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Evaluating velocity measurement techniques in shallow streams

Evaluation des techniques de mesure de vitesse dans les écoulements peu profonds

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ABSTRACT

Accurate flow field measurements in shallow rivers are necessary for many applications including biological investigations and numerical model development. Unfortunately, river velocity data is difficult to obtain due to the limitations of traditional velocity meters. Acoustic Doppler Current Profilers (ADCP) provide a potential alternative to traditional point-velocity measurements. However, these instruments have not been thoroughly tested against accepted techniques in natural streams. The objectives of this research were to evaluate the adequacy of ADCP instruments for conducting velocity measurements in quasi-wadeable streams and to provide instrument selection guidance for similar flow environments. These objectives were met by conducting ADCP, Acoustic Doppler Velocimeter (ADV), and Price current meter measurements at nine coinciding verticals in two rivers. The performance of each instrument was evaluated with regards to data accuracy, desired parameters, and required sampling time. ADCP measurements compared favorably with ADV and Price meter data for velocity profiles and depth-averaged velocities. The ADCP also showed a significant improvement in estimates of local bed shear stress when compared to global estimates determined from the water surface profile. However, excessive noise reduced the effectiveness of ADCP measurements of velocity standard deviation and velocity components. The results are discussed in the context of instrument selection for parameterization of models.

RÉSUMÉ

Des mesures en nature précises dans les écoulements en faible profondeur sont nécessaires pour de nombreuses applications comprenant des investigations biologiques et le développement de modèles numériques. Malheureusement, les données de vitesse en rivières sont difficiles à obtenir en raison des limitations des vélocimètres traditionnels. Les Profileurs de Courants Doppler Acoustiques (ADCP) fournissent une alternative potentielle aux mesures traditionnelles de vitesse. Cependant, ces instruments n'ont pas été complètement testés par rapport aux techniques admises dans les écoulements naturels. Les objectifs de cette recherche ont été d'évaluer l'adéquation des instruments d'ADCP pour mener des mesures de vitesse dans les courants quasi-franchissables à gué et de fournir des conseils pour choisir les mieux adaptés aux environnements de tels écoulements. Ces objectifs ont été remplis en réalisant des mesures par ADCP, par Vélocimétrie Acoustique Doppler (ADV) et par compteur Price sur les mêmes verticales, au nombre de neuf, dans deux rivières. La performance de chaque instrument a été évaluée quant à l'exactitude des données, aux paramètres désirés, et au temps d'échantillonnage requis. Les mesures obtenues par ADCP se sont comparées favorablement aux données par ADV et par compteur Price pour les profils de vitesse et les vitesses moyennées en profondeur. L'ADCP a également montré une amélioration significative dans les évaluations de l'effort de cisaillement local de lit, comparé aux évaluations globales déterminées à partir du profil de surface de l'eau. Cependant, le bruit excessif a réduit l'efficacité des mesures ADCP d'écart type de vitesse et des composantes de vitesse. Les résultats sont discutés dans le contexte du choix d'instrument pour la paramétrisation des modèles.

Keywords: Acoustic instruments, velocity profiles, ecohydraulics, field methods, turbulence.

1 Introduction

Accurate descriptions of flow fields are necessary to investigate stream processes. A stream's velocity field impacts aquatic habitat, mixing, and sediment transport. However, measuring velocity remains a challenging endeavor; particularly in quasi-wadeable streams (where wading is possible in all but small portions of the stream or at high flows). In wadeable streams, mechanical, electronic, and acoustic point-velocity meters are typically attached to a wading rod or sampling platform and measurements are taken at one or more depths. In large rivers, velocity is typically measured from a boat or stream-crossing using a point-velocity meter or an Acoustic Doppler Current Profiler (ADCP). The appropriate measurement technique is less clear in quasi-wadeable streams where the flow is often too deep or too fast to safely wade, but possibly too shallow to apply ADCP instruments. Further, the spatial resolution and desired parameters (e.g. depth-averaged velocity, velocity profiles, velocity components, shear stress, turbulence statistics) must be considered when selecting the most appropriate measurement technique.

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The objectives of this research were to evaluate the adequacy of ADCP instruments for conducting velocity measurements in quasi-wadeable streams and to provide instrument selection guidance for similar flow environments. These objectives were met by conducting ADCP, Acoustic Doppler Velocimeter (ADV), and Price current meter measurements at nine coinciding verticals in two quasi-wadeable cobble-bed rivers. The appropriateness of each instrument was evaluated with regards to data accuracy, desired parameters, and required sampling time.

2 Background

2.1 Velocity data requirements

Development of one-, two-, and three-dimensional river models requires accurate flow field data for parameterization, calibration, and validation (Biron *et al.*, 2004; Crowder and Diplas, 2000; Duan, 2004; Lane *et al.*, 2004). Flood prediction, hydraulic design, sediment and contaminant transport, and ecosystem restoration are a few of the simulated processes. We will demonstrate the need for velocity data by describing the data required for parameterization and calibration of aquatic habitat evaluation models. Other river process models (e.g. hydrodynamics and sediment transport) have similar data requirements.

