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Application of a portable measuring system with acoustic Doppler current profiler to discharge observations in steep rivers

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Abstract

Obtaining discharge measurements during high flows is very difficult in steep rivers (slopes greater than about 0.1%) because of the highly unstable free surfaces and bed elevations. In this study, a portable flow measuring system with an acoustic velocimeter was developed. The proposed system has been proved to be better than existing systems for streamflow measurements in steep rivers. Field data collected by conventional velocimeters were analyzed, and compared with the flow measurements using the portable system with an ADP (acoustic Doppler profiler) or ADCP (acoustic Doppler current profiler). The effects of channel patterns on the applicability of the highly efficient discharge estimation method, as proposed by C.L. Chiu [An efficient method of discharge measurement in rivers and streams. In: Lecture of the workshop for development and application of discharge measurement in Taiwan. Taichung (Taiwan): National Chung-Hsing University, 1996. p. 55 [in Chinese]], were also discussed. In general, the method was applicable to higher flows where the measuring verticals were reasonably stable.

Keywords: Streamflow measurement; Acoustic velocimeter; Steep river; Channel type

1. Introduction

Streamflow information is the basis for planning, designing and operating water management and development projects. High flow discharge measurements are difficult, especially for rivers with steep gradients (slopes greater than about 0.1%) due to the shallow flow depths and the extreme turbulence (Jarrett [2]). These data, however, are very important for the verification of mathematical models, the establishment of stage-discharge rating curves, and flood forecasting.

There are many methods available for direct or indirect river discharge measurements (Herschy [3]). The most common current meter is based on the mechanical theory with either cup-type (e.g. Price meter) or propeller-type. The stream is divided into a number of vertical sections. The average of the velocities at two-tenths and eight-tenths depth below the water surface is used to estimate the mean velocity in the vertical. For a very shallow sub-section near the shore, the velocity at six-tenths depth below the water surface may be used to approximate the mean velocity in the vertical (Chow [4]). Although this conventional method is easy to operate, it has several disadvantages. It takes a long period of time to complete the velocity measurements of the whole cross-section. The upper limit of the flow velocity is usually about 3 m/s. Also, the positioning of the measuring point is not very easy.

Many non-contact discharge measuring methods have made great progress in recent years due to the advances in remote sensing and data processing techniques. Particle image velocimetry (PIV; Fujita et al. [5]), radio current meter (Yamaguchi et al. [6]), and the pulse radar system (Costa et al. [7], Lee et al. [8,9]) are three typical examples. The non-contact feature can prevent the equipment from being damaged by debris in the flow during extreme weather conditions. However, most of these methods can only measure the surface velocities of the flow. Difficulties encountered in estimating the flow depth and mean velocity of each vertical may limit their practical applications.

The acoustic Doppler current profiler (ADCP or ADP) uses the Doppler effect to measure the motion of the water

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Nomenclature

A_{est}	estimated flow area (m^2)
A_{obs}	observed flow area (m^2)
B	water surface width (m)
a, b, c	parameters in the relationship of $A_{est} = a \cdot (BD - c)^b$
D	flow depth at the y-axis (m)
H	flow stage (m)
M	dimensionless entropy parameter
Q_{est}	estimated flow discharge (m^3/s)
Q_{obs}	observed flow discharge (m^3/s)
r^2	coefficient of determination
u	flow velocity (m/s)
$\bar{u}$	cross-sectional mean flow velocity (m/s)
$\bar{u}_{est}$	estimated mean flow velocity in a channel cross-section (m/s)
$\bar{u}_{obs}$	observed mean flow velocity in a channel cross-section (m/s)
u_{max}	maximum velocity in a channel cross-section (m/s)
x	distance from left bank (m)
$\overline{X}_y$	mean location (distance from left bank, x) of the "y-axis" in a cross-section (m)
y-axis	vertical passing through the point with maximum velocity in a cross-section (m)
ϕ	ratio of $\bar{u}$ to u_{max}
σ	standard deviation
ξ	variable of coordinate on an isovel on which the velocity is equal to u
ξ_0	minimum value of ξ at which $u = 0$
ξ_{max}	maximum value of ξ and occurs at the location of u_{max}

(Kraus et al. [10]). The Doppler effect refers to the compression or expansion of the transmitted sonar signal caused by the relative motion between the ADCP and the scattering material in the water column. The ADCP can determine both the velocity and direction of the water current. The major difference between the ADCP and the conventional current meters is that ADCP is capable of measuring a profile of the water current through the water column. It can also measure the flow depth. The maximum flow velocity that ADCP can measure is 10 m/s. The ADCP has been used in many different ways, e.g. attached to telemetering surface buoys, fixed on stationary platforms, or installed in submerged vehicles. However, in general, it is very difficult to apply these methods to unsteady flows in steep rivers because of the large variations in the bed levels (erosion or deposition) and the highly unstable water surfaces that have an significant amount of air entrainment.

Based on the probability concept, Chiu [11] analyzed the relationship between the maximum and mean velocities in open channel flows, and proposed an efficient discharge estimation method for unsteady open channel flows (Chiu [1]). Most of the tested field data, however, were collected in rivers of mild slope. In this study, a portable ADCP flow measuring system is adopted to measure the flows in steep rivers. The efficient discharge estimation method was also tested for different channel types, including straight, meandering and braided channels.

2. Methods

(1) Acoustic Doppler type profilers

Both real-time, three-dimensional (3-D) ADP (3 MHz) and Workhorse-ADCP (1.2 MHz) were used in this study. The transducer of an ADCP/ADP transmits sound bursts with a fixed frequency into the water. Particles carried by the water currents scatter the sound waves back to the transducer as echoes. As echoes return from deeper in the water column, the ADCP/ADP assigns different water depths to the corresponding parts of the echo records. Motion of particles in the water relative to the transducer causes the echo to change in frequency. The ADCP/ADP measures this change, the Doppler shift, as a function of depth to obtain the water velocity vector at different locations (depth cells; also see Fig. 3) through the water column (RDI [12], Sontek [13]). The echo intensity returning from a hard surface such as the river bottom is very much stronger than that from scatters in the water. The water depth can thus be estimated according to the "jump" in the echo intensity profile at the river bed.

Table 1 shows a comparison between the characteristics of ADP and those of Workhorse-ADCP used in this study. The ADCP transmits acoustic pulses from a transducer assembly along four beams (one reference beam), while the ADP has only three beams.

(2) Portable measuring system

The flows in steep rivers are usually very rapid, especially during high flow periods. It is therefore impractical to measure these flows with an ADCP/ADP mounted on vessels in-the-hull. In this study, a flexible suspension system is mounted on a 3.5 tons truck. A real-time ADCP/ADP is installed inside a 300 pounds sound weight (lead fish) as shown in Fig. 1. The sound weight can protect the equipment. Its shape may also minimize possible separation and the disturbance of the flow. Fig. 2 shows the operation of the portable measuring system with an ADCP (top view). The lead fish containing an ADCP is located near the water surface. Its head usually faces upstream automatically. The 4-beam ADCP can be replaced by a 3-beam ADP. Schematic diagrams of the portable flow measuring systems with ADP and ADCP are shown in Fig. 3. After collecting the velocity profile at a vertical, the lead fish can be raised above the water surface and moved to the next station (vertical) if the velocity profiles of the whole cross-section are needed.

(3) Discharge theorem

(a) Chiu's velocity profile

By applying the concepts of probability and entropy (Shannon [14]), Chiu [11] derived the following velocity

Table 1
Comparison of instrument specifications for ADP and ADCP

Instrument	ADP	ADCP
Manufacturer	Sontek, Inc.	RDI, Inc.
Model type	PC-based	Workhorse monitor (direct-reading)
Frequency	3 MHz	1.2 MHz
Velocity accuracy	±1% of measured velocity, ±0.5 cm/s	±0.25% of the water velocity relative to the ADCP, ±0.25 cm/s
Velocity resolution	0.1 cm/s	0.1 cm/s
Depth cell	0.25–2 m	0.05–10 m
Number of beams	3 Beams	4 Beams (one reference beam)
Beam angles	25	20
Number of depth cells	1–64	1–128
Velocity range	±10 m/s	±10 m/s
Blanking area	0.2 m (default, fixed)	0.44 m (default, adjustable)
Bottom tracking	Optional	Included
Compass, tilt (pitch and roll), temperature sensors	Optional	Installed (no compass)

Fig. 1. Picture of ADCP/ADP portable flow measuring system.

