obs}$ to determine ϕ for a given cross-section in a stream is the key in developing the efficient method. The observed mean velocity of the cross-section is calculated as Q_{obs}/A_{obs}. The complete flood discharge measurements over the full cross-section are very important for establishing the relationship between mean and maximum velocities and it possibly will take several years to collect enough data. Therefore it is necessary to measure discharge and cross-sectional area by sampling velocities and depth in each vertical for determining mean velocity in each vertical and segment area. Then the discharge is derived from the sum of the product of mean velocity, depth and width between verticals. The velocity distribution made on y-axis is used to calculate maximum velocity of the cross-section for determining ϕ. The gauge height and cross-sectional area are used to establish the relation of gauge height and cross-sectional area.

Looking for the location of *y*-axis in a stream is difficult. For a straight and regular artificial channel, the *y*-axis usually occurs at the center of the cross-section. The location of *y*-axis in a natural channel can be located anywhere in the cross-section. Fortunately, the velocities used to determine the discharge reveal the location of *y*-axis. By using the measured velocity data, isovel patterns of a stream can indicate the location of *y*-axis.

Once the efficient method is established, only the velocity distribution on *y*-axis and gauge height are needed to be measured for estimating flood discharge. The maximum velocity determined by velocity distribution and ϕ can be used to estimate mean velocity of the cross-section. The cross-sectional area can be determined by the gauge height. Finally the flood discharge can be easily be estimated by $\phi u_{\max} A_{est}$.

4. **Description of study catchment and data**

The study site is located at the Lansheng Bridge on the Nanshih River. Fig. 2 shows the locations of the catchment area and gauge stations. Situated southeast of Taipei, Taiwan, the Nanshih River, an upstream branch of the Tanshui River, is a major fresh water source for the Taipei metropolitan area. To safeguard water quality and quantity, access to this area is restricted; thus, most of the area is untouched and forested. The area covers 331.6 km^2 and has an annual precipitation of 3082–4308 mm (average, 3600 mm). Days with precipitation are mostly concentrated in winter. The northeastern winds in winter create fine rain, whereas typhoons in summer bring heavy rains. The average monthly precipitation in the area from June to October exceeds 300 mm from 1992. Although a discharge measuring system that is composed of radar sensor for measuring water stage and current meter for measuring velocity has been in place on the Lansheng Bridge since 2005, flood discharge was not measured until 2007. The average discharge of the Nanshih River at the Lansheng Bridge is 26.9 m^3/s; the minimum is 0.9 m^3/s, and the maximum is 2295 m^3/s. The Nanshih River is about 35 km long to the Lansheng Bridge and 45 km to the confluence of the Nanshih River and the Beishih River; the highest altitude is 2,101 m on Mount Babobkoozoo, and the altitude of the river bed at the Lansheng Bridge is 106.8 m. Thus the stream gradient, which is the grade measured by the ratio of drop in elevation of a stream per unit horizontal distance, of the upstream of the Nanashih River exceeds 10% and the average stream gradient to the Lensheng Bridge is 5.7%. The stream gradient at the study site is about 1.5%, which is still relatively steep.

5. Measurement of Flood Discharge

This study was conducted on the Nanshih River at the Lansheng Bridge from 2007 to 2010. During the typhoon season, flood discharges were measured using the proposed flood measurement system. Fig. 3 shows the flood discharge measurement during Typhoon Krosa. Since maximum water depth during the non-typhoon season is usually less than 1.5 m, discharge is measured by current meter, not the ADP. At the *y*-axis (22 m from relative point situated at the left bank), velocity measurements are taken at 0.1 m intervals from the water surface to the channel bed when water is shallow and the ADP cannot be applied to measure velocity distribution.

The velocity distribution and water depth are measured at 3 m intervals during the typhoons for computation of discharge. The probabilistic velocity distribution equation is then utilized to simulate velocity profiles and calculate the mean velocities of the verticals. Finally, each segmental discharge can be obtained, the sum of which is the river discharge. As shown in Fig. 4, the flood discharge per unit width, mean velocity at each vertical and the corresponding depth are plotted over the water surface line. The top of Fig. 4 is the segmental mean velocity and discharge, and the bottom is the flow pattern. It also shows that most of discharge occurs in the main channel. By using the ADP, the cross-section can be easily and quickly surveyed for determining cross-sectional area. Table 1 shows the ADP measurements taken during typhoons in 2007 and 2008, of which 8 discharges were measured for five typhoons.

The bottom of Fig. 4 shows the velocity distribution of maximum measured flood discharge in 2007. z in Fig. 4 is the distance from relative point. The discharge was around 185.3 m^3/s. The dot in Fig. 4 is the actual velocity measurement on each vertical, and the solid line is the velocity distributions based on Eq. (3), indicating that vertical maximum velocity does not always occur on the water surface. Additionally, no definite relationship exists between mean and water surface velocity of the river. Hence, an accurate measurement of flood discharge must be based on the flow pattern below the water surface and not water surface velocity. However, if the maximum velocity always occurs on water surface, the relationship between mean and surface velocity can be developed using Eq. (2). The maximum velocity occurred at the vertical, 22 m away from the relative point. The maximum velocity of the cross-section estimated by Eq. (3) was 4.83 m/s and occurred on the water surface. Fig. 5 shows the isovels based on the observed velocities in Fig. 4. In Fig. 5, the vertical dash line reveals the location of y-axis. Owing to the effect of bridge piers, velocities around z = 15 m and z = 37 m are lower. Both Figs. 4 and 5 indicate that the major flood discharges are 15–30 m from the relative point, a sign that velocity on the right bank is slow, and the maximum velocity occurs around the 6th vertical from the left bank and on the water surface. Additionally, the observations of other flow patterns indicate that the maximum velocities always occur on the 6th vertical. This finding suggests that the *y*-axis locates on the 6th vertical. The *y*-axis is stable and unaffected by other factors such as stages and discharges. Fig. 6 shows the cross-sectional variation of the channel bed. The main course of the river bed does not change drastically, whereas the right side of the river bed has obvious scouring and deposition during flooding. For instance, on 28 November, the right bank shows obvious signs of scouring, and on 29 November, is deposited; the cross-section gradually returns to its previous stage. Based on the cross-section on 29 November, the scouring and depositing areas in the cross-section on 8 October and 28 November are 13.9 and 7.74 m^2, respectively. Table 2 shows the variation of area between two typhoon events. The area varies slightly between Typhoon and Krosa. At the beginning of Typhonn Mitag, the right side of the river bed is scoured deeply. However the Nanshih River tends to deposit it sediment in the end of Typhoon Mitag. After scouring and depositing, the change in area is 6.7 m^2 between Typhoon Sepat and Typhoon Sinlaku. It shows that the Nanshih River at the Lansheng Bridge is in the conditions of dynamic stability and near-equilibrium. Comparing with the cross-sectional area during flood, the scouring and depositing areas are relatively small. Therefore the observed cross-sectional areas can be used to establish the relation of water stage and cross-sectional area.