Flow influences aquatic organism energy expenditure, food delivery, waste removal, predator avoidance, and disturbance (Hart and Finelli, 1999). Improving velocity measurement techniques is necessary to advance habitat assessment procedures (Bunn and Arthington, 2002; Hardy, 1998). Data requirements for investigating aquatic ecosystems depend on the project objectives. Common habitat evaluation techniques use mean velocity or discharge to determine minimum instream flow requirements (Bovee, 1996). Such investigations use point measurements to determine habitat preference criteria (Kondolf, 2000), combined with one-dimensional (1D) or quasi-two-dimensional (Q2D) hydraulic models. Measurements of mean flow velocity at designated cross-sections, or mean flow velocity segregated into several regions within each cross-section, are required to set boundary conditions and to calibrate these models. The influence of flow heterogeneity on fish habitat was investigated by Crowder and Diplas (2000) using a two-dimensional (2D) hydrodynamic model. 2D models require mean flow velocity (or discharge and water surface elevation) at the upper and lower boundary conditions, along with 2D (depth averaged) velocity measurements throughout the study reach, for model calibration. Nestler *et al.* (2005) used strain rate (shear stress) to predict salmonid swimming behavior in reservoirs using a three-dimensional (3D) hydrodynamic model. 3D models require velocity profiles for boundary conditions, turbulence measurements for parameterization of turbulence closure routines, and 3D velocity data for model calibration.

2.2 Flow characteristics

Stream flow fields are often described through a combination of theoretical and empirical equations. The "law of the wall" developed by Prandtl (1932) and von Karman (1930) for smooth-boundaries was modified by Nikuradse (1933) and others (Rotta, 1962) to the following log–law for rough boundaries:

$$\frac{\bar{u}}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z + \Delta z}{k_s}\right) + B \tag{1}$$

where $\bar{u}$ is the local time-averaged velocity, u_* is the friction velocity, κ is the von Karman constant, z is the distance from the bed, Δz is the displacement length, k_s is the roughness height and B is an integration constant. The log–law can be used to assist in the interpretation of measured data. Log–law application to measured data is dependent on assumptions made in choosing Eq.(1) parameters. The appropriate assumptions depend on project objectives, flow conditions, and data availability. Extensive laboratory and field experiments have demonstrated that κ can be assumed between 0.4 and 0.41 for fixed beds (Nikora and Goring, 2000; Kirkgoz, 1989) and B is approximately 8.5 for equilibrium flow conditions (Song and Chiew, 2001). The roughness height is a function of the boundary roughness. For a uniform grain distribution, it is appropriate to use the particle diameter (Nikuradse, 1933). However, k_s is not clearly defined for heterogeneous streambeds and can be further complicated by the presence of bedforms. k_s is often assumed to be a function of a particle size distribution statistic, such as the median particle size (Blanckaert and Graf, 2001; Papanicolaou and Hilldale, 2002). The displacement length is a correction from the local streambed elevation to the velocity profile origin ($u = 0$ when $z + \Delta z = 0$). The profile origin is difficult to define for natural streams as it depends on local bed geometry. Δz is often determined by curve-fit to collected data or neglected altogether (Nikora *et al.,* 2002).

The friction velocity is directly related to the bed shear stress as:

$$u_* = \sqrt{\frac{\tau_o}{\rho}} \tag{2}$$

where τ_o is the bed shear stress and ρ is the fluid density. u_* is often the desired result of Eq. (1) and is determined from measured velocity data using a regression technique. Shear stress can also be estimated at the reach scale, referred to as global in this paper, from the bed shear stress as determined from the water surface slope as:

$$\tau_g = \gamma R_H S \tag{3}$$

where γ is the fluid specific weight, R_H is the stream hydraulic radius, and S is the water surface slope. The shear stress can also be estimated from the Reynolds shear stress distribution, τ_{RSS}. The Reynolds shear stress represents an upward momentum flux due to turbulent velocity fluctuations. The total shear stress is the result of viscous and Reynolds stresses, which can be represented for 2D flow as:

$$\tau = \mu \frac{\partial u}{\partial z} - \rho \overline{u'w'} \tag{4}$$

where u' and w' are the fluctuating streamwise and vertical velocity components, respectively, and μ is the dynamic viscosity. The term $-\rho\overline{u'w'}$ is the Reynolds shear stress. For a cobble bed river,

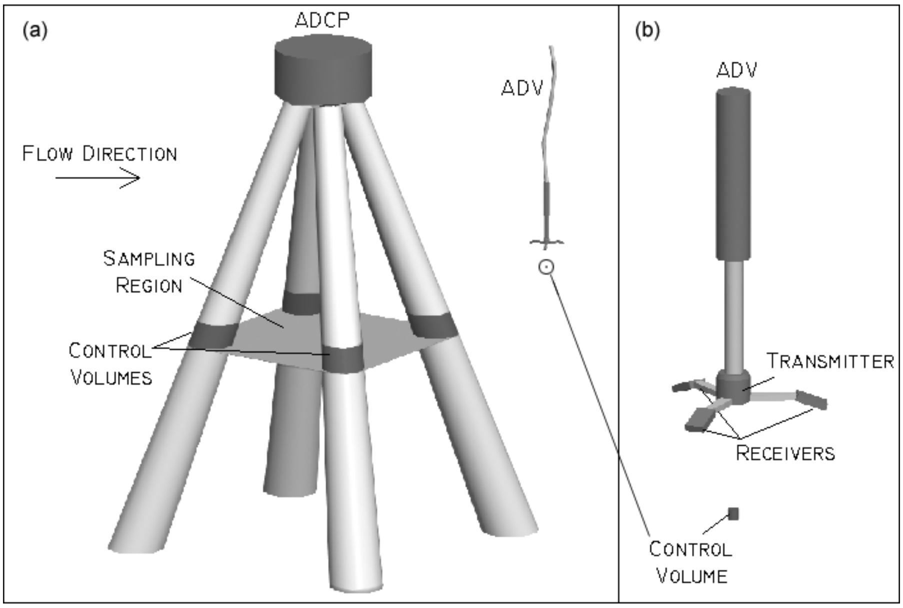

Figure 1 (a) ADCP and ADV instruments and control volumes and (b) expanded view of the ADV probe and control volume.

