Comparison of different methods to predict the mean flow velocity in step-pool channels

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Abstract

Steep mountain streams have irregular bed topography, where the mean flow velocity is heavily affected by the coarsest bed components and by their arrangement to form step pools, cascades, and rapids. According to literature findings the mean flow velocity is often related with water discharge, channel slope, and grain-size related variables through power relationships. Several approaches consider dimensionless hydraulic geometry terms to develop the analysis over a wide range of channel sizes and hydraulic conditions. The aim of this research is to test the performance of some literature formulas to directly compute the mean flow velocity (V) in step-pool sequences.

The study area deals with two fish ladders located in the Vanoi torrent (Trento Province, Italy), which were built by mimicking the step-pool morphology. Three reaches were selected to cover different channel slopes (2.6-10%). Data collection entailed three main phases: (1) topographical surveys, (2) granulometric analysis, and (3) flow discharge measurements (salt dilution method). Geometric and hydraulic variables were measured for the following step-pool cross sections: step head, pool center, and intermediate position between pool end next step. Particular attention has been reserved to determine the effective mean flow velocity over the whole path of each step pool sequence. The performance of different literature equations to predict V has been verified. The relations have been shared in three groups: dimensional (V), dimensionless with respect to the grain size (V^*) or to a combination of grain size and slope (V^{**}). In general, the V group of equations has produced the highest errors between computed and measured values. The dimensionless V^*, V^{**} groups have shown the best performance. In particular the V^* equations, which use unit discharge and channel slope, have provided the better fitting, and the lowest root mean square error. The results highlight the difficult to estimate flow velocity in step-pool sequences, and the attitude of this channel-bed morphology to be highly dissipative. The good performance of some dimensionless equations to predict V could also support the hydraulic designer in case the 'morphological rebuilding' of mountain creeks is opportune. Further analyses are required to better understand the flow behavior in streams where very rough bed forms and hydraulic drops are the primary sources of flow energy dissipation.

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Introduction

In mountain environments, alluvial channels with gradients greater than 0.02 (Grant *et al.*, 1990) can form step-pool sequences, which are characterized by large-scale roughness. Step-pools are functionally important in river systems because they maximize flow resistance and increase the bed stability (Abrahams *et al.*, 1995; Chin, 2003; Curran and Wohl, 2003; MacFarlane and Wohl, 2003). The step-pool regime alternates supercritical and subcritical flow conditions and results very similar to that of consolidation check-dams. Previous investigations suggest that the step-pool reach gradient (S) and liquid discharge represent dominant controls of the flow kinematic of mountain creeks (David *et al.*, 2010). In field study of rough and narrow streams the flow discharge measurement is usually more accurate than the flow depth measurement. In fact, these streams exhibit irregular bed topography that makes difficult the determination of a representative flow depth (Rickenmann and Recking, 2011). Consequently several authors have calibrated equation for the direct estimation of the mean flow velocity (V) using both field data (Jarrett, 1984; Rickenmann, 1994; Ferguson, 2007; Comiti *et al.*, 2007) and laboratory data on self-formed steps (Comiti *et al.*, 2009; Zimmermann, 2010). These equations have the following form:

$$V \propto g^{0.20}\, S^{0.20} q^{0.60} D_c{}^{-0.40} \qquad [1]$$

where q is the unit discharge, D_c the grain roughness, and g the gravity acceleration. Rickenmann (1991) proposed to use $D_c = D_{90}$ (diameter for which the 90% of the sieve diameter is finer), while Aberle and Smart (2003) and Zimmermann (2010) adopted the standard deviation of bed longitudinal profile (σ_z), resulting more appropriate in streams with substantial bed forms.

Comiti *et al.* (2007) introduced the hydraulic geometry equation in a dimensionless form:

$$V^* = a\, q^{*m} \qquad [2]$$

being α and m two empirical parameters and:

$$V^* = \frac{V}{\sqrt{g\, D_c}} \qquad [3]$$

$$q^* = \frac{q}{\sqrt{g\, D_c{}^3}}. \qquad [4]$$

Ferguson (2007) has remarked that [Eq. 2] performs better than other equations since q^* is a better predictor than the depth (h) over grain size ratio (h/D_c) and is probably less affected by measure error.