The data of discharge is split into two independent subsets: the calibration and validation subsets. The calibration subset with 19 observed discharges is used for parameter estimation. The validation subset, which consists of 5 observed discharges, is devoted to access the performance of the proposed method. Correlation coefficient indicating the strength of relationship between observed and estimated discharges and root-mean-square error (RMSE) evaluating the residual of observed and estimated discharges are used to evaluate the performance of the efficient method.

An efficient method of measuring flood discharges of mountain rivers can be established through repeated measurements. Fig. 7 shows the relationship between mean and maximum velocities of the Nanshih River at the Lansheng Bridge. It is a straight line goes through origin, and $\bar{u}_{est} = 0.51u_{\max}$. The maximum velocity of the cross-section can be calculated by Eq. (4), and the mean velocity is obtained by dividing the measured discharge by the cross-sectional area. All maximum velocities during floods exceed 3 m/s, whereas the $u_{\max}$ on ordinary days can reach 0.8 m/s, indicating a swift current. Moreover, the relationship between mean and maximum velocities is constant and quite stable in a wide range of discharge. It does not vary with time, water stage and sediment concentration, regardless of whether the flow is steady or unsteady. Using gauge height and cross-sectional area, the relationship between stage and area can be established. It is $A_{est} = 14.39(G - 107.32)^{1.68}$, as shown in Fig. 8. Fig. 9 shows the accuracy of the cross-sectional area estimated by the water stage. The correlation coefficients in both phases of calibration and validation are very high and RMSEs are low. The estimated areas agree quite well with the observed areas. Therefore, during floods, cross-sectional areas can be estimated based on gauge height.

During flood, maximum velocity can be observed on the *y*-axis, 22 m from the relative point. The channel cross-sectional area is calculated using gauge height, and mean velocity is obtained using the ϕ value and maximum velocity. Finally, discharge can be estimated by Q_{est}=7.34$u_{\max}$(G-107.32)$^{1.68}$. Fig. 10 shows the evaluation of discharge estimation accuracy for the Nanshih River at the Lansheng Bridge. All the data points nicely fall on the line of agreement. The RMSE of the calibration and evaluation are 16.4 and 15.2 m^3/sec. Moreover, the ρ of the calibration and evaluation are 0.99 and 0.96, respectively. The results show that the method performance is accurate and consistent in two different subsets. Both correlation coefficients are very close to unity, and both RMSEs are relatively smaller. It demonstrates that the proposed method can be successfully applied to estimate flood discharge of mountain rivers.

Fig. 11 shows the frequency functions for a normal distribution fitted to the ε%. Fig. 11(a) shows the relative frequency of error percentage. Fig. 11(b) shows the cumulative frequency (dots) and probability distribution function (curve). The mean of the errors approaches zero and the absolute measure of error is 7%. Thus the 95.44% confidence interval for the discharge error is from -2.11% to 2.69%. The χ^2 test is employed to determine whether the normal distribution adequately fits data. The χ^2 test statistic is χ_c^2=0.57 and the value of $\chi_{v,1-\alpha}^2$ for a cumulative probability is $\chi_{2,0.95}^2$=5.99. Since $\chi_{2,0.95}^2 > \chi_c^2$, these errors are mutually independent and normally distributed with a mean approaching zero and small variance. Clearly, the proposed method can be utilized to accurately and reliably measure flood discharge of mountain rivers.

The gauge station on the Lansheng Bridge was established in 2005 and it collected discharge data under low water levels by using the current meter method. In 2007, the station began to be used to collect data under high water levels with the method developed in this paper. Once the efficient method for measuring flood discharge of mountain rivers is established, the flood discharges during Typhoon Jangmi in 2008 are estimated only depending on maximum velocities and gauge heights. Fig. 12 shows the velocity distribution measured by ADP on *y*-axis during Typhoon Jangmi. Therefore the maximum velocity can be calculated by using Eq. (3) with the collected velocity distribution. The estimated flood discharges during Typhoon Jangmi are summarized in Table 3. In Table 3, Q is discharge estimated by the proposed method, and Qr is discharge estimated by stage-discharge rating curve. The discharge estimated by only the velocity distribution on *y*-axis is very close to the discharge estimated by rating curve. It shows that the method presented in this paper is reliable and accurate for estimating flood discharge. By using the proposed method, the flood discharge can be estimated quickly within 1 minute.

Real-time discharge at a stream-gauging station can be computed from a real-time stage using the stage-discharge relationship, which is also called the rating curve. Recorded discharges over a wide range are rare. Notably, measurement accuracy of conventional instruments and methods can be adversely affected and restricted by both location and weather; these instruments are most reliable during stable and low-flow conditions. Thus, long-term observations can be used to establish the lower part of a rating curve. However, to create a complete rating curve, high flow discharge data are needed. Fig. 13 is the water-stage rating curve of the Nanshih River at the Lansheng Bridge. When water stages are 113, 112, and 111 m, the differences between the discharges estimated by the old and new rating curve are 118, 109, and 81 m^3/s, respectively. The old rating curve severely underestimates discharge under high water levels, whereas the curve for 2010 was likely adjusted according to flood discharge, markedly improving its accuracy and efficiency. It indicates that the importance of flood discharge for establishing a stage-discharge rating curve. The accurate rating curve with the actual measurements during high water also demonstrates this method has improved the overall discharge measurement of the river.