τ_{RSS} dominates, and the viscous term can be neglected (Nezu and Nakagawa, 1993). By integrating the Navier–Stokes equations for the water depth, h, a theoretical τ_{RSS}distribution can be derived as:

$$\frac{-\overline{u'w'}}{u_*^2} = 1 - \frac{z}{h} \tag{5}$$

In addition to the Reynolds shear stress descriptions, turbulence characterization consists of statistical, correlation and spectral analyses. Statistical analyses of velocity data, including mean, standard deviation, skew and kurtosis, are often used to describe turbulence characteristics. The standard deviation (turbulence intensity) is a general indicator of flow field turbulence. It describes the scatter in velocity measurements resulting from flow field variations or instrument uncertainty.

2.3 Instruments

The details of ADCP operation are described by numerous authors (Mueller, 2003; Stacey, 2003) and are briefly summarized here. A 1200 kHz Workhorse Rio Grande ADCP, manufactured by RD Instruments, was used in this research. The ADCP transmits and receives an acoustic signal with four beams, separated by 90° (Fig. 1a). Each beam is oriented outward 20° from the vertical. This configuration results in four control volumes (bins), which increase in size and diverge with distance from the ADCP. Velocity profile data are collected at uniformly spaced bins. The Workhorse Rio Grande was configured for flow depths greater than 0.3 m.

Several limitations result from the ADCP sampling technique. Firstly, flow field heterogeneity across the four diverging beams results in measurement error. The error can be substantial when applied to natural streams. Secondly, velocity in the top 10–50 cm and bottom 6% of the water column cannot be measured due to acoustic ringing and echoes. This is a serious limitation if data near the bed is required or when operating in shallow flow, such as the quasi-wadeable streams addressed in this study. Additionally, the large sampling volume, which increases with depth, makes it impossible to measure small-scale turbulent fluctuations.

Originally developed for marine flow environments, ADCP technology was applied to tidal channels and large rivers in the 1990s (Barua and Rahman, 1998; Lu and Lueck, 1999; Stacey, 2003). The popularity of ADCP stream discharge measurements has grown consistently (Simpson, 2001). Recently, researchers have investigated the use of ADCPs to measure spatial flow features including velocity and turbulence distributions (Muste *et al.,* 2004a, 2004b; Schemper and Admiraal 2002); Shields *et al.,* 2003. However, the validity of ADCP velocity measurements have not been adequately tested against accepted techniques in shallow streams.

Alternatively, flow fields may be characterized using point-velocity current meters. Point velocity meters can be categorized as mechanical, electronic, or acoustic. In this study, we compared ADCP results with data collected with an ADV and a Price pygmy current meter. The ADV used for this research was a 16 MHz MicroADV, manufactured by Sontek/YSI, Inc. The ADV operates on a pulse-to-pulse coherent Doppler shift. An acoustic signal is emitted by a transducer towards a sampling volume located approximately 5 cm away. The signal is reflected by ambient particles in the flow field and measured by three receivers separated by an angle of 120° and a distance of 7 cm (Fig. 1b). The Doppler shift frequency along each receiver is used to calculate the 3D water velocity. The resulting control volume is 0.09 cc with a 50 Hz maximum sampling rate. Figure 1 demonstrates the contrast in ADCP and ADV sampling volumes. A more detailed description of ADV operation principles can be found in Song and Chiew (2001).

The ADV configuration allows analysis of detailed flow features including small-scale turbulent fluctuations. ADV instruments have been used to describe velocity and turbulence distributions in laboratory flumes (Ferro, 2003), irrigation canals

Table 1 Physical and hydraulic descriptions of the sampled reaches

	Potlatch	St. Maries	How determined
Discharge, Q ($m^3 s^{-1}$)	11.4	7.9	ADCP measurement
Mean Velocity, U ($cm\,s^{-1}$)	87.6	61.5	ADCP measurement
Mean Depth, H (m)	0.81	1.02	Survey
Hydr. Rad., R_H (m)	0.77	0.87	Survey
Top Width, T_W (m)	15.4	12.8	Survey
Aspect Ratio, T_W/H	19.0	12.5	Survey
Froude Number, Fr	0.31	0.21	$U/(gR_H)^{0.5}$
Reynolds Num., Re	6.0×10^5	4.8×10^5	$\rho UR_H/\mu$
Bed Slope, S_b	0.0008	0.0004	Survey
Water Slope, S	0.0010	0.00052	Survey
Global Friction Velocity, u_{*g} ($m\,s^{-1}$)	0.088	0.066	Eqs (2) and (3)
Global Shear Stress, τ_g ($N\,m^{-2}$)	7.8	4.4	Eq. (3)
d_{16}, d_{50}, d_{84} (cm)	7.2, 11.4, 18.7	5.8, 10.9, 16.8	Wolman
Relative Roughness, $d_{50}\,H^{-1}$	0.14	0.11	Wolman, Survey
Critical Shear, τ_c ($N\,m^{-2}$)	92	88	Shields Parameter