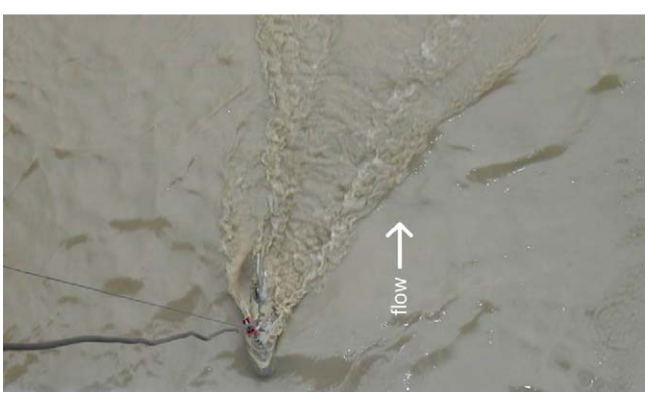


Fig. 2. Operation of portable flow measuring system with ADCP (top view).

distribution:

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

in which $u_{\max}$ = maximum velocity in a cross-section; M is the parameter of entropy; ξ is the variable of coordinate on an isovel on which the velocity is equal to u; ξ_0 is the minimum value of ξ at which $u = 0$ (the river bed); and $\xi_{\max}$ is the maximum value of ξ and occurs at the location of $u_{\max}$. In the physical space, $(\xi - \xi_0)/(\xi - \xi_{\max})$ is the fraction of the channel cross-section in which the velocity is less than or equal to u. Eq. (1) represents the vertical velocity distribution of the flow along the y-axis (vertical passing through the point with maximum velocity in a cross-section; see Fig. 4).

(b) Chiu's discharge theorem

Chiu [11] indicated that one of the regularities of open-channel flow is that the average location of the y-axis in a channel section tends to be stable and stays at the same place. The entropy parameter M and the ratio ϕ (mean velocity $\bar{u}$ over maximum velocity $u_{\max}$) of a natural channel can be assumed as constants, and can be expressed as:

$$\phi = \frac{\bar{u}}{u_{\max}} = \frac{e^M}{e^M - 1} - \frac{1}{M} \quad (2)$$

By measuring the maximum velocity $u_{\max}$ along the y-axis, one can estimate the mean velocity $\bar{u}_{\text{est}}$ of a cross-section from

$$\bar{u}_{\text{est}} = \phi \cdot u_{\max} \quad (3)$$

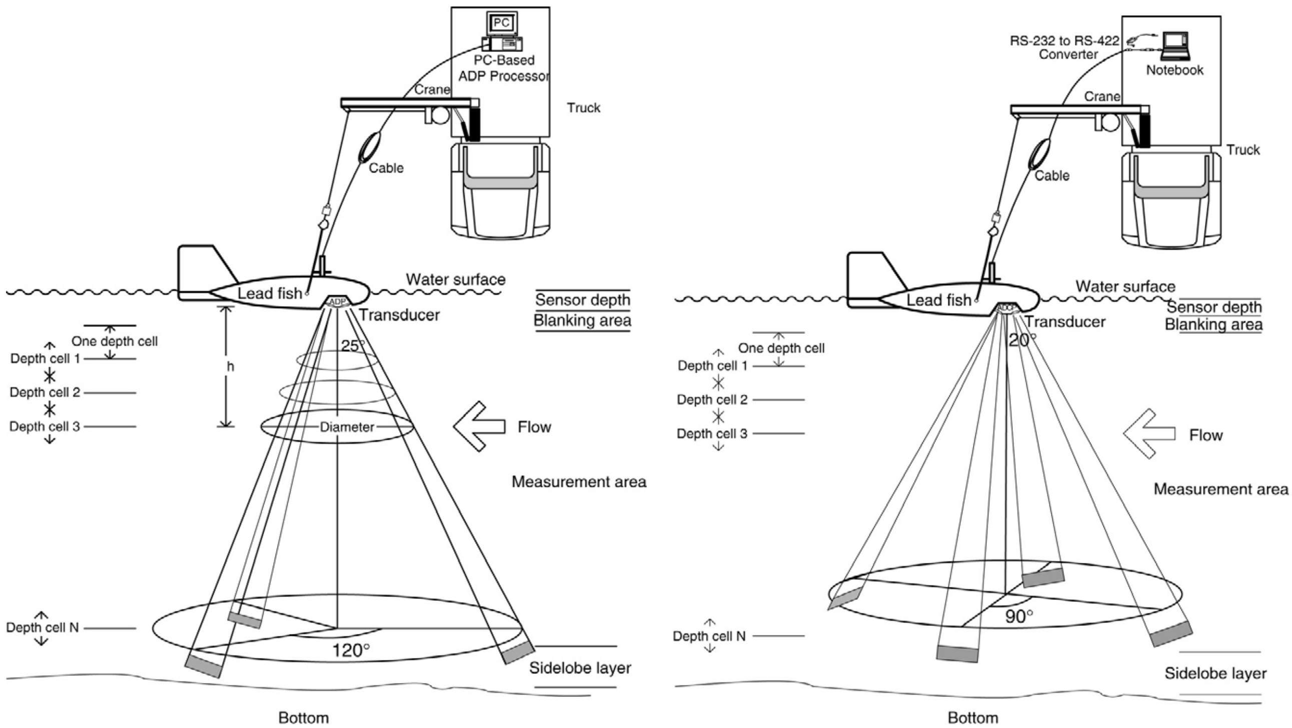
Combining with the estimation of cross-sectional area A_{est}, Chiu's discharge theorem (Chiu [1]) can be expressed mathematically as:

$$Q_{\text{est}} = \bar{u}_{\text{est}} \cdot A_{\text{est}} = \phi \cdot u_{\max} \cdot A_{\text{est}} \quad (4)$$

in which Q_{est} is the estimated discharge.

(c) Highly efficient flow measurements for steep rivers

Based on the analysis of 86 important hydrological stations selected by the Water Resources Agency in Taiwan, with slope ranging from 0.03% to 5.68%, Lu et al. [15–17] found that Chiu's discharge theorem was applicable to higher flows in steep rivers (slopes greater than about 0.1%), except for extreme floods (e.g. 100-year flood) which cause severe cross-sectional changes. In other words, the y-axis and the ratio of mean velocity to maximum velocity of a cross-section (ϕ value) were fairly stable for higher flows. As for low flows, the flow stages might be very low and the divided channels might easily occur in steep rivers. This tendency is especially true for braided rivers, as will be explained later in the section dealing with results.



(a) ADP. (b) Workhorse-ADCP.

Fig. 3. Schematic diagrams of portable flow measuring systems with (a) 3-beam ADP; (b) 4-beam ADCP.

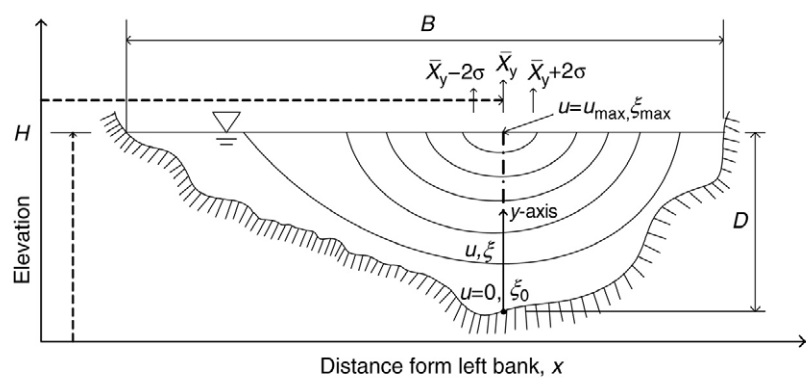


Fig. 4. Definition sketch of velocity distribution and y-axis for open channel flow (B = water surface width, H = flow stage, y-axis = vertical axis passing through the point with maximum flow velocity of the cross-section $u_{\max}$).

The application of this highly efficient flow measuring method can be divided into the following two stages:

(i) Parameter relationships development stage

According to flow measurements conducted at a hydrological station, one needs to (1) analyze the stability of the y-axis, (2) develop the relationship between the mean velocity and maximum velocity of a cross-section, and (3) develop formulae for flow area estimations. If the maximum velocity is not available, it can be calculated by using Eq. (1), which is based on the data collected by a current meter along the y-axis by means of the conventional "two-point method".