6. Conclusions

Flood discharge measurement is always a difficult and dangerous task. The characteristics of mountain rivers make it impractical to use conventional methods and instruments to measure discharges during floods. Concerns for personal safety, accuracy, reliability, and efficiency, a new measurement method and system have to be developed for flood discharge measurement in Taiwan. According to the hydrological characteristics of the Nanshih River at the Lansheng Bridge, a flood measuring system composed of useful techniques and tools is applied to collect velocity and water depth data over the full cross-section for calculating discharge and determining the location of *y*-axis. The efficient discharge measurement method based on the relation of mean and maximum velocities and the relation of gauge height and cross-sectional area is developed to estimate the flood discharge in the Nanshih River at the Lansheng Bridge. Therefore the flood discharge can be easily estimate by sampling gauge height and the velocity distribution on *y*-axis for calculating maximum velocity. Those flood data used for establishing stage-discharge rating curve makes real time flood discharge estimation possible. Like the other index velocity methods converting the velocity at a point or in a section to the mean velocity, the efficient method is also an index velocity method for measuring flood discharge in mountain rivers. The merits of the proposed measuring system and method for measuring flood discharge of mountain rivers in Taiwan are as follows: 1) considerably accuracy and efficiency; 2) flood discharges can be measured - an impossible task previously; and, 3) hydrologists are not exposed to harsh environments during typhoons and floods too long. The proposed measurement system is used to measure flood discharge in the mountain area of Taiwan to verify this efficient method. The results provide evidence that this efficient method can offer good performance in measuring flood discharge of the Nanshih River at the Lansheng Bridge.

This research is limited to an initial study of the application of the efficient method in estimating flood discharge in the Nanshih River at the Lansheng Bridge. Further studies could be extended to measure more flood discharges of the other mountain rivers for validating the efficient method. Even the proposed method is a fast and minimally intrusive measurement method; it is still very dangerous to measure the velocity distribution on y-axis during floods. It is necessary to develop a model for estimating maximum velocity not on y-axis.

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Table 1. Flood discharge measurement of the Nanshih River by using ADP at the Lansheng Bridge in 2007 and 2008.

Typhoon	Date	G (m)	A_{obs} (m^2)	Q_{obs} (m^3/s)
Sepat	9/8/2007	110.95	142.5	308.6
		110.77	119.0	266.2
Wipha	9/19/2007	110.31	91.7	171.9
Krosa	10/7/2007	111.57	169.2	447.6
	10/8/2007	110.50	101.3	185.3
Mitag	11/28/2007	110.45	118.8	193.6
	11/29/2007	109.88	86.6	136.8
Sinlaku	9/15/2008	111.52	146.9	341.1

Table 2. Area variation between two typhoon events.

Typhoon	Date	G (m)	A_v (m^2)	%
Sepat	9/8/2007	100.95		
		110.77	4.1	2.9
Wipha	9/19/2007	110.31	-3.4	-2.9
Krosa	10/7/2007	111.57	-5.3	-5.8
	10/8/2007	111.50	-0.1	-0.1
Mitag	11/28/2007	111.45	-22.5	-22.2
	11/29/2007	109.88	6.7	5.6
Sinlaku	9/15/2008	111.52	27.0	31.2
Total			6.7	

Table 3. Flood discharge of the Nanshih River at the Lansheng Bridge estimated by the efficient method during Typhoon Jangmi in September 28, 2008.

Time	G (m)	$u_{\max}$ (m/s)	$\overline{u}_{est}$ (m/s)	A_{est} (m^2)	Q_{est} (m^3/s)	Q_r (m^3/s)	Q_{est}-Q_r (m^3/s)
11:35 am	112.30	4.05	2.09	213.8	448.6	496.3	-47.7
12:35 pm	112.20	4.51	2.33	207.8	485.4	475.9	9.5
2:05 pm	112.30	4.43	2.29	213.9	504.6	496.3	8.3
2:54 pm	112.63	4.22	2.18	233.9	511.3	566.4	-55.1
3:58 pm	113.18	4.93	2.55	268.0	684.4	691.6	-7.2

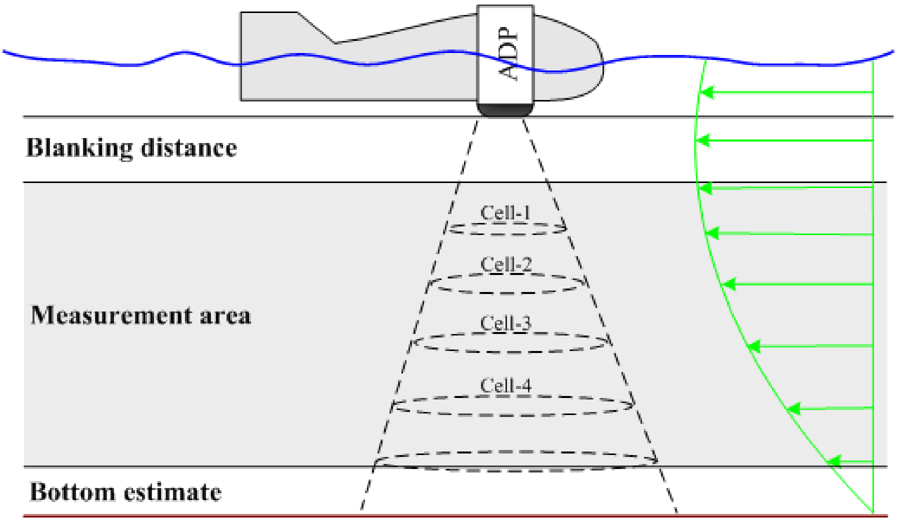


Fig. 1. Unmeasured areas of ADP.