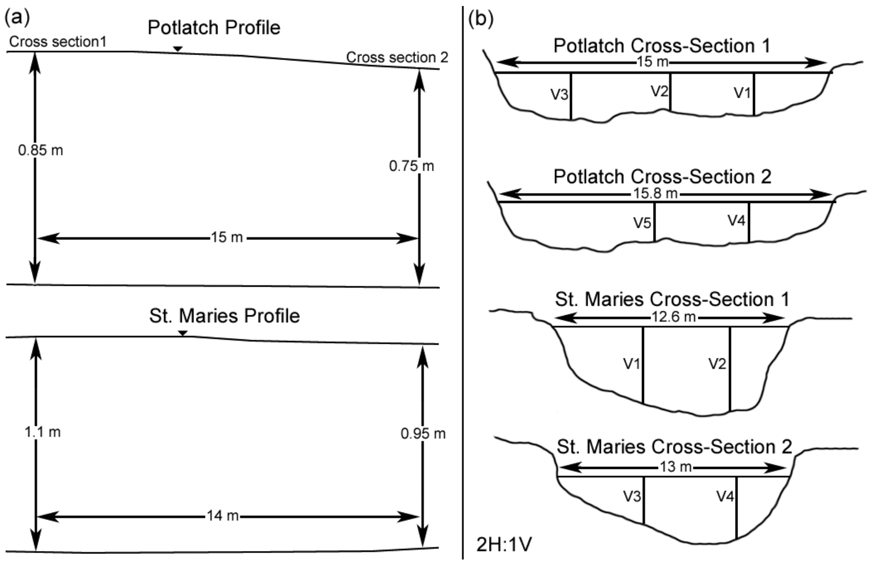

Figure 2 (a) Elevation and (b) cross-section views of the sampled reaches.

(Nikora and Goring, 2000), and natural channels (Rennie *et al.,* 1999; Stone *et al.*, 2003). However, this technique has several drawbacks compared to the ADCP approach. Foremost, the small sampling volume makes characterization of large areas very time consuming. Further, instrument placement can be difficult and dangerous in deep or rapid flows.

Price-type current meters determine the water velocity using mechanical means. A Price pygmy type current meter was used in this study. Detailed descriptions of the principles and performance of Price meters can be found in numerous reports (e.g. Wahl *et al.*, 1995). Briefly, the vertical-axis meter contains six cups attached to a 127 mm rotor. The rotor revolves at a speed determined by the velocity of the fluid passing through it. The flow field velocity is determined by counting the number of rotor revolutions in a given period of time. Price meters are easily deployed in wadeable streams. However, deep or fast flows require the meters to be deployed from a stream-crossing, such as a bridge or cableway.

3 Measurements and analysis

3.1 Site characterization

Measurements were conducted at two cross-sections in the St. Maries River near Clarkia, Idaho and two cross-sections in the Potlatch River near Kendrick, Idaho, USA. Stream geometry data were collected with a total station using standard surveying techniques (stream banks, water surface and bed slopes, and cross-section geometries). Survey data were used to calculate mean depth (H), hydraulic radius (R_H), top width (T_w), Reynolds number (Re), Froude number (Fr), and global shear stress (τ_g). The water surface slope was measured by surveying the water surface elevation at six to eight points over a length of approximately 400 meters and conducting a linear regression on the data. Table 1 contains physical and hydraulic descriptions of the sampled reaches, and stream geometries are shown in Fig. 2.

The sediment particle size distributions (PSD) were obtained using a Wohlman pebble count (Wolman, 1954). Approximately

150 stones were collected at each sampling vertical. Median particle diameters were 10.9 and 11.4 cm for the St. Maries and Potlatch rivers, respectively. Both reaches were classified as cobble bed (Bunte and Abt, 2001). The critical shear stress values, τ_c, were estimated for the d_{50} using the Shields parameter. Global shear stress estimates were far below critical values.

The Potlatch River reach is a high gradient stream resulting in a relatively large PSD, high mean velocity, and shallow depth. The left bank is nearly vertical bedrock and the right bank is vegetated cobble. The St. Maries reach has a more moderate slope and therefore, a lower mean velocity and smaller PSD. The reach has a minor lateral expansion and both banks are covered with vegetation, which was partially submerged at the time of sampling.

3.2 ADCP sampling

The ADCP was mounted within a RiverBoat, manufactured by OceanScience (Fig. 3). Two taglines were attached to the Riverboat and threaded through eyebolts, which were driven into the river banks. The RiverBoat was fitted with flowvanes to align the ADCP and was moved to the desired location and anchored by tying the taglines to the eyebolts. The boat was held relatively stable but minor movements due to flow field turbulence were observed. Data were collected for 20 min at a frequency of approximately 1 Hz, providing approximately 1200 samples (Schemper and Admiraal 2002; Muste *et al.,* 2004b). ADCP data were transferred to a laptop computer with wireless modems. The instrument configuration was adjusted to optimize data quality. Because of high velocity and turbulence levels, the ADCP was operated in RDI Mode 12 with a 5 cm bin size. Although more robust, Mode 12 provides less precision than the available pulse-to-pulse coherent modes (5, 8 and 11). For the St. Maries reach, two verticals were sampled in each cross-section at one-third the stream width from each bank. In the Potlatch reach three verticals were sampled in each cross-section at the centerline and one-quarter the top width from each bank (one vertical was discarded due to corrupt data).

ADCP data were analyzed with vendor and custom software programs. WinRiver (RD Instruments) was used for instrument configuration, data archiving, and data extraction. A custom FORTRAN code was written to compute and format velocity statistics including mean velocity vectors, standard deviation, skew, and kurtosis (Stone, 2005).

3.3 ADV measurements

An aluminum sampling stand was built to hold the ADV. The stand was 1 m wide and 0.5 m long and fitted with four adjustable legs and an adjustable sampling arm. The sampling arm extended a maximum of 0.5 m from the stand's front to avoid flow field interference, while cross-bracing prevented flow induced stand vibrations. The ADV processing canister and laptop computer were set on top of the stand. The ADV position was measured with a combination of Vernier gages.

Following ADCP data collection, instrument location was surveyed and marked with a florescent monument. The ADV was positioned over the monument and the location was verified by surveying the probe. The streambed, water surface, and all four stand legs were also surveyed. The ADV was initially positioned with the control volume approximately 1 cm from the streambed. Data were collected for 2 min at a frequency of 50 Hz. The adequacy of the 2 minute sample duration was confirmed by collecting data at several points for 20 min and evaluating divergence of velocity statistics (mean and standard deviation). Data were collected at 10 elevations within each vertical profile. The data were processed using WinADV (Sontek/YSI) and a custom FORTRAN code (Stone, 2005).