To estimate the flow area, three different variables: (1) stage H, (2) flow depth at y-axis D, and (3) surface width of the flow B times D (BD) can be used. It was found (Lu et al. [17]) that among these three methods, in general, BD gave the best prediction for the flow area. Therefore, a simple equation $A_{\text{est}} = a \cdot (BD - c)^b$ will be used in this study.

(ii) Application stage

During the application stage, a proper velocimeter (either conventional or acoustic type) is placed near the y-axis to measure the maximum velocity $u_{\max}$ and the flow depth D. The mean velocity of the cross-section $\bar{u}_{\text{est}}$ and the flow area A_{est} can be estimated by the ϕ value ($\bar{u}/u_{\max}$, by regression) and the empirical formula $A_{\text{est}} = a \cdot (BD - c)^b$, respectively. The flow discharge can then be calculated accordingly.

In contrast to the conventional method that usually obtains the flow discharge by means of measuring the velocity profiles (or two points) and depths of all the verticals in a cross-section, the highly efficient flow discharge estimation method can save a significant amount of time and labor. These advantages are

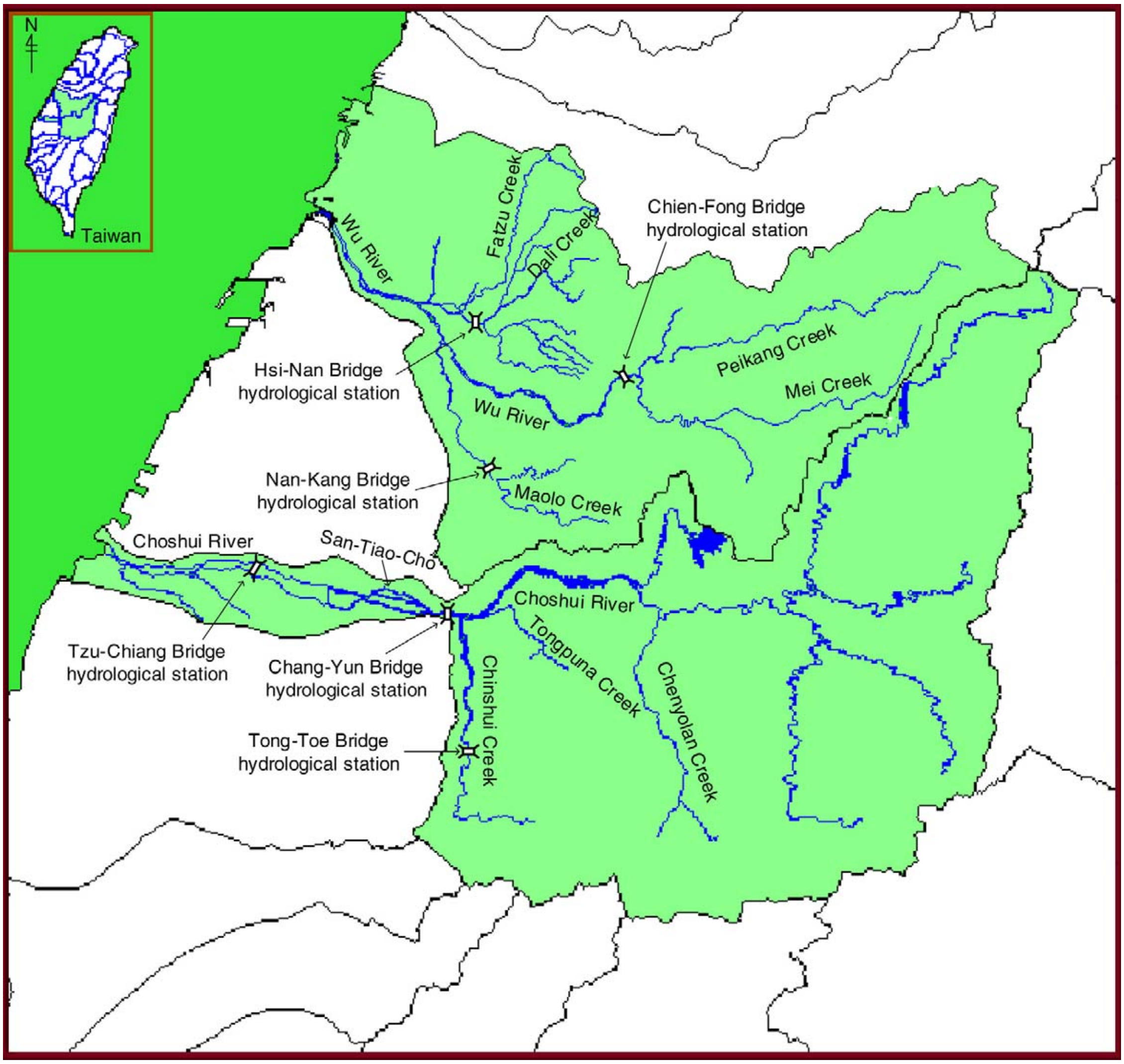


Fig. 5. Sketch of the study area with hydrological stations.

especially important for measuring unsteady flows in wide rivers.

3. Study areas

In this study, data collected at five hydrological stations of the Wu River and Choshui River watersheds in central Taiwan, as shown in Fig. 5, are discussed. The source of the Wu River is located at the southern Hohuan Mountain in the Central Mountains. The drainage area is 2025 km^2, and the total length of the main river is 119 km. The average slope of channel bed for the upstream area is about 1.7%. Its major tributaries include the Fatzu Creek, Dali Creek, Maolo Creek, Peikang Creek, and Mei Creek.

The source of the Choshui River is located at the eastern Hohuan Mountain (elevation 3417 m). The drainage area of the Choshui River is 3157 km^2, and is ranked second largest in Taiwan. The length of its main channel is 186.6 km. It is the longest river in Taiwan. The average slope of the channel bed is 0.53%. The major tributaries include the Chenyolan Creek, Chinshui Creek and Tongpuna Creek.

4. Results

(1) Flow measurements by conventional current meter

(a) Chien-Fong Bridge hydrological station

The Chien-Fong Bridge hydrological station is located upstream of the Wu River. The river has gravel bed with a bedrock that is partially exposed and is fairly straight near the reach of the bridge. The drainage area upstream from the bridge is 960 km^2. The average bed slope is about 3.8% near the Chien-Fong Bridge.

Fig. 6(a) shows the variations in the cross-sectional shape for the Chien-Fong station during the period 1997–2001. The cross-sectional data were collected by the Water Resources Agency with a level (within an accuracy of about ±1 mm) during the dry seasons (usually mid-October through to the following mid-February). It can be seen that the channel shape was fairly stable, since the bedrock was somehow exposed. Fig. 6(b) gives the relationship between the location of the y-axis (vertical passing through the point with the maximum velocity in a cross-section) and the stage H. Values of the mean

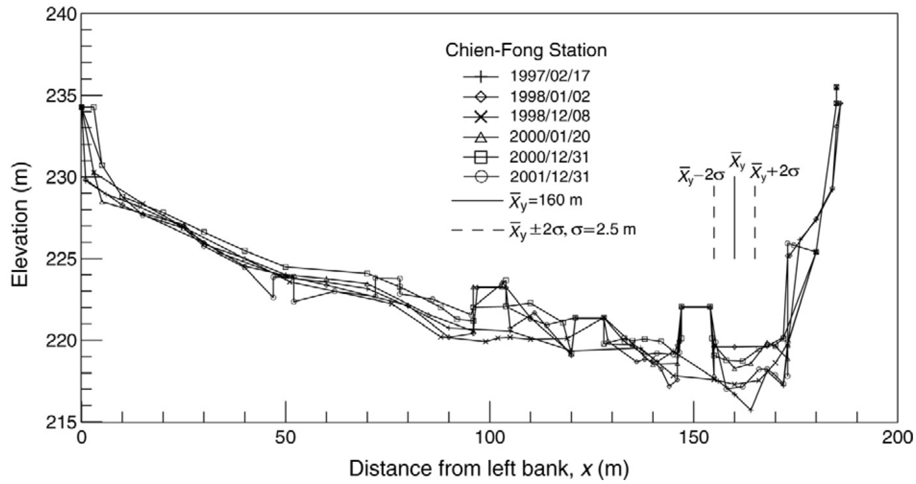


Fig. 6(a). Variations in channel cross-section at the Chien-Fong Bridge hydrological station, Wu River.