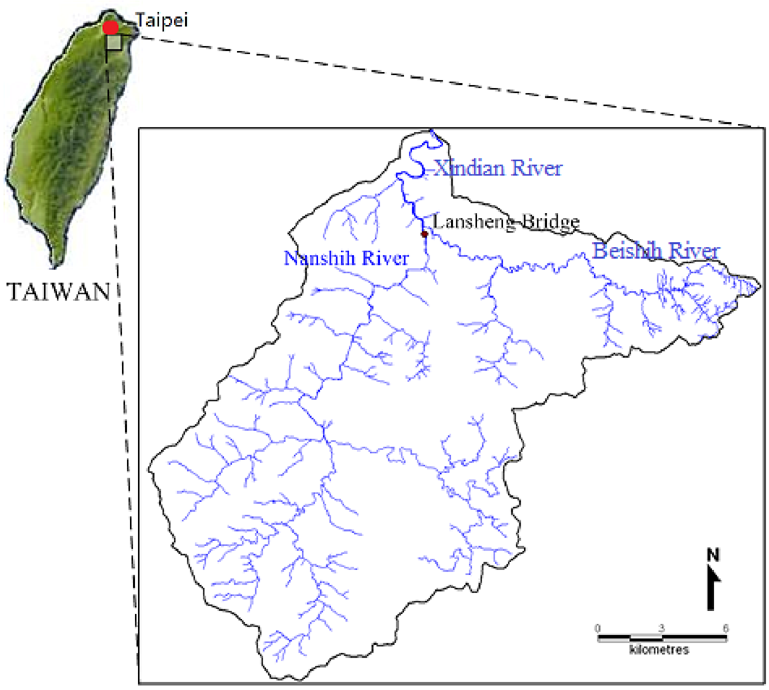


Fig. 2. Location of the study site in the catchment of the Nanshih River, Taiwan.

Fig. 3. Flood discharge measurement during Typhoon Krosa.

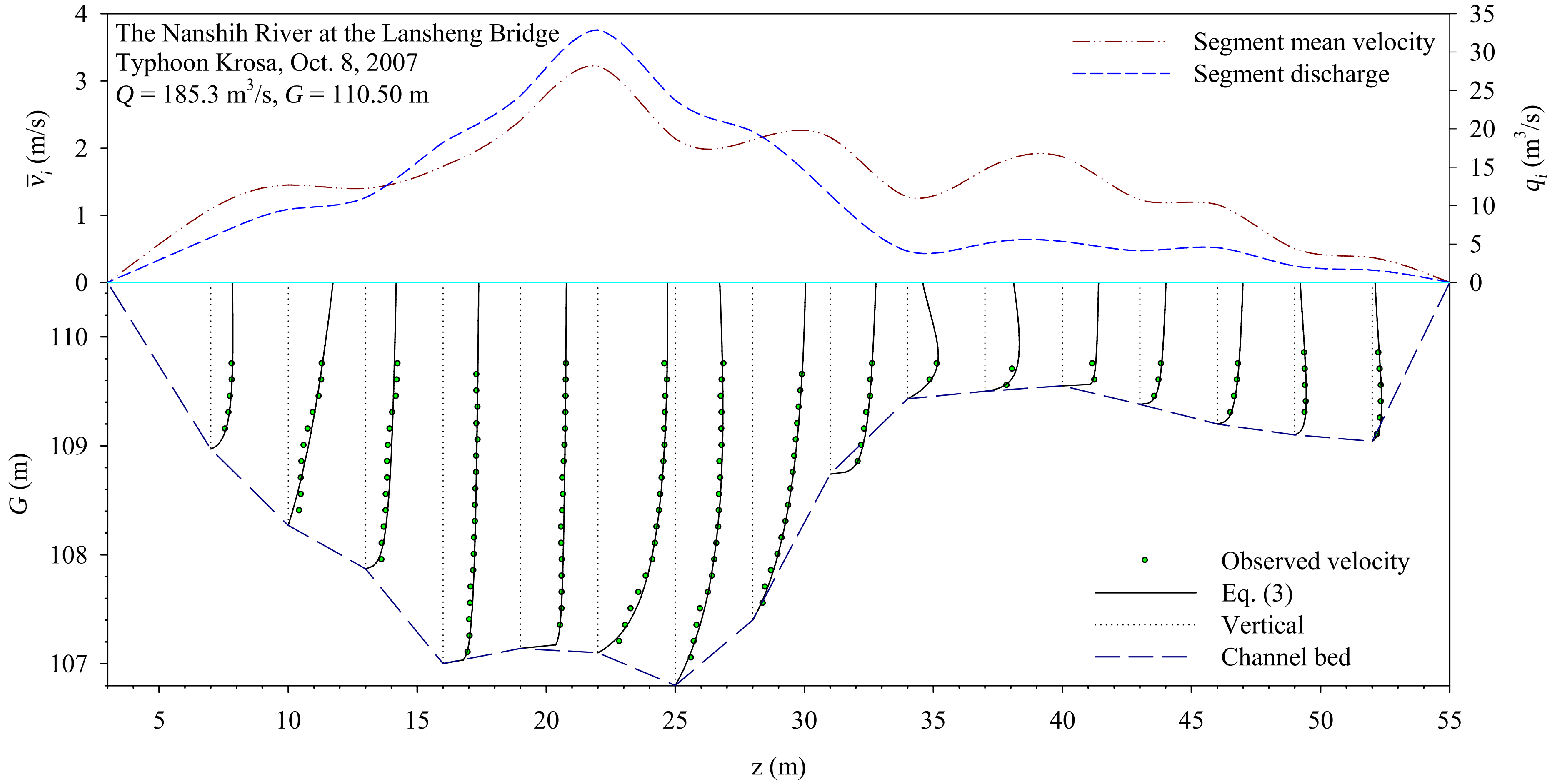


Fig. 4. Depth velocity graph during Typhoon Krosa (Oct. 8, 2007).