3.4 Price current meter measurements

Following ADV data collection, the Price meter was used to collect velocity data using standard USGS protocols (Sauer and Meyer, 1992). Measurements were conducted at three depths (0.2, 0.4 and 0.8H). A one minute sampling duration was used.

3.5 Steady flow assumption

The flow was assumed to be steady throughout the sampling routine at each vertical. ADCP, ADV and Price measurements were completed within one hour per vertical. The assumption of steady flow was investigated using two methods. Firstly, both sampling reaches were located less than two kilometers from USGS streamflow gages with discharge data available in 15 min intervals. Incremental changes in discharge were less than one percent for all verticals. Second, Style A USGS staff gages were installed at both sampling reaches. The change in water surface elevation was less than 3.05 cm (0.1 ft) for all verticals.

4 Results

ADCP performance was evaluated by comparing velocity measurements to ADV and Price meter data. Evaluated parameters included velocity profiles, depth-averaged velocity, velocity standard deviation, 3D velocity components, and local bed shear stress. ADCP and Price meter errors were assessed by assuming ADV data represented true velocity values.

4.1 Velocity profiles

A typical profile (St. Maries, Vertical 2) of velocity magnitude is shown in Fig. 4. ADCP, ADV, and Price measurements were comparable throughout the vertical profile. A similar pattern was observed for all other verticals (see Stone 2005 for the complete dataset). The various sampling techniques are evident from the vertical spacing of the data. Price data were collected at the standard relative depths of 0.2, 0.6, and 0.8H from the water surface. ADV measurements were collected at a high spatial resolution near the bed, with increased spacing toward the water surface. ADCP measurements were collected at evenly

Figure 3 ADCP measurements in the Potlatch River.

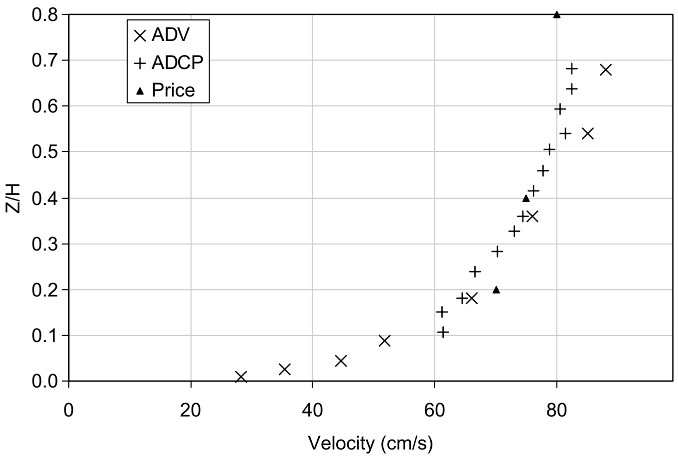

Figure 4 ADV, ADCP and Price meter velocity magnitude profiles for Vertical 2 of the St. Maries River.

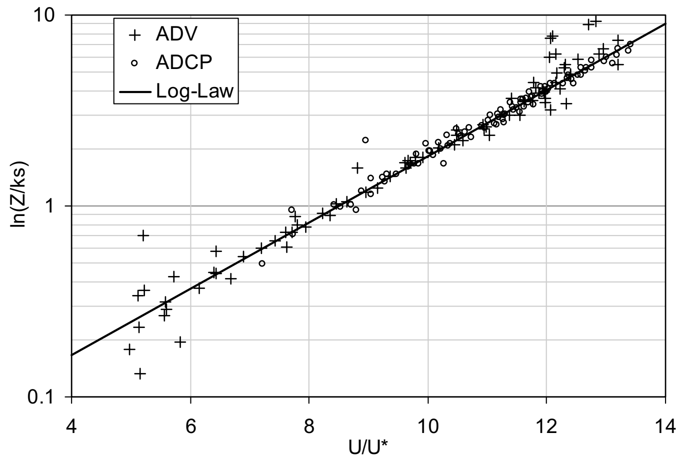

Figure 5 ADV and ADCP logarithmic velocity profiles and the theoretical log–law (u_* determined by applying the least-squares method to observed values).

spaced bins throughout the water column, with data near the bed and water surface discarded. Because of the variable vertical sampling locations, point-velocity data cannot be quantitatively compared between instruments.

The ADV and ADCP measured vertical velocity profiles were compared with the predicted log–law distributions (Fig. 5). The log–law was applied by solving for the friction velocity and displacement length using a least-squares method (Papanicolaou and Hilldale, 2002). Results from both instruments closely resembled the expected log–law profile. Resulting log-law parameters and correlation (R^2) values are shown in Table 2. R^2 values were greater than 0.96 for all verticals. Outliers were observed in ADV velocity data at both the water surface and near the bed. Local wake features caused by large roughness features were likely responsible for disrupting the near-bed log–law. Outliers near the surface may have been caused by air entrainment, secondary currents, or a velocity dip effect.

4.2 *Depth-averaged velocity*

The results were quantitatively compared between instruments at each vertical by depth-averaging the velocity magnitude data. The depth-averaged velocity for the Price meter was calculated using an arithmetic mean. The log–law, determined from a curve-fit to measured data, was extrapolated to the streambed and water surface and integrated over the water depth to calculate the ADV and ADCP depth-averaged values. The resulting depth-averaged velocities are shown in Table 2. Similar values were reported for all three instruments at nearly every vertical. The average errors (departure from ADV) were −4.9 and −6.4% for the ADCP and Price meter, respectively. The ADV depth-averaged velocities were equal to, or greater than, the other two instruments for every vertical. This could be attributed to the ADV's ability to measure a more complete vertical profile.