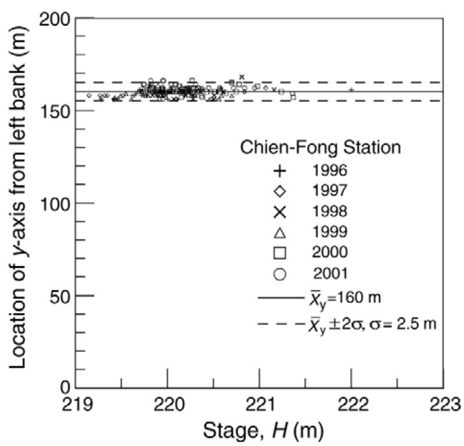


Fig. 6(b). Location of the y-axis vs. stage H for the Chien-Fong Bridge hydrological station, Wu River.

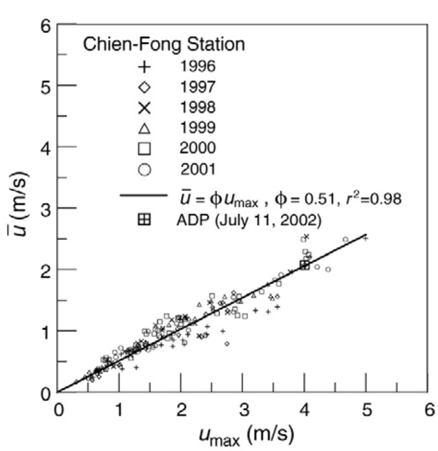


Fig. 6(c). Relationship between $\bar{u}$ and u_{max} for the Chien-Fong Bridge hydrological station, Wu River.

($\overline{X}_y$), standard deviation (σ), and the 95% confidence interval ($\overline{X}_y \pm 2\sigma$) for the "$y$-axis" are also plotted in Fig. 6(b). As shown in the figure, the y-axis was also fairly stable (σ = 2.5 m), and was located about 160 m from the left bank (facing downstream) most of the time.

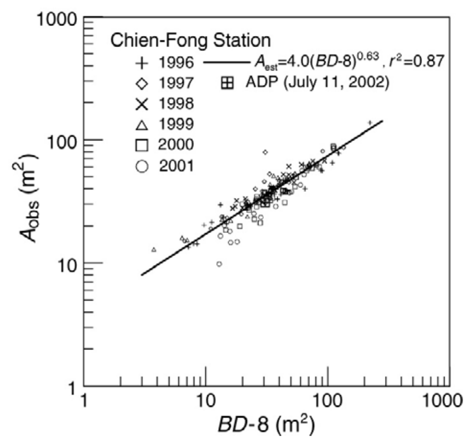


Fig. 6(d). Relationship between flow area and BD for the Chien-Fong Bridge hydrological station, Wu River.

Fig. 6(c) shows the relationship between the mean flow velocity $\bar{u}$ and the maximum velocity u_{max} of the cross-section for the Chien-Fong station during 1996–2001 based on the data collected by the Price current meter. The average ratio of $\bar{u}$ to $u_{max}(\phi)$ was 0.51 and the coefficient of determination (r^2) was 0.98. Fig. 6(d) presents the relationship between the observed flow area A_{obs} and the variable BD (top width of flow B times flow depth at y-axis D), i.e. $A_{est} = 4.0(BD - 8)^{0.63}$, with a r^2 value of 0.87. Using Eq. (4), one can estimate the flow discharge from ϕ, u_{max} and A_{est}. Fig. 6(e) is a comparison of the estimated flow discharge Q_{est} and observed discharge Q_{obs}. The r^2 value 0.96 was fairly high, indicating that the highly efficient flow discharge estimation method was applicable to this station. The standard error of the estimate was 12.7 cm.

(b) Hsi-Nan Bridge hydrological station

The Hsi-Nan Bridge is laid across the Dali Creek, which is a tributary of the Wu River in central Taiwan. The station was established only in 2000 and is an important station for monitoring flood flow during typhoon periods. The drainage area upstream from this station is 269 km^2, and the average bed slope near it is about 0.31%.

Both 2002 and 2003 were dry years in central Taiwan. Fig. 7(a) shows the cross-sectional variation of the Hsi-Nan

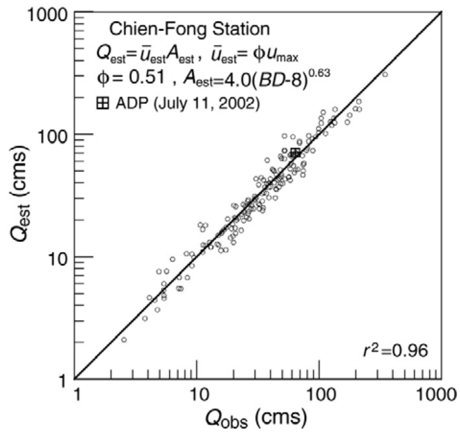


Fig. 6(e). Comparison of observed and estimated flow discharges for the Chien-Fong Bridge hydrological station, Wu River.

station during the period 2000–2001. It can be seen that the cross-sectional shape was reasonably stable. The river near the bridge has been managed by the Third River Management Bureau of the Water Resources Agency of Taiwan.

Fig. 7(b) shows the relationship between the location of the y-axis and the flow stage H. Values of the mean $(\overline{X}_y)$, standard deviation (σ), and the 95% confidence interval $(\overline{X}_y \pm 2\sigma)$ for the "y-axis" are also illustrated in Fig. 7(b). Based on the data collected in 2000 and 2001, on average the y-axis was located about 225 m from the left bank (facing downstream).

Fig. 7(c) is a plot of the relationship between the mean flow velocity $\bar{u}$ and the maximum velocity u_{max} of the cross-section for the Hsi-Nan station based on the velocity measurements by the Price current meter. From the regression analysis, the average ratio of ϕ was found to be 0.64, with a r^2 value of 0.97. Fig. 7(d) shows the relationship between the observed flow area A_{obs} and the variable BD (top width of the flow B times flow depth D along the y-axis). The predictions were reasonably good, especially for higher flows. The flow discharges estimated by the highly efficient flow discharge estimation method [Eq. (4)] Q_{est} were compared with the observed values Q_{obs} in Fig. 7(e). The r-squared value for the linear relationship between Q_{est} and Q_{obs} was 0.99. It can be seen that the predictions were reasonably good for higher flows. The standard error of the estimate was 11.5 cm.

(2) Flow measurements by portable ADP/ADCP system

(a) Chien-Fong Bridge hydrological station

Data collection. The portable flow measuring system with a 3 MHz ADP was used to measure flow at the Chien-Fong station on July 11th, 2002 when Typhoon Nakri landed in Taiwan. The sampling time (ensemble averaging interval) was one minute for each vertical. A depth cell size (see Fig. 3) of 0.25 m and a blanking area (the distance near the acoustic sensors, where the acoustic echo from the water cannot be accurately measured) of 0.2 m were chosen. The flow depth for each vertical was estimated on the basis of the "jump" in the echo intensity profile. Fig. 8 shows eight velocity profiles and the flow depths for the whole cross-section. The horizontal distance between consecutive verticals was 2 m.

The result of Fig. 8 indicates that the "y-axis" is located at about 162 m from the left bank, which is consistent with that of Fig. 6(b). It also shows that the maximum velocity occurs below the water surface. The flow depth along the y-axis, D, and the maximum velocity, u_{max}, from the ADP are 2.15 m and 4.01 m/s, respectively. The flow velocities near the water surface (blanking area 0.2 m and sensor depth 0.3 m) were estimated by Eq. (1). By the "mid-section method" (i.e. integration of the velocity profile with depth), the observed flow area, discharge and average velocity were found to be: $A_{obs} = 30.87$ m^2, $Q_{obs} = 64$ cm, and $\bar{u}_{obs} = 2.07$ m/s, respectively. Fig. 9 gives an isovel map with the vertical velocity profiles.