Rickenmann and Recking (2011) introduced the following new dimensionless terms:

$$V^{**} = \frac{V}{\sqrt{g\ S\ D_c}} \quad [5]$$

$$q^{**} = \frac{q}{\sqrt{g\ S\ {D_c}^3}} \quad [6]$$

and then they formulated a hydraulic-geometry type equation:

$$V^{**} = a\ q^{**m} \quad [7]$$

The authors calibrated equation [Eq. 7] through a data set of 2890 field measurements. They divided the result into three different domains as to q^{**} ($q^{**} \geq 100$; $1 \leq q^{**} < 100$; $q^{**} < 1$). To obtain a smoother transition for the velocity predictions between the three domains, the authors used the logarithmic matching technique proposed by Guo (2002). The aim of this research is to test the predictive capacity of available literature formulas, which are more appropriate to compute directly the mean flow velocity in channels with a step-pool morphology. The verification has been carried out by using field data of small-scale step-pool sequence and assessing the performance of the equations listed in Table 1.

Materials and methods

A dataset of hydraulic and geometric variables were collected in three artificial step-pool reaches, which were built with the function of fish ladders by passing check dams in the Vanoi torrent (Trento Province, Italy). Three step-pool reaches (*TA*, *TB*, *TS*; channel widths from 0.62 to 1.65 m) were selected in order to test different channel slopes (6.0%, 10.0%, and 2.6% respectively). Field experiments were performed in three main phases: (1) topographical surveys, to draw longitudinal profiles and cross-sections of the channel; (2) grain-size measures of the bed surface; the sediment sampling was conducted by line (fixed spacing) and using a caliber; (3) measurements at controlled steady conditions of flow depth and water discharge using the salt dilution method. A number of 65 cross-sections were surveyed in the following characteristics positions: step heads (SH), pool centers (PC), and intermediate positions (INT) between the pool end and the following step. The mean flow velocity (V) in each cross-section was back-calculated as the ratio discharge (Q) flow area (A). In the elaboration of field data particular attention was reserved to quantify the effective mean flow velocity over the whole path of each step-pool reach. This velocity, here defined as 'reach-averaged flow velocity', resulted from the ratio between the sequence length and the total travel time, which was calculated accounting for partial mean velocities within the all sub-reaches SH-PC, PC-INT, and INT-SH. The reach-averaged V values were compared with V values that can be computed via the

Table 1. Equations for flow velocity prediction tested in this study; Rh=hydraulic radius; hm = hydraulic depth (m); H/L = step height-length ratio; σ_z = standard deviation of the residuals of a thalweg longitudinal profile regression (m); D_{90} (diameter for which the 90% of the sieve diameter is finer) (see text for the other symbols).

Matakiewicz (1932)	$V = 2.38\ Rh^{0.70}$	[8]
Bray (1979)	$V = 8\ Rh^{0.60} S^{0.29}$	[9]
Jarrett (1984)	$V = 3.17\ Rh^{0.83}\ S^{0.12}$	[10]
Rickenmann (1991)	$V = 1.3\ g^{0.20} S^{0.20} q^{0.60} D_{90}^{-0.40}$	[11]
Rickenmann (1994)	$V = 0.37\ g^{0.33} S^{0.20} Q^{0.34} D_{90}^{-0.35}$	[12]
Aberle and Smart (2003)	$V = 0.96\ g^{0.20} S^{0.20} q^{0.60} {\sigma_z}^{-0.40}$	[13]
D'Agostino (2005)	$V = 1.42\ q^{0.48}$	[14]
D'Agostino et al. (2006)	$V = 1.21\ g^{0.245} S^{0.16} q^{0.51} D_{84}^{0.265}$	[15]
Comiti et al. (2007)	$V^* = 0.29\ q^{*\ 0.66}$	[16]
Comiti et al. (2007)	$V^* = 0.74\ q^{*0.59} \left(\frac{H/L}{S}\right)^{0.52}$	[17]
Ferguson (2007)	$V^* = 1.44\ q^{*\ 0.60} S^{0.2}$	[18]
Comiti et al. (2009)	$V^* = 1.24\ q^{*\ 0.83}$	[19]
Zimmermann (2010)	$V^* = 0.58\ q^{*\ 0.39}$	[20]
Yochum et al. (2012)	$V^{**} = q^{**\ 0.16}$	[21]
Yochum et al. (2012)	$V^{**} = 0.9 \left(\frac{hm}{\sigma_z}\right)^{**\ 0.16}$	[22]
Rickenmann and Recking (2011)	$V^{**} = 1.5471\ q^{**0.7062} \left[1 + \left(\frac{q^{**}}{10.31}\right)^{0.6317}\right]^{-0.4930}$	[23]

relationships listed in Table 1. Observed values were then plotted against measured values. The predictive performance of each equation was assessed by means of the normalized root mean square error (*RMS*), quantifying the following standard deviation of residuals:

$$RMS = \sqrt{\frac{\sum \left(\frac{V_{predicted} - V_{observed}}{V_{predicted}} \right)^2}{N}} \quad [24]$$