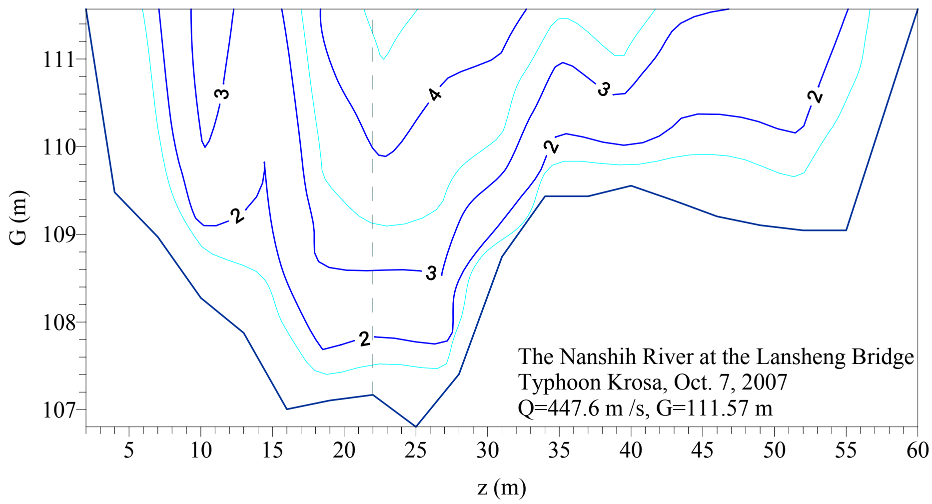


Fig. 5. Isovels in the Nanshih River at the Lansheng Bridge during Typhoon Krosa.

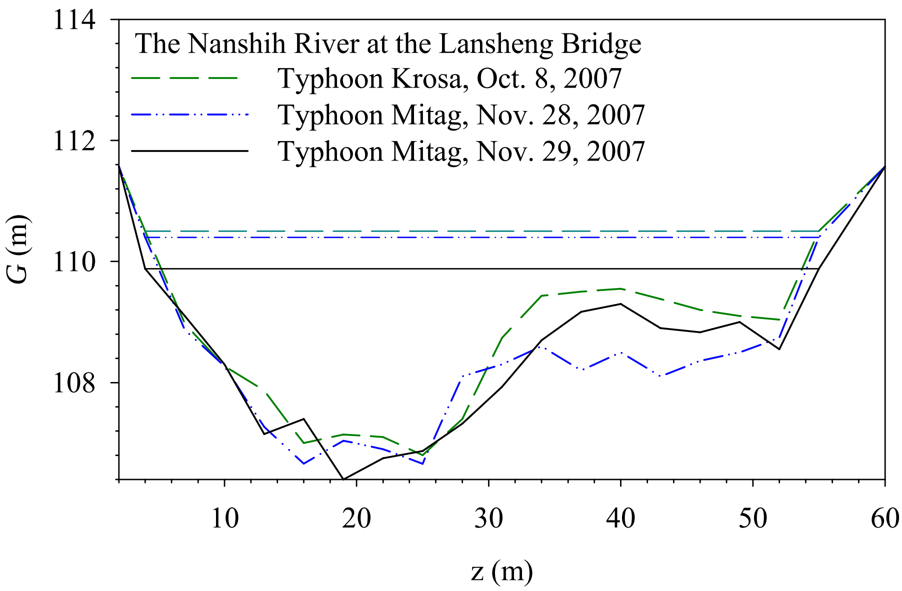


Fig. 6. Scour and deposit of channel bed during Typhoon Mitag.

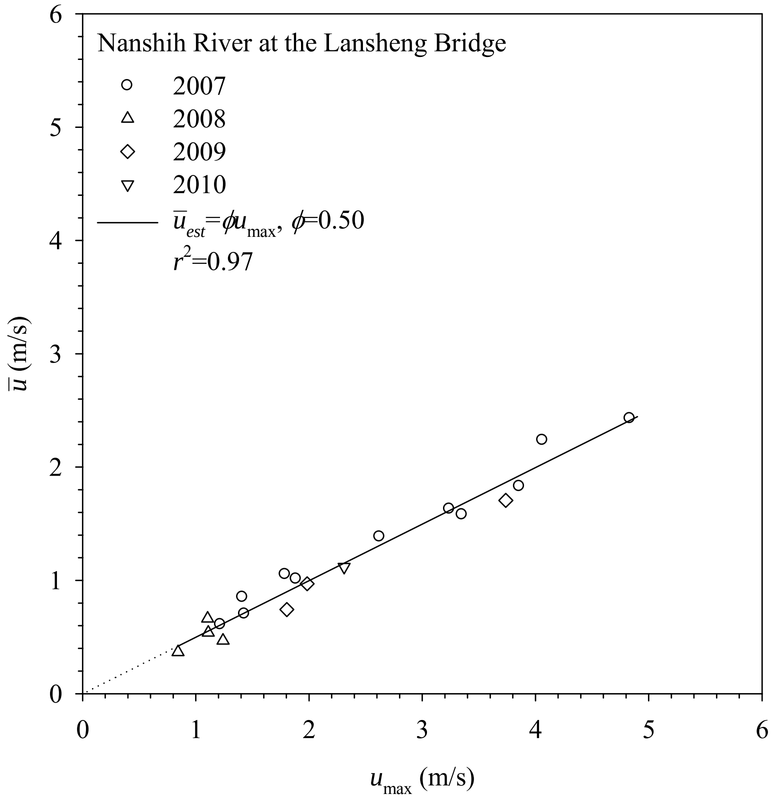


Fig. 7. Relation between mean and maximum velocities.