Accuracy of discharge estimation. From Fig. 6(c), the ϕ value for the Chien-Fong station was 0.51. Since $u_{max} = 4.01$ m/s, the estimated mean velocity of the cross-section ($\bar{u}_{est}$) was 2.05 m/s. Based on the BD value, the flow area can be estimated as $A_{est} = 4.0(BD - 8)^{0.63} = 34.6$ m^2. With the highly efficient flow discharge estimation method, the flow discharge was $Q_{est} = \bar{u}_{est} \cdot A_{est} = 0.25 \times 34.6 = 70.8$ cm. In comparison with the observed value ($Q_{obs} = 64$ cm), the error was about 10%. The observed and estimated flow discharge values are plotted in Fig. 6(e).

(b) Hsi-Nan Bridge hydrological station

Data collection. On May 31st, 2002, the portable flow measuring system with a 1.2 MHz ADCP was selected to conduct a field experiment at the Hsi-Nan station. In comparison with the 3 MHz ADP, the 1.2 MHz ADCP has a lower frequency and higher penetration energy—such advantages are helpful to the measurement of high concentration sediment-laden flow. The water surface width B was about 70 m during the measurement of the rain storm.

Fig. 10 shows 13 vertical velocity profiles with a horizontal interval of 5 m. The blanking area below the transducer and the selected depth cell size were 0.44 m and 5 cm, respectively. The sampling time for each vertical was one minute. Again, the flow depth was determined by the "jump" in the backscatter intensity profile.

From Fig. 10, one can see that the y-axis occurs at about 220 m from the left bank; this result is consistent with the analysis in Fig. 7(b). The flow depth along the y-axis, D, and the maximum velocity taken by the ADCP are 1.45 m and 2.10 m/s, respectively. The velocities for the unmeasurable zone near the water surface were estimated by Eq. (1). By the integration of flow velocity over depth using the "mid-section method", the observed flow discharge Q_{obs} was estimated to be 125.6 cm (observed flow area $A_{obs} = 85.75$ m^2, average velocity $\bar{u}_{obs} = 1.46$ m/s). An isovel map with the vertical velocity profiles is plotted in Fig. 11.

Accuracy of discharge estimation. As shown in Fig. 7(c), the ϕ value was about 0.64 for the Hsi-Nan station. The flow area can be estimated by the BD value, i.e. $A_{est} = 0.1(BD - 1.5)^{1.48} = 0.1 \times (70 \times 1.45 - 1.5)^{1.48} = 91$ m^2. Based on the velocity

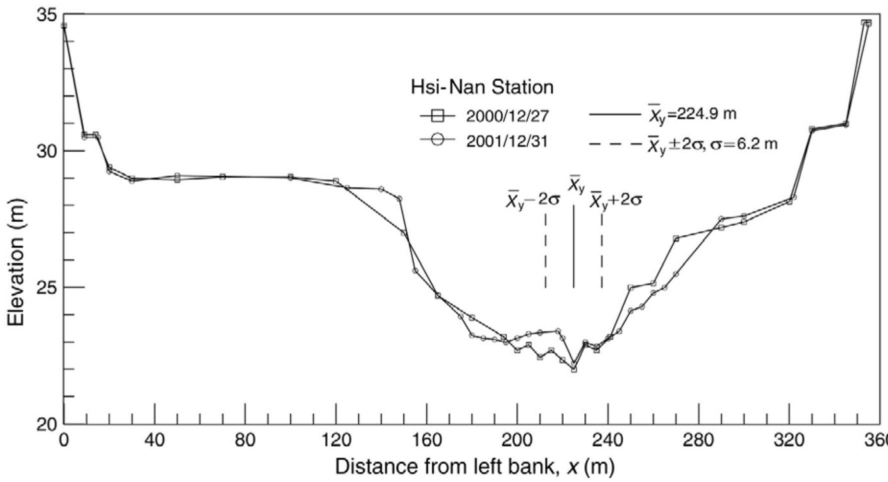


Fig. 7(a). Variations in channel cross-section at the Hsi-Nan Bridge hydrological station, Dali Creek (tributary of Wu River).

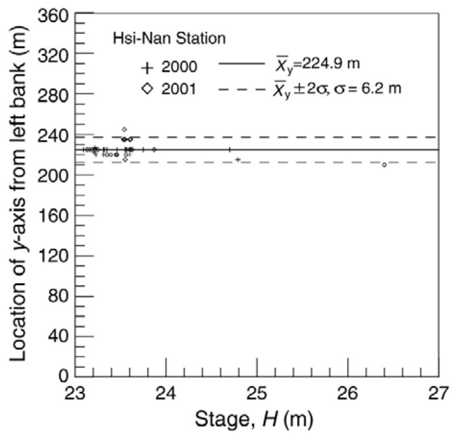


Fig. 7(b). Location of the y-axis vs. stage H for the Hsi-Nan Bridge hydrological station, Dali Creek (tributary of Wu River).

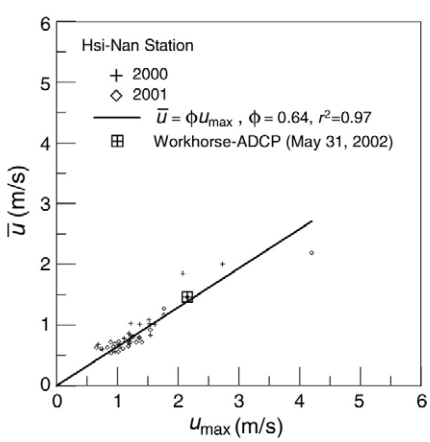


Fig. 7(c). Relationship between $\bar{u}$ and $u_{\max}$ for the Hsi-Nan Bridge hydrological station, Dali Creek (tributary of Wu River).

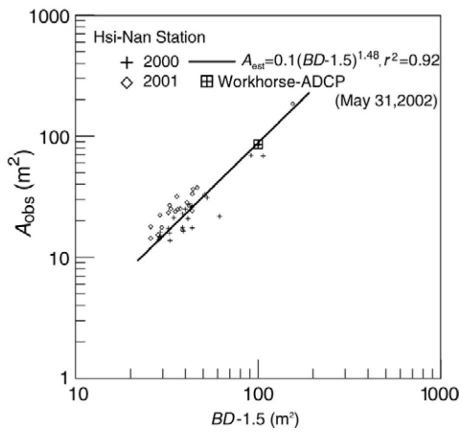


Fig. 7(d). Relationship between flow area and BD for the Hsi-Nan Bridge hydrological station, Dali Creek (tributary of Wu River).

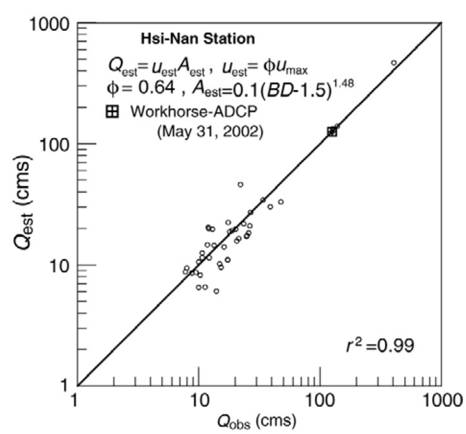


Fig. 7(e). Comparison of observed and estimated flow discharges for the Hsi-Nan Bridge hydrological station, Dali Creek (tributary of Wu River).

profile measured along the y-axis, the maximum velocity of the cross-section ($u_{\max}$) was estimated to be 2.15 m/s by Eq. (1). Therefore, with the highly efficient flow discharge estimation method, the flow discharge can be calculated as $Q_{\text{est}} = \bar{u}_{\text{est}} \cdot A_{\text{est}} = \phi \cdot u_{\max} \cdot A_{\text{est}} = 0.64 \times 2.15 \times 91 = 125.2$ cm. The difference between this estimated value and the observed flow discharge Q_{obs} (125.6 cm) was only 0.3%. The observed and estimated flow discharge values are also plotted in Fig. 7(e) for comparison.