Table 2 Physical and hydraulic data

River	Potlatch					St. Maries			
Vertical	1	2	3	4	5	1	2	3	4
H (cm)	84	65	94	83	81	106	113	87	102
d_{50}(cm)	10.4	10.4	15.3	10.9	11.2	11.0	10.8	11.1	10.8
U_{ADV} (cm/s)	84.7	80.3	81.9	82.8	71.4	74.3	79.1	72.7	81.4
U_{ADCP} (cm/s)	84.1	78.7	81.0	82.8	69.2	70.9	72.9	67.3	67.1
U_{Price} (cm/s)	81	76	79	77	68	71	74	66	71
E_{ADCP} (%)	−0.7	−2.0	−1.1	0.0	−3.1	−4.6	−7.8	−7.4	−17.6
E_{PRICE} (%)	−4.4	−5.4	−3.5	−7.0	−4.8	−4.4	−6.4	−9.2	−12.8
τ_{ADV} (N/m^2)	5.7	5.8	6.0	5.6	4.2	4.1	4.4	4.2	4.9
τ_{ADCP} (N/m^2)	5.6	5.5	5.9	5.6	4.0	3.7	3.8	3.6	3.3
τ_{RSS} (N/m^2)	4.9	4.2	5.1	3.3	3.0	3.1	4.0	2.9	1.8
R^2_{ADV}	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.97	0.97
R^2_{ADCP}	0.99	0.99	0.99	0.98	0.96	0.99	0.98	0.99	0.98
$\sigma_{ADV0.5H}$	10.1	11.6	12.8	11.4	10.8	8.6	8.7	10.9	6.4
$\sigma_{ADCP0.5H}$	28.2	27.2	27.5	27.1	27.0	26.2	26.8	26.9	26.3

H = depth, d_{50} = median particle size, U_{ADV} = ADV depth integrated mean velocity magnitude, U_{ADCP} = ADCP depth integrated mean velocity, U_{Price} = Price meter depth integrated mean streamwise velocity, E_{ADCP} = ADCP error in depth average velocity, E_{Price} = Price error in depth average velocity, τ_{ADV} = ADV log–law derived bed shear stress, τ_{ADCP} = ADCP log–law derived bed shear stress, τ_{RSS} = ADV Reynolds shear stress derived bed shear stress, R^2_{ADV} = ADV log–law correlation coefficient, R^2_{ADCP} = ADCP log–law correlation coefficient, $\sigma_{ADV0.5H}$ = ADV velocity standard deviation at mid-water column, $\sigma_{ADCP0.5H}$ = ADCP velocity standard deviation at mid-water column.

4.3 *Velocity statistics*

Improved insight into instrument performance can be gained by investigating the statistical parameters of the velocity time series. Statistical parameters also provide information regarding the instruments ability to observe turbulent flow features. Figure 6 contains a typical standard deviation vertical profile as measured by the ADCP and ADV instruments (St. Maries, Vertical 2). The standard deviation measured by the ADCP was approximately three times larger than the ADV results. The elevated ADCP standard deviation appeared to be the result of high instrument noise when operated in RDI Mode 12. The discrepancy between ADCP and ADV standard deviation was similar to the level of uncertainty predicted by the ADCP deployment software (provided by RD Instruments) for the measured flow environment. The noise level can be reduced with alternative instrument configurations, but the "*low-noise*" modes require slower flows than those measured in this study.

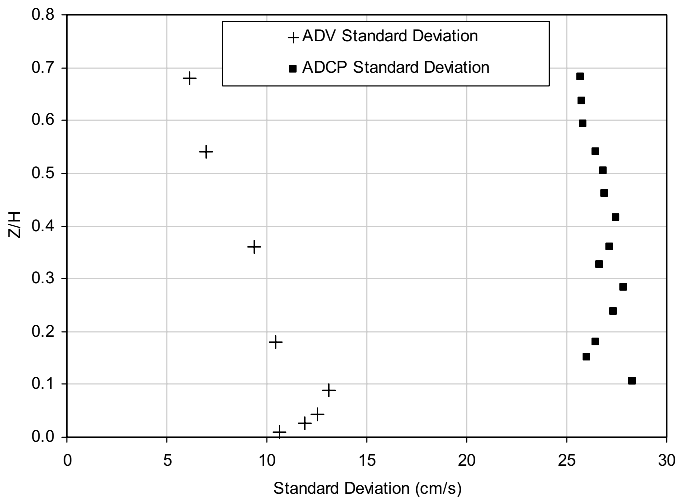

Figure 6 ADV and ADCP velocity magnitude standard deviation profiles for Vertical 2 of the St. Maries River.

4.4 *Velocity components*

ADCP and ADV measurements were also compared by decomposing the velocity magnitudes into streamwise (s), transverse (t) and vertical (v) components using a streamline coordinate system (Wilczak *et al.*, 2001). Although every attempt was made during data collection to orient the instruments to the direction of flow, a slight misalignment was unavoidable. The tilt correction algorithms (method number 2 proposed by Wilczak *et al.*, 2001) were used to realign the data to the actual streamline coordinate system. The transform was applied to the measured velocities in the entire profile for the entire time series. This resulted in the time and depth averaged transverse, vertical, and cross-correlation (transverse multiplied by vertical) velocities being set equal to zero. A unique coordinate system was defined for both instruments. However, the variation between ADCP and ADV coordinate systems was less than 5° for all verticals.