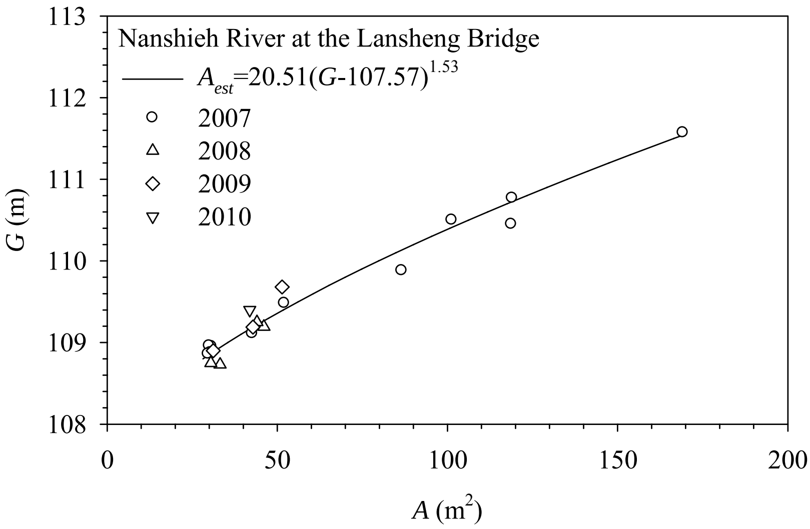
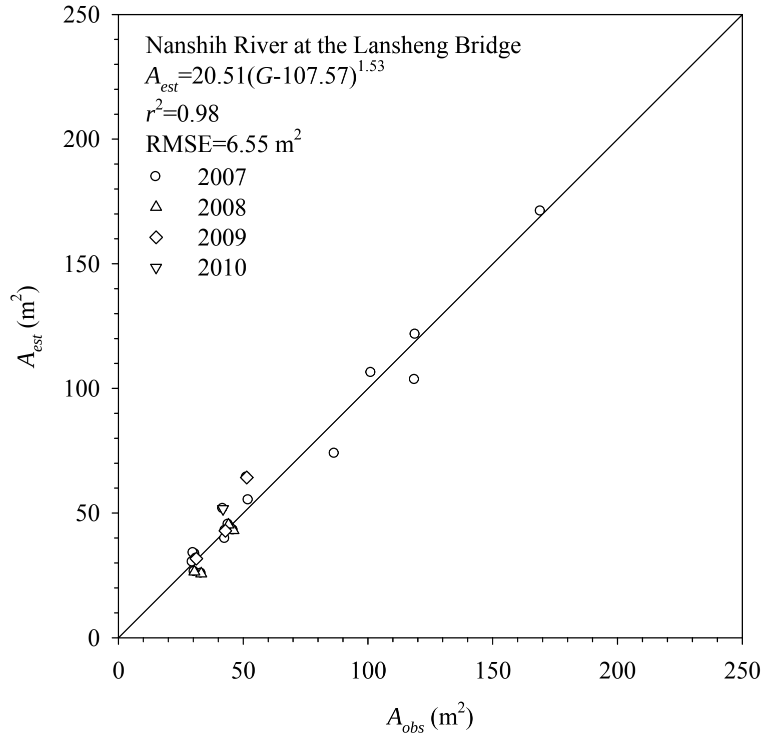
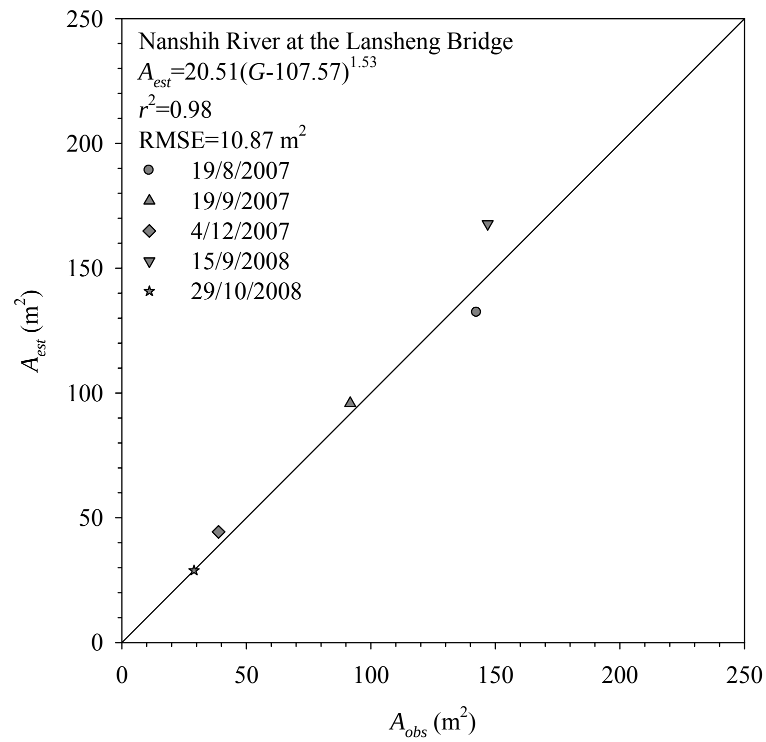


Fig. 8. Relation between gauge height and cross-sectional area.