(c) Comparison of systems with ADP and ADCP

Steep rivers are characterized by shallow flow depths and extreme turbulence. Therefore, it is important to select an

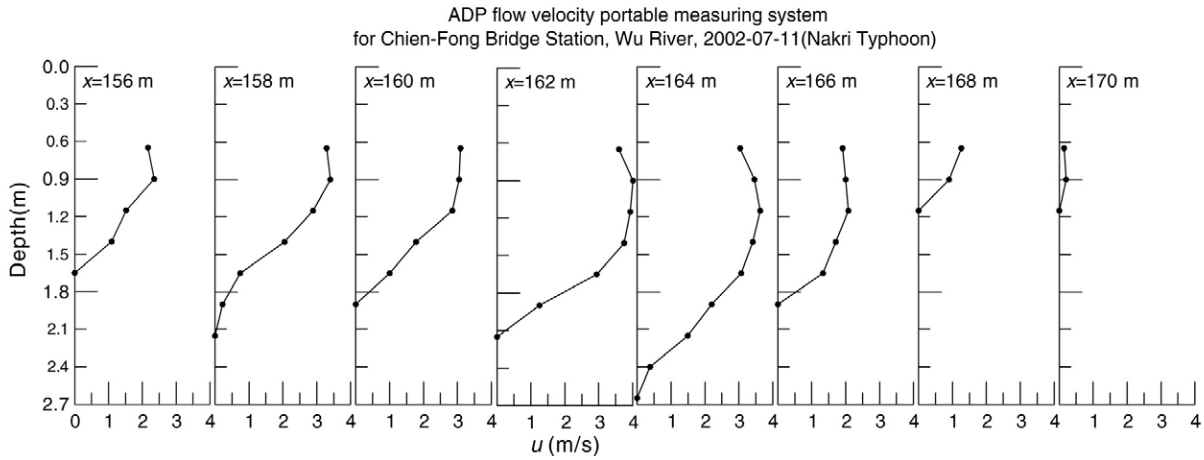


Fig. 8. Velocity profiles measured by ADP portable measuring system for the Chien-Fong Bridge hydrological station, Wu River (location printed on the top of each figure is the distance from the left bank x).

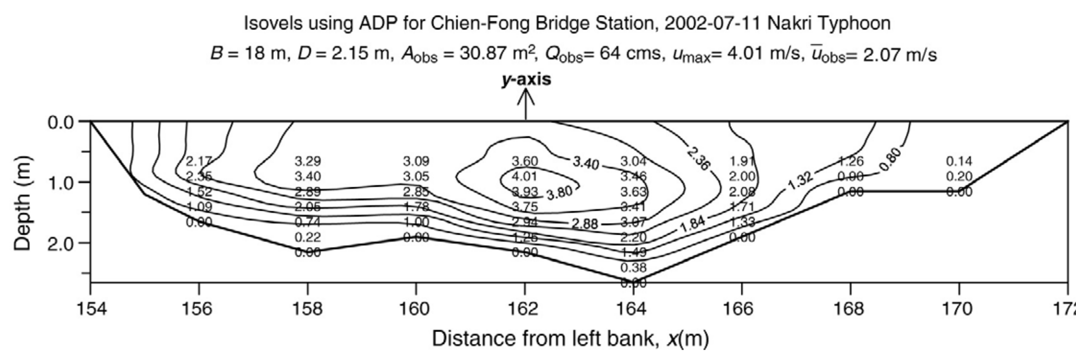


Fig. 9. Velocity measurements and isovels by ADP portable measuring system for Chien-Fong Bridge hydrological station, Wu River.

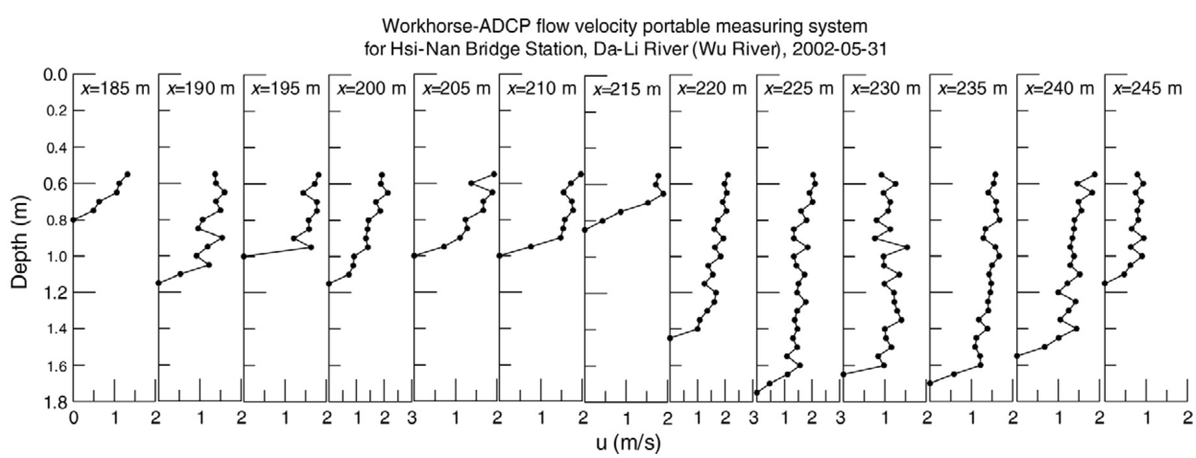


Fig. 10. Velocity profiles measured by Workhorse-ADCP portable measuring system for the Hsi-Nan Bridge hydrological station, Dali Creek (tributary of Wu River; location printed on the top of each figure is the distance from the left bank x).

appropriate frequency and depth cell for ADP or ADCP. Based on our experiences (Lu et al. [15–17]), 1.2–3 MHz is an appropriate frequency range for steep rivers. As shown in Table 1, the lowest value of the depth cell for a 1.2 MHz ADCP is 5 cm, while the corresponding value for a 3 MHz ADP is 25 cm. Therefore, more detailed velocity profiles can be measured using the ADCP compared with ADP. However, the fluctuations in the velocity profiles from ADCP were greater than those from ADP, as shown in Figs. 10 and 8. In addition, the ADP is slightly easier to operate and cheaper in cost than the ADCP.

5. Application to different channel types

There are many ways to classify channel types. One of the most widely used geomorphological classifications of channel type was proposed by Leopold and Wolman [18]. Channels are classified into three distinct types, i.e. straight, meandering

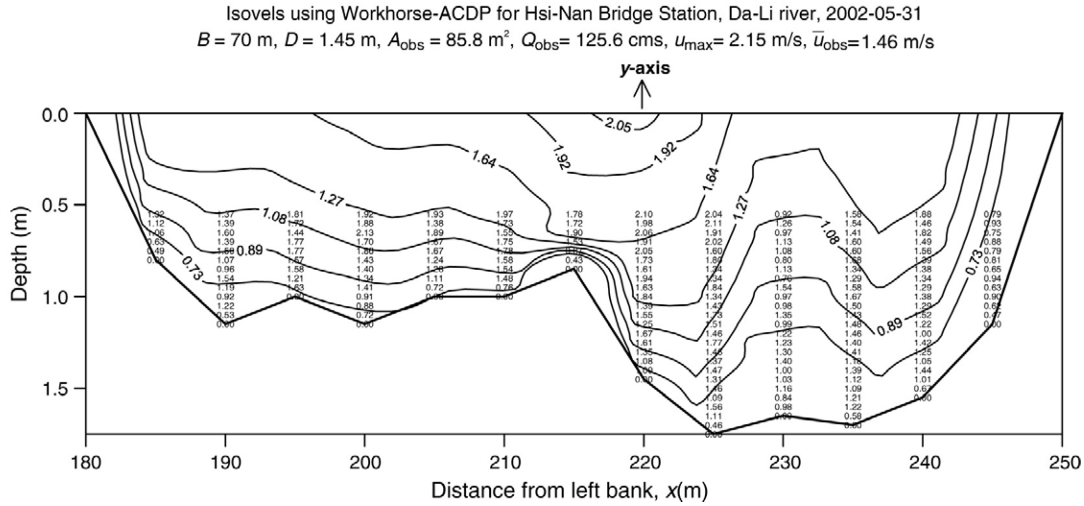


Fig. 11. Velocity measurements and isovels by Workhorse-ADCP portable measuring system for the Hsi-Nan Bridge hydrological station, Dali Creek (tributary of Wu River).

and braided patterns. Bridge [19] summarized many criteria for the quantitative predictions of these channel patterns. A river may have different channel patterns in different reaches. In this section, the applicability of the highly efficient flow discharge estimation method to the reaches of different channel types near the hydrological stations is discussed.

(1) Straight channel

A straight river refers to one that does not have a distinct meandering pattern. Its sinuosity (ratio of valley slope to channel slope) is less than about 1.5.

The Wu River near the Chien-Fong Bridge hydrological station mentioned previously is a typical straight channel. The y-axis was fairly stable for this station, as shown in Fig. 6(b).