Results

The main results of topographical surveys, granulometric analysis and flow measurements are summarized in Table 2 and Table 3. The reach-averaged V data versus predicted values are shown in Figure 1 along with *RMS*, which was calculated both separately for each reach (TA, TB, TS) and for the whole sample (Tot in Figure 1). All comparisons and performance evaluations were conducted in terms of dimensional flow velocity (V), thus always transforming the equation results

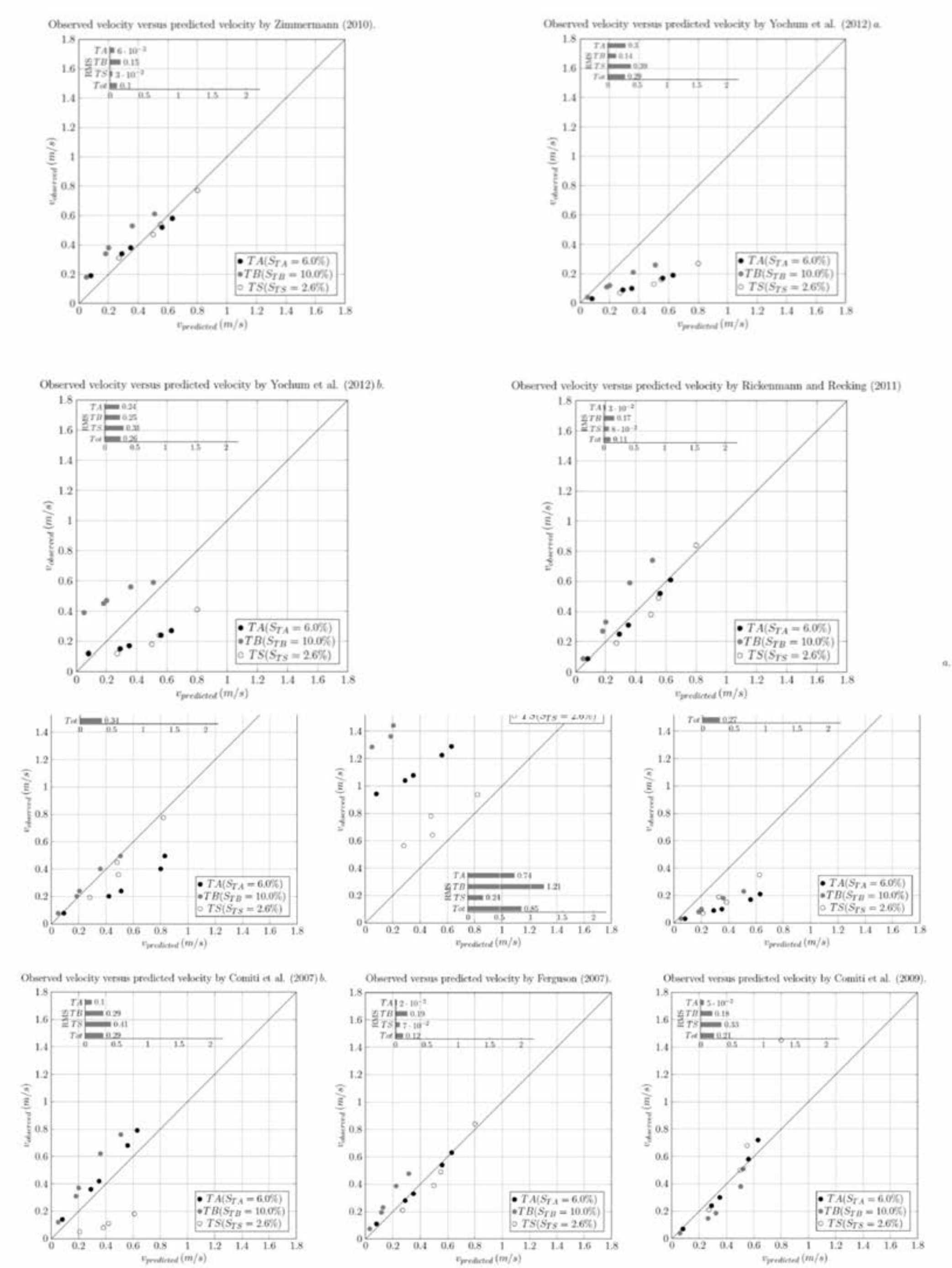

Figure 1. Observed values of mean flow velocity ($V_{observed}$) versus predicted values ($V_{predicted}$) from the application of equations in Table 1.

of those equations (e.g. Eq. [17] or [23], Table 1), which adopt dimensionless variables.