Although the mean velocity magnitudes for the ADV and ADCP observations were similar at most locations, the ADCP appeared to under-measure the streamwise velocity components at points in the upper half of the water column. The discrepancy between ADV and ADCP streamwise velocity measurements were likely due to flow disturbances caused by the ADCP boat in the shallow flow. The ADCP boat appeared to increase noise in the downstream beam, introducing bias to the streamwise velocity

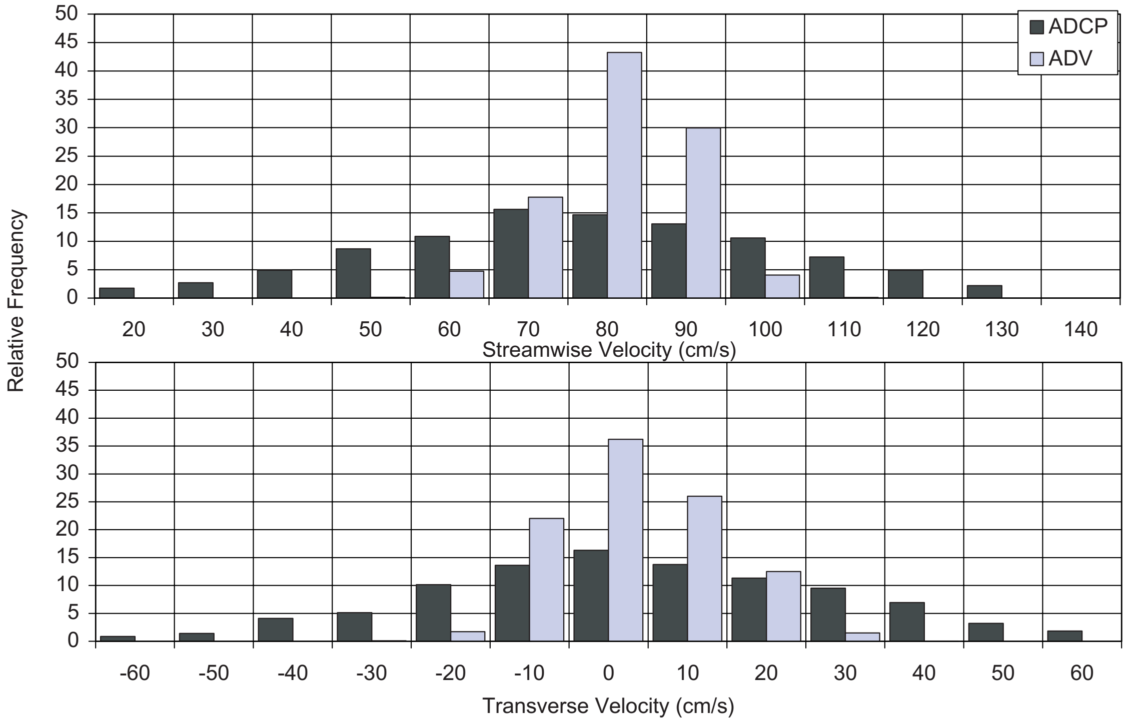

Figure 7 ADV and ADCP streamwise and transverse velocity histograms for mid-water column of Vertical 2 in the St. Maries River.

measurements. This notion was further investigated by comparing noise levels between upstream and downstream beams. Higher noise was observed in the downstream beam for bins in the upper half of the water column; corresponding to data points where ADCP measurements deviated from ADV values. Velocity histograms for the streamwise and transverse velocity components are shown in Fig. 7. Although the magnitudes of these measurements were similar, the elevated ADCP standard deviation resulted in a broader velocity distribution.

4.5 Bed shear stress

The adequacy of ADCP derived shear stress estimates was assessed through comparisons with ADV and water surface slope methods. The log–law (Eq. (1)) was used to estimate bed shear stress using ADV and ADCP velocity data. ADV Reynolds shear stress measurements, τ_{RSS}, were also used to estimate local bed shear stress and the water surface slopes were used to estimate global shear stress, τ_{g}. ADCP Reynolds shear stress measurements were not used because the preceding results demonstrated the inadequacy of ADCP statistical parameters such as standard deviation.

Bed shear stress estimates are contained in Table 2. For nearly every value, global shear stress was greater than the local estimates. Results of a one-sample *t*-test showed a significant mean difference between global and local bed shear stress estimates. This was likely the result of roughness not measured locally including bank shear (irregular geometry and submerged vegetation), losses due to secondary currents (both reaches were downstream from meanders), and bedforms. Among local shear stress estimates, ADV log–law values were the highest and RSS estimates were the lowest. ADV RSS estimates were considered less reliable due to low correlation values in calculations from Eq. (5) ($R^2 < 0.4$). This was likely caused by submerged flow obstructions, bank protrusions, and secondary currents. Stone (2005) demonstrated that the linearity of the RSS profiles in shallow rivers is heavily influenced by secondary currents. ADCP log–law estimates compared well with ADV log–law values. The results of a two-sample *t*-test showed that the mean difference between ADCP and ADV shear stress estimates was not statistically different. Therefore, ADCP bed shear stress values derived from the log–law adequately matched ADV results.

4.6 Sampling time

An additional consideration in selecting an appropriate instrument is the amount of time required to conduct the measurements. In this study ADV and ADCP measurements were collected for at least 2 and 20 min, respectively, at each location. We evaluated the appropriateness of the sampling times by investigating the convergence of velocity statistics (mean and standard deviation). Figure 8 contains a typical example of the mean measured velocities as a function of time for both instruments. For the data shown, the ADV and ADCP velocity data stabilized at sampling times of approximately 100 and 250 sec, respectively. Similar analyses were conducted for velocity and standard deviation at all sampling verticals. It was concluded that for the measured environment the 2 min ADV sampling time was adequate. Further, an ADCP sampling time of only 5 min would have produced nearly identical results to the 20 min period used in this study. It is important to note that ADV measurements must be conducted at multiple points in the vertical to describe the velocity profile.