Fig. 12(a) is the cross-sectional shape of the Tong-Toe Bridge hydrological station at Chinshuei Creek (a tributary of Choshui River) in central Taiwan. The channel is fairly straight near the station. However, the bottom of the cross-section at the station is tilted. As a result, the location of the y-axis consistently shifted rightward upon increasing the stage until the stage reaches an elevation of about 224 m ($H \approx 224$ m). The y-axis is fairly stable when the stage H is higher than about 224 m, as shown in Fig. 12(b), since the channel width is nearly constant above that elevation (see the dashed-line of Fig. 12(a)).

(2) Meandering channel

A meandering river has a sinuosity greater than about 1.5. Usually one prefers to set up the hydrological stations near the straight channel reaches. However, sometimes the observations of the flow stages for meandering channels are also needed.

Fig. 13(a) is a plan view of the Maolo Creek (a tributary of the Wu River) near the Nan-Kang Bridge hydrological station. As can be seen from the figure, the channel reach near the bridge is a meander bend. The variations in the cross-sectional shape from 1992 to 1994 are plotted in Fig. 13(b). The right bank is located about 240 m from the left

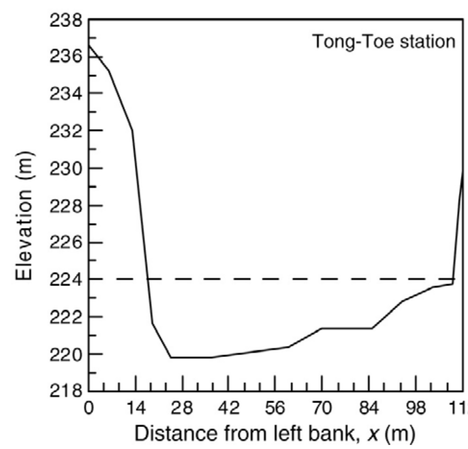


Fig. 12(a). Sketch of channel cross-section at the Tong-Toe Bridge hydrological station, Chinshui Creek (tributary of Choshui River).

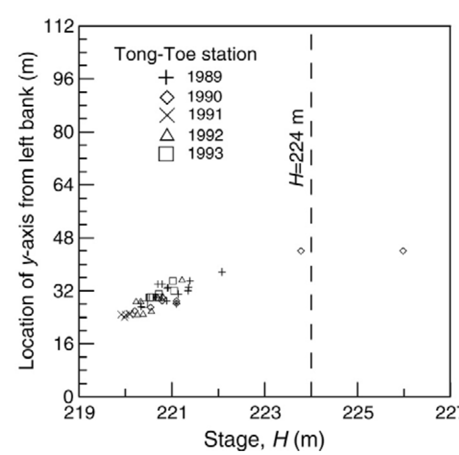


Fig. 12(b). Location of the y-axis vs. stage H for the Tong-Toe Bridge hydrological station, Chinshui Creek (tributary of Choshui River).

bank. The main channel was located closer to the concave bank of the bend during this period. Severe cross-sectional changes

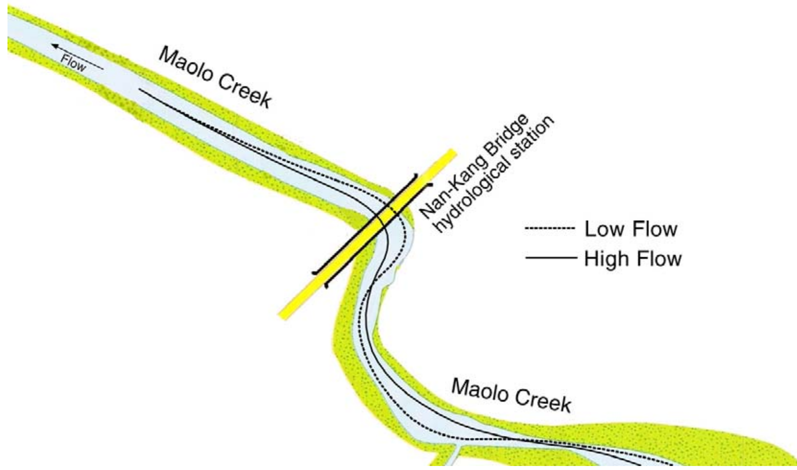


Fig. 13(a). Schematic diagram of the meander bend at the Nan-Kang Bridge hydrological station, Maolo Creek (tributary of Wu River).

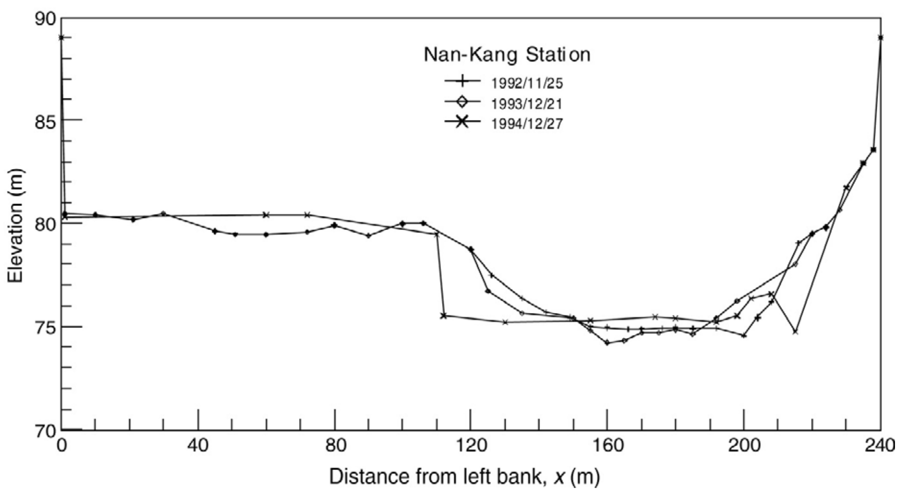


Fig. 13(b). Variations in channel cross-section at the Nan-Kang Bridge hydrological station, Maolo Creek (tributary of Wu River).

occurred after 1995 due to channel dredging. Therefore, the data collected after 1995 are not included in this study.

Fig. 13(c) shows the variation in the location of the y-axis (measured from the left bank, facing downstream) with stage H. One can see that the location of the y-axis for the low flow is closer to the concave bank of the bend in comparison with that for the high flow (see schematic diagram in Fig. 13(a)). In fact, this is consistent with the characteristics of the meander pattern. In general, the low-stage thalweg follows the outside or concave bank of a meander bend, thus traveling a relatively long flow path through the reach. Because of the increased momentum, the high-stage flow line generally short circuits the meander pattern, and follows a shorter flow path through the reach. Fig. 13(c) implies that the y-axis for higher flows gradually approaches a constant value of about 100 m from the left bank. The meander migration of the bend did not occur during this period due to the existence of the levees along the Maolo Creek.

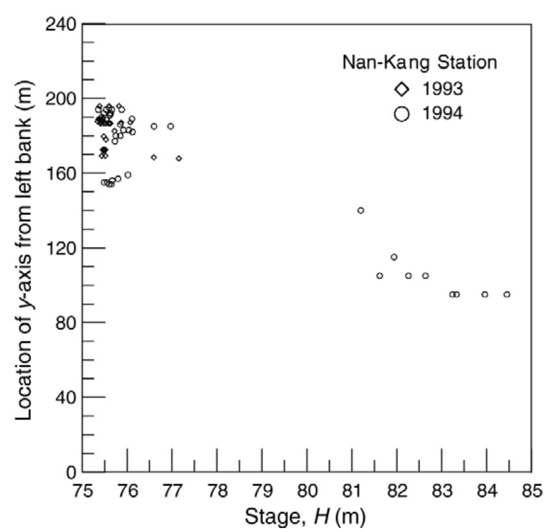


Fig. 13(c). Location of the y-axis vs. stage H for the Nan-Kang Bridge hydrological station, Maolo Creek (tributary of Wu River).