Between the classical power law relationships directly computing the mean velocity (*V*), the D'Agostino (2005) equation provided predictions with the best performance (lowest *RMS* = 0.297). Considering the equations based on the *V** group, that of Zimmermann (2010) produced the lowest *RMS* (0.098) and this value was also the best one on the whole (V, V* and V** group). A quite similar *RMS* value (0.121) resulted from the relations of Ferguson (2007) and Comiti *et al.* (2009), and both equations showed a general tendency to an overestimation. Analysing the dimensionless *V*** group of equations, the lowest *RMS* (0.109) was generated by the equation of Rickenmann and Recking (2011), with a *RSM* value very close to that Zimmermann (2010). Equation 22, proposed by Yochum *et al.* (2012), is the only one containing a relative submergence, and exhibited a tendency of underestimation. Comiti *et al.* (2007) equation, which employs a steepness factor, produced a high dispersion of data around the line of perfect agreement.

Looking at the three reaches (*TA*, *TB*, and *TS*) separately, the Ferguson (2007) equation provided the lowest *RMS* (0.020) and the best fit for the reach TA. Good predictions for the reach *TA* was also obtained with Rickenmann and Recking (2011) and Comiti *et al.* (2009) relations. For the reach *TB*, Yochum *et al.* (2012), equation [21], and Zimmermann (2010) predicted the more correct values. It was also observed that the dimensionless equation introduced by Zimmermann (2010) provided the lowest sum of the three partial *RMS* values.

Table 2. Principal results of topographical and grain-size measurements.

Reach	Cross-sections	Total Length (m)	Slope (m/m)	D_{84} (m)	σ (m)
TA	22	35.39	0.060	0.26	0.244
TB	19	19.99	0.100	0.26	0.279
TS	23	42.98	0.026	0.18	0.078

Table 3. Data set of the experiments in the artificial step-pool reaches.

Reach aged	Experiment	Discharge Q (m^3/s)	Reach-ave flow velocity V (m/s)
TA	TA_1	0.01	0.627
	TA_2	0.03	0.048
	TA_3	0.04	0.185
	TA_4	0.12	0.204
	TA_5	0.18	0.357
TB	TB_1	0.01	0.505
	TB_2	0.03	0.275
	TB_3	0.04	0.492
	TB_4	0.11	0.426
	TB_5	0.19	0.823
TS	TS_1	0.01	0.069
	TS_2	0.04	0.151
	TS_3	0.07	0.224
	TS_4	0.23	0.412

Discussions and conclusions

The capability to predict the mean flow velocity V for a given discharge is essential for hydraulic and hydrological modelling, stream restoration design, geomorphic analysis, and ecological studies (Yochum *et al.*, 2012). An unique approach is not available to predict V in each fluvial-morphological type, and, in particular, in steep channels. As to step-pool sequences the application of traditional laws of flow resistance provides serious problems because the V estimation is highly sensitive to the choice of representative cross-sections and roughness parameters due to great irregularity of thalweg and stream banks. Therefore, when the discharge is known, the direct estimation of V from the unit water discharge is preferable (Rickenmann, 1990; Aberle and Smart, 2003; D'Agostino, 2005; Ferguson, 2007). In this research, a new database of cross section geometry and hydraulic variables was collected for small-scale step pools under well controlled steady flow conditions. The mean flow velocity has been extracted in terms of a reach-averaged velocity resulting from the 'travelling' time along the whole step-pool sequence. The study results indicate the dimensionless unit discharge, [Eq. 4], is a robust predictor of V over a significant range of step-pool slopes (3-10%). The Zimmermann (2010) equation generated the best fit and the lowest errors, hinting that the used roughness parameter ($D_c=\sigma_z$) is more suitable for the V assessment in step-pools. Furthermore Yochum *et al.* (2012) equation, [Eq. 22], which also contains σ_z and well predicts V, confirms the previous remark. In few words, the standard deviation σ_z of the residuals of the thalweg profile regression allows capturing the influence of the largest clast on the flow resistance and then avoiding a more problematic grain size sampling. The good performance of Rickenmann and Recking (2011), Comiti *et al.* (2009), and Ferguson (2007) equations has turned out to be in accordance with Comiti *et al.* (2007) and David *et al.* (2010) findings. In fact, our study confirms that variations in flow resistance are mostly explained by unit discharge and slope, whereas the relative submergence hm/D_{84} is not an appropriate explanatory variable of V for step-pool creeks, and a macro-roughness variable, like the step height-length ratio, can be more effective. Finally, the good predictions provided by the Rickenmann and Recking (2011) equation for the three step-pool reaches suggest to better investigate on the transitional behaviour between shallow and deep flows and to dedicate further efforts in assessing the boulder concentration and protrusion (Nitsche *et al.*, 2012), which interact with such a transition.

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