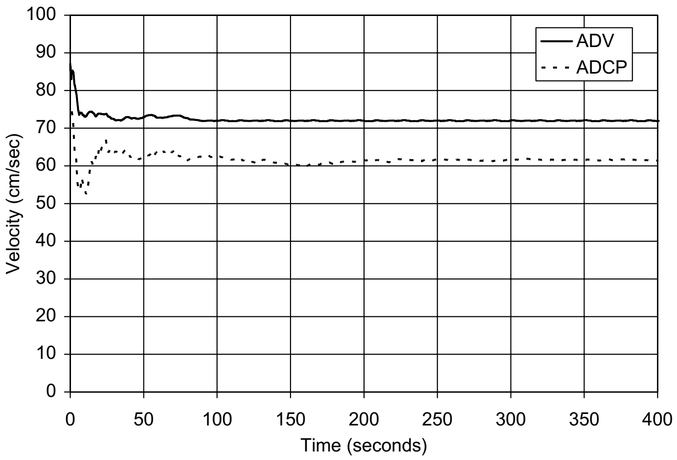

Figure 8 Mean velocity as a function of time for the ADV and ADCP measurements.

5 Discussion

The results can be used to guide instrument selection for velocity measurements in quasi-wadeable streams. The most appropriate instrument depends on the intended application of the data, and thus the required parameters. ADCP measurements of velocity profiles displayed the expected log–law velocity distribution, which compared favorably with ADV results. The depth-averaged velocities were similar for all instruments. Also, the ADCP showed a significant improvement in local bed shear stress estimates when compared to global estimates calculated from the water surface profile. However, excessive noise reduced the effectiveness of ADCP measurements of velocity vectors and standard deviation. Increased flow velocity likely would not have had a major influence on the results, because the ADCP was operated in RDI Mode 12, which is suitable for flow velocities up to $5\,\mathrm{m\,s^{-1}}$. However, ADCP performance would have likely improved under lower velocities, because a *"low-noise"* pulse-to-pulse coherent mode could have been used.

The results suggest that ADCP instruments are a suitable choice for collecting boundary conditions and calibration data for 1D habitat, hydraulic, and hydrodynamic models. ADCP instruments are also appropriate for collecting habitat data related to depth-averaged and point velocities (such as habitat preference criteria for fish). Further, ADCP data could be used to measure boundary condition data for 2D hydrodynamic models, including depth-averaged velocity distributions and local bed shear stress. However, ADV measurements still are necessary for calibration of 2D flow features. Likewise, ADCP measurements are acceptable for the collection for velocity profiles and bed shear stress distributions 3D hydrodynamic model boundary conditions of. ADCP measured velocity profiles are also appropriate for the partial calibration of 3D models. However, ADV measurements of velocity vectors and turbulence statistics are also desirable for proper calibration of 3D models.

The study results indicate that an appropriate ADCP sampling time in quasi-wadeable streams is approximately 5 min (appropriate sample durations should always be verified under local flow conditions). This suggests that in quasi-wadeable streams, ADCP velocity profile measurements can be collected much faster than with an ADV and with only a slight loss in data accuracy. The 5 min sampling time also compares favorably with Price meter measurements. An ADCP may be preferred over a Price meter when a complete velocity profile is needed (e.g. when calculating the bed shear stress or setting boundary conditions for a 3D model) or when the flow is too deep or fast to wade safely. The Price meter remains as an attractive option for wadeable streams where point or depth-averaged velocities are desired.

6 Conclusion

Improved flow-field descriptions are needed for a wide range of applications. ADCP instruments provide a potential alternative to traditional point-measurement techniques. The objectives of this research were to evaluate the adequacy of ADCP instruments for conducting velocity measurements in quasi-wadeable streams and to provide instrument selection guidance for similar flow environments. These objectives were met by conducting ADCP, ADV and Price meter measurements at coinciding verticals in two quasi-wadeable cobble-bed rivers. The following conclusions can be drawn from this study:

(1) The ADCP adequately measured velocity profiles, depth averaged velocities, and local bed shear stress distributions (computed by log–law).
(2) High instrument noise prevented the adequate ADCP measurement of velocity standard deviation and velocity components.
(3) ADCP instruments are appropriate for collecting data for 1D, 2D and 3D habitat and hydrodynamic models in quasi-wadeable streams. However, ADV measurements are also necessary for the proper calibration of 2D and 3D models.
(4) The required ADCP sampling duration in the measured quasi-wadeable streams was approximately 5 minutes per vertical; providing a potentially time efficient alternative to traditional point-measurement techniques.

Future research should investigate ADCP performance over a wider range of instrument configurations and environments.

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Notation

B = Log–law integration constant
d_{50} = Median particle size diameter
E = Error between ADCP, Price, and ADV velocity measurements
F_r = Froude number
h = Local water depth
H = Mean water depth
ks = Roughness height
Q = Discharge
Re = Reynolds number
R_{H} = Hydraulic radius
S = Water surface slope
S_{b} = Bed slope
T_{w} = Top stream width
U = Mean velocity
$\bar{u}$ = Time-averaged velocity
u_* = Friction velocity
u', w' = Fluctuating streamwise and vertical velocity components, respectively
z = Distance from streambed
Δz = Displacement length
γ = Fluid specific weight
κ = von Karman constant
μ = Dynamic viscosity
ρ = Fluid density
σ = Velocity standard deviation
τ = Shear stress
τ_{o} = Bed shear stress
τ_{g} = Global shear stress
τ_{c} = Critical shear stress
τ_{RSS} = Critical shear stress

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