(3) Braided channel

There are several features of a braided stream (Chien [20]). For example, it has a wide and shallow bed choked with sand bars. Another basic feature is constant shifting of its river course. Based on the analysis of the braided stream and the data

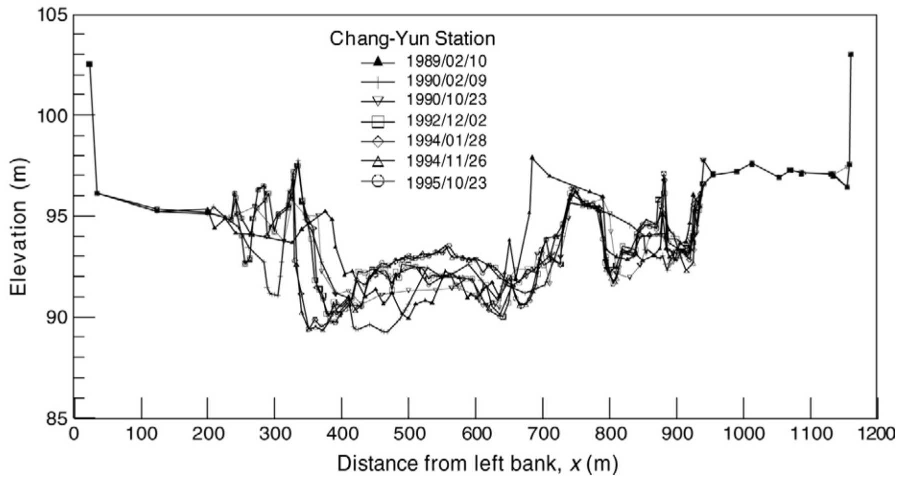


Fig. 14(a). Variations in channel cross-section at the Chang-Yuan Bridge hydrological station, Choshui River (1989–1995).

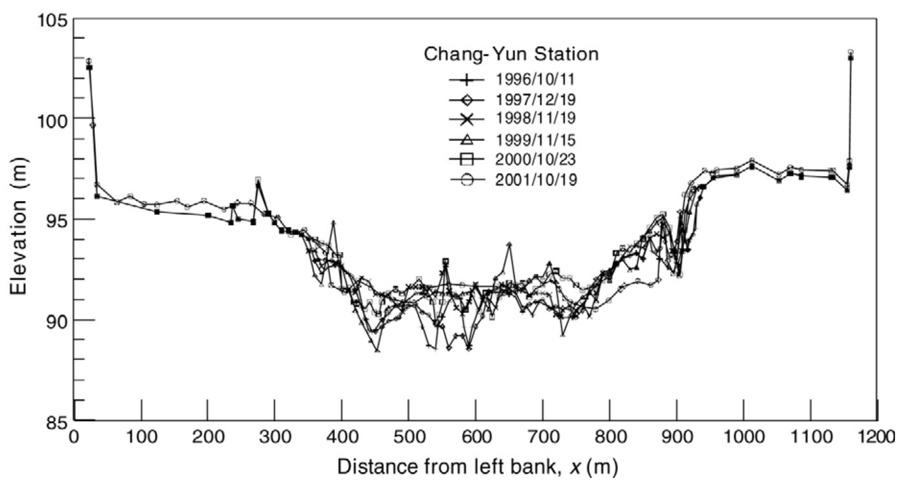


Fig. 14(b). Variations in channel cross-section at the Chang-Yuan Bridge hydrological station, Choshui River (1996–2001).

collected from 31 gauge stations of 10 different sandy rivers in China, a parameter known as the "wandering-index" of alluvial streams was proposed by Chien. This determines the stability in the transverse direction of an alluvial stream.

As mentioned before, the Choshui River is the longest river in Taiwan. Its lower reach, downstream of San-Tiao-Cho (see Fig. 5) to the mouth of the river, is a typical braided channel reach. In this section, data collected at the Chang-Yun Bridge hydrological station (see Fig. 5), which has a width between the levees of about 1.1 km, are analyzed. The Chang-Yun station is located downstream from the confluence of the Choshui River and its tributary Chinshui Creek. The channel bed slope is about 0.95% near this station.

A 200-year flood with a peak flow discharge of 183,000 cm occurred in the Choshui River from July 31st to August 1st in 1996 (Typhoon Herb). Figs. 14(a) and 14(b) show the variations in the transverse section at the station before (1989–1995) and after (1996–2001) the typhoon, respectively. Both Figs. 14(a) and 14(b) reveal the multiple-channel feature of the braided stream. The drastic change in the cross-section before and after the 200-year flood is indeed impressive. There was also a significant change in the cross-section between 650 m and 750 m from the left bank due to Typhoon Sarah (September 10th-13th, 1989; peak discharge 8230 cm) as shown in Fig. 14(a).

Fig. 14(c) shows the relationship between the location of the y-axis and the stage H. The graph clearly indicates the large variability in the location of the y-axis. However, the variability decreases with an increase in the stage. This is especially true for higher flows ($H > 93$ m), where the y-axis is located at about 600 m from the left bank.

6. Discussion

The portable flow measuring system with an ADCP/ADP and the highly efficient discharge estimation method proposed in this paper can be applied in many steep rivers, as demonstrated in the previous sections. However, there are still some limitations in their application that need clarification.

For high concentration sediment-laden flow, the sound bursts from the acoustic velocimeter may not be able to penetrate the whole flow depth. This occurred in 1996 when a 3 MHz ADP was used to measure an extreme flood (200-year flood) near the Tzu-Chiang Bridge (see Fig. 5), Choshui River, central Taiwan. The sediment concentration was over 30,000 ppm. In such

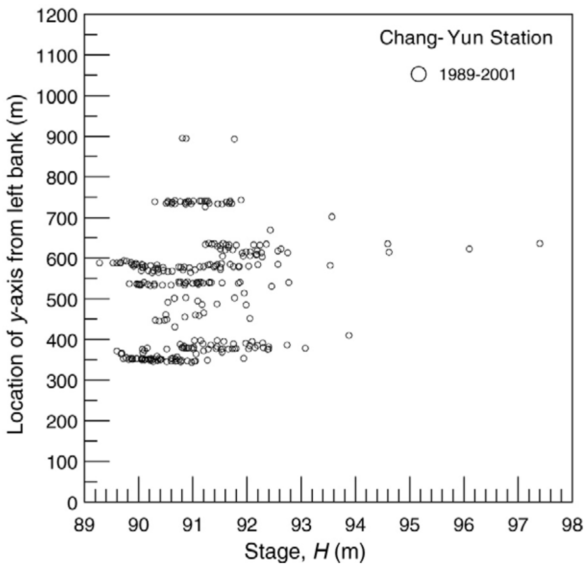


Fig. 14(c). Location of the y-axis vs. stage H for the Chang-Yuan Bridge hydrological station, Choshui River (1989–2001).

situations, one possible solution is to use a lower-frequency velocimeter.

The highly efficient discharge estimation method has an advantage of drastically reducing the time and cost of discharge measurements, especially for unsteady flows. One major requirement for its application is the stability of the "y-axis". The method may not be applied if a very severe change in the cross-section occurs due to either a large earthquake or an extreme flood (e.g. a 100-year or 200-year flood). Under such conditions, the discharge parameters (e.g. the y-axis, ϕ value, and flow area estimation) may need to be re-analyzed after the extreme events.

7. Conclusions

A portable flow measuring system with an ADCP/ADP and a highly efficient discharge estimation method are proposed to measure the flow discharges in the steep rivers (bed slopes greater than about 0.1%). Based on the field tests, the following conclusions have been drawn:

1. A portable flow measuring system with an ADCP/ADP has successfully been developed and tested in several steep rivers with rapid flows and shallow flow depths, and highly unstable free surfaces and bed elevations. The proposed system has been proved to be better than existing systems (e.g. attached ADCP or ADP to telemetering surface buoys, fixed on stationary platforms, or installed in submerged vehicles) for streamflow measurements in the steep rivers.
2. The highly efficient discharge estimation method as proposed by Chiu [11] for mild rivers may also be applicable to steep rivers except during extreme conditions, e.g. very high and very low flows. The major advantage of the method is its economy in cost, especially for unsteady flows in wide rivers. Regarding the flow measurements collected by the conventional current meter, the standard errors of the flow discharges were 12.7 cm and 11.5 cm at the Chien-Fong Bridge and Hsi-Nan Bridge hydrological stations, respectively. As for the flow measurements collected by the portable ADP/ADCP system, in comparison with the observed flow discharges, the errors of the estimated values were 10% and 0.3% at the Chien-Fong Bridge and Hsi-Nan Bridge hydrological stations, respectively.
3. Based on the field data, the effects of channel patterns on the applicability of the highly efficient discharge estimation method have been investigated. In general, the method was applicable to higher flows where the measuring verticals (y-axis) were reasonably stable.

Acknowledgments

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