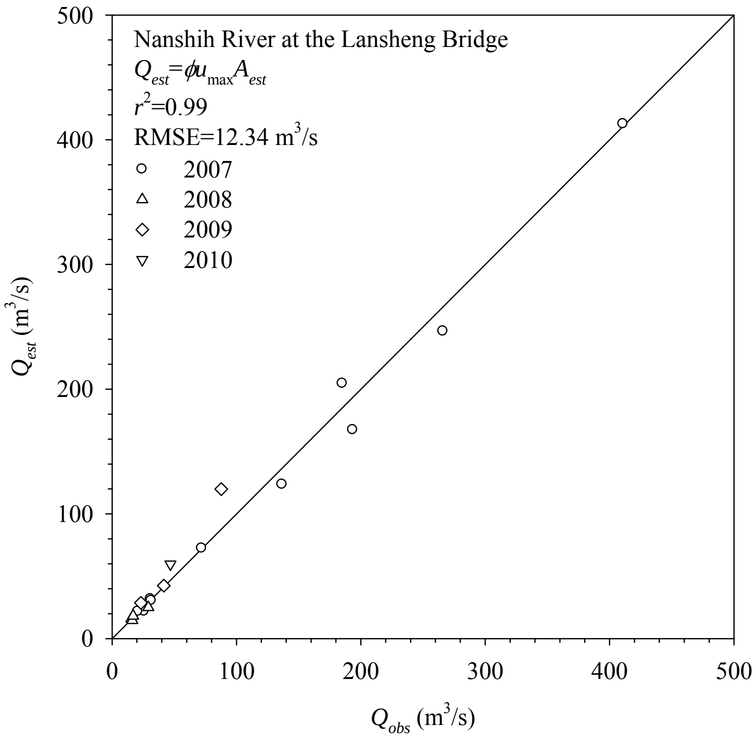


(a)

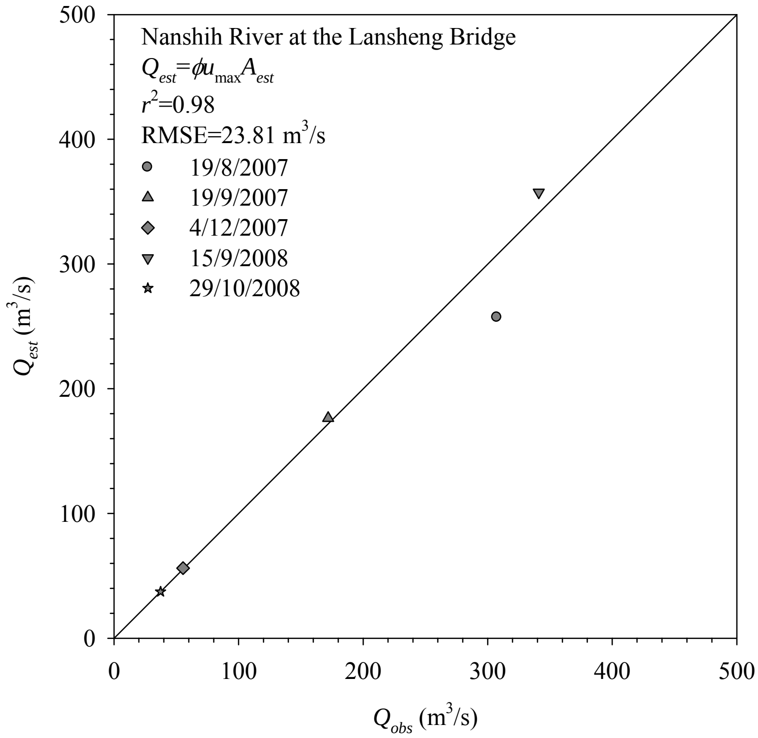


(b)

Fig. 9. Accuracy of estimated cross-sectional area in the Nanshieh River at the Lansheng Bridge; (a) Calibration; (b) Validation.

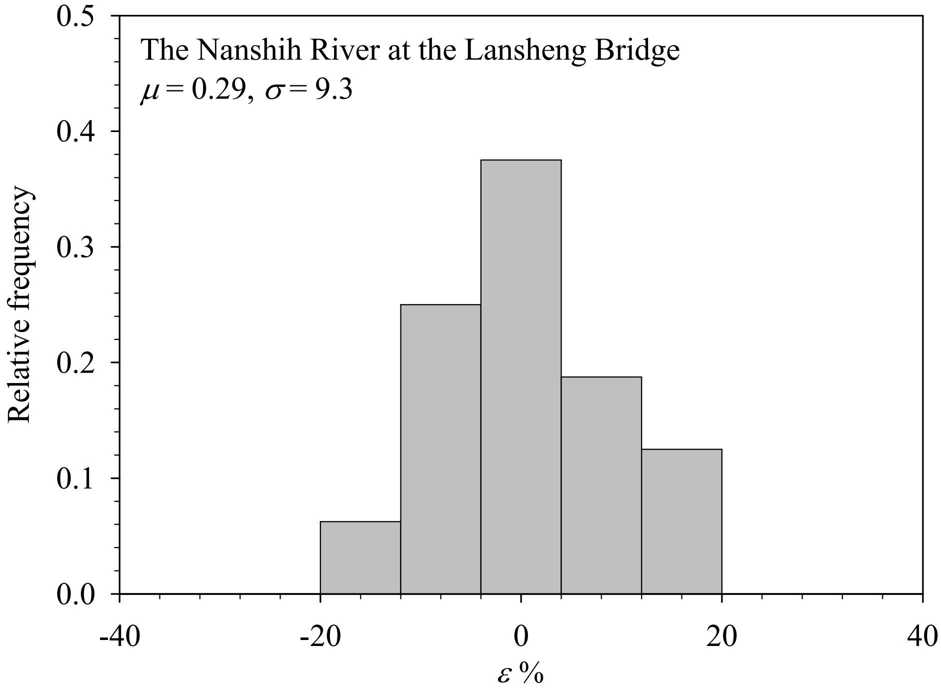


(a)

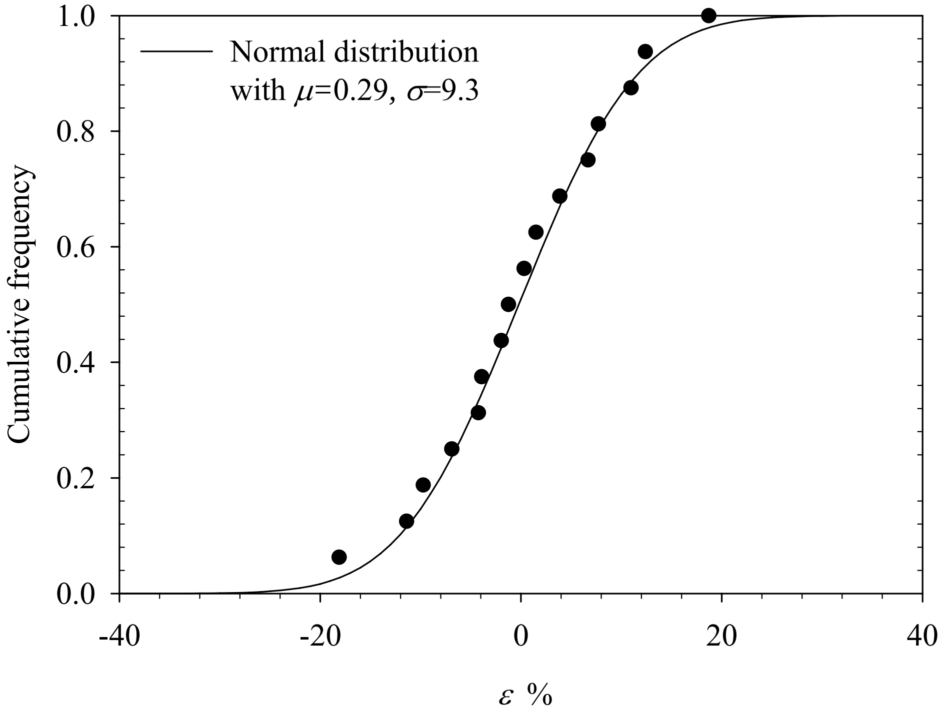


(b)

Fig. 10. Accuracy of estimated discharge in the Nanshieh River at the Lansheng Bridge; (a) Calibration; (b) Validation.



(a)



(b)

Fig. 11. Frequency functions for a normal distribution fitted to error %; (a) Relative frequency of error %; (b) Cumulative frequency of error %.

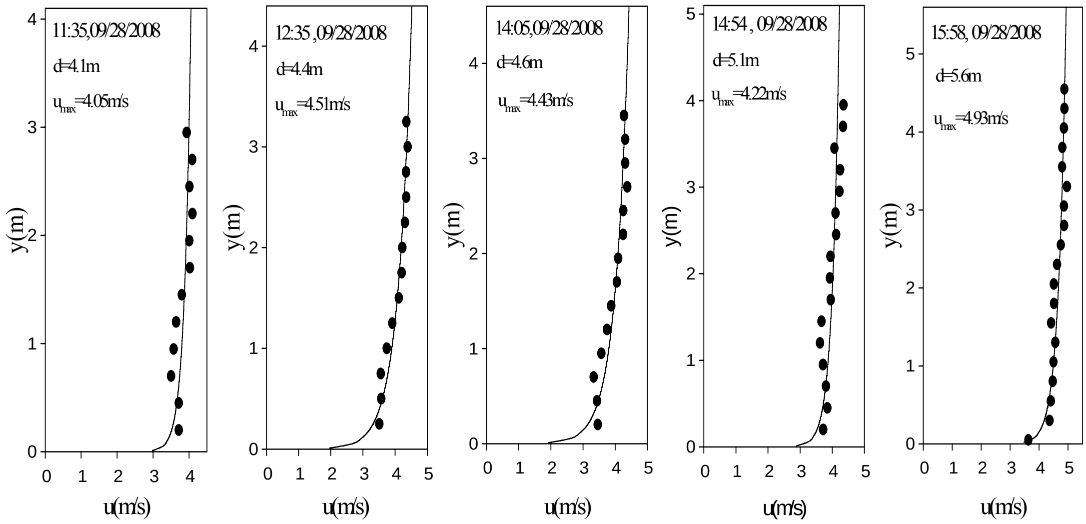


Fig. 12. Velocity distribution on *y*-axis during Typhoon Jangmi in 2008.

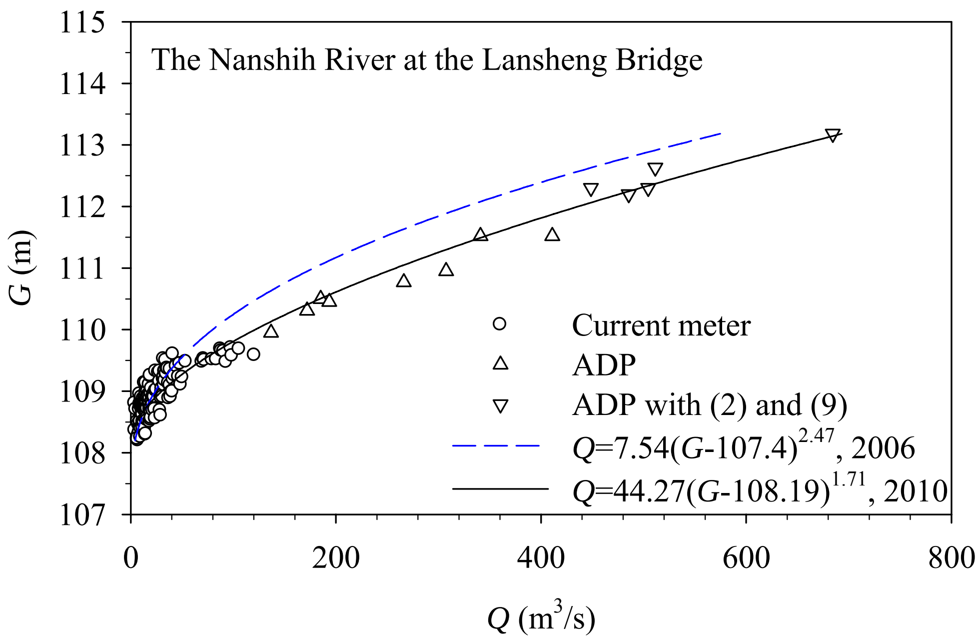


Fig. 13. Stage-discharge rating curve of the Nanshieh River at the Lansheng Bridge.