UDC (UDK) 551.4.042

Paolo BILLI,
Emanuele PRECISO, Enzo SALEMI [1]

FIELD INVESTIGATION ON STEP-POOL MORPHOLOGY AND PROCESSES IN STEEP MOUNTAIN STREAMS

SUMMARY

Main objective of this paper is to compare the field data measured on a few step-pool reaches of the Aneva River in the Northern Apennines with a reference database including a large number of fields and laboratory data derived from the wide literature on step-pool streams in order to contribute to describe their geomorphology and to understand their generating processes. A field experiment with painted particles is carried out on the Aneva River to investigate the entrainment threshold conditions for particle as large as those making up the steps, and, consequently, for the formation of new or removal of old steps. Theories about the factors controlling the development of these coarse-grained bedforms are tested against the data sets available and the antidune hypothesis is investigated and discusses as well. The reference database and the Aneva data confirm the keystone hypothesis as the most likely to account for the development of step-pool sequence.

Key words: step-pool, antidunes, keystones, mountain streams, gravel-bed rivers

INTRODUCTION

Mountain streams are the most ubiquitous kind of streams in the world. They are the largest in number and represent an important environment in terms of biodiversity, geomorphic processes and recreational activities. Steep, boulder-bed streams are characterised by staircase morphology, consisting of boulder steps and finer grained pools (Figure 1) that may alternate with other channel morphologies such as runs or plane beds (Montgomery and Buffington, 1997; Halwas and Church, 2002). Boulder steps are distinctive, transverse, roughness elements punctuating mountain streams steeper than 2-4% (Whittaker and Davies, 1982; Grant *et al*., 1990; Billi *et al*., 1994; Chin, 1999a, 2003; Chartrand and Whiting, 2000; Weichert *et al*., 2008) and replacing riffle and pool sequences, typical of lower gradient (less than 2%) and finer grained rivers.

Notwithstanding the large number of studies on the geomorphology and generating processes of step-pool sequences (see for instance Chin and Wohl, 2005, for a review on step pool formation), still an animate debate persists among

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[1] Paolo Billi (corresponding author: bli@unife.it), University of Ferrara, Department of Physics and Earth Sciences – Ferrara, Via G. Saragat 1, 44122 Ferrara, Italy; Emanuele Preciso, ARPA Veneto – Padova, Italy; Enzo Salemi, University of Ferrara, Department of Physics and Earth Sciences – Ferrara, Via G. Saragat 1, 44122 Ferrara, Italy.

river scientists about the identification of the main factors controlling their geometry and occurrence. This may depend on intrinsic difficulties in the field observation of step-pool sequences formation and, likely, by the non-homogeneous methods used by different authors for the identification of step-pools and measurement of their basic geometry parameters (Hayward, 1980; Zimmermann and Church, 2001; Wooldridge and Hickin, 2002; Nickolotsky and Pavlowsky, 2007).

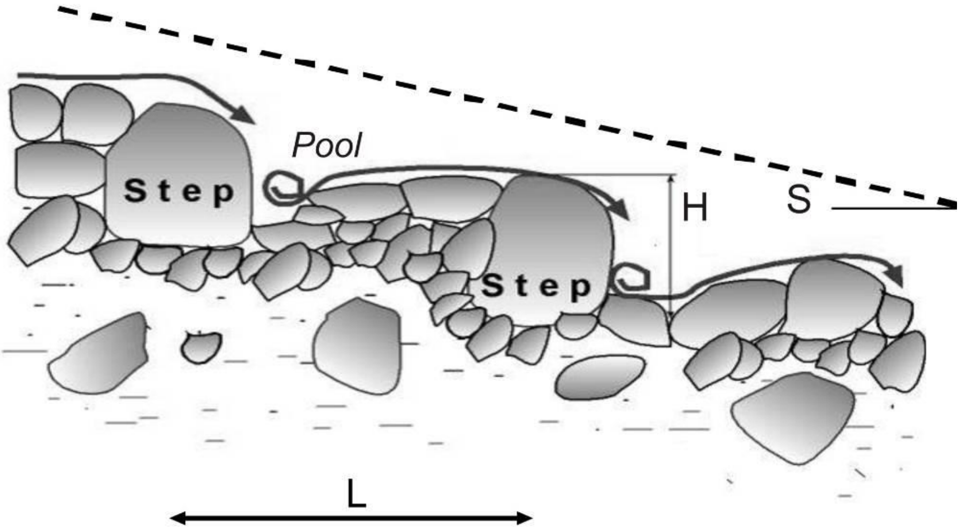

Figure 1. Step-pool morphology and geomorphic parameters:
L = step spacing; *H* = step height; *S* = bed gradient.

The review of the abundant literature has shown that only very few concepts about step-pool morphology and flow hydraulics can be considered as well established. According to several authors (e.g. Chin, 1989; Grant *et al.*, 1990; Church and Zimmerman, 2007), it seems that for the formation of boulder steps, large particles available on the streambed or supplied from slopes bounding the channel, a steep gradient and some lateral confinement are necessary. Moreover, the step wavelength is reported by several authors as inversely related to bed slope (Judd, 1964; Allen, 1982; Whittaker, 1987; Chin, 1989; Grant *et al.*, 1990; Zimmerman and Church, 2001; Gomi *et al.*, 2003; Chin and Wohl, 2005), whereas others did not find such a clear correlation (Lenzi *et al.*, 1997; Chartrand and Whiting, 2000; Wooldridge and Hickin, 2002; Nickolotsky and Pavlowsky, 2007). A few authors found also some correlation between boulder steps wavelength with the size of the step particles (Grant *et al.*, 1990; Wohl and Grodek, 1994; Chin, 1999a; Chartrand and Whiting, 2000), though this finding is not shared by others (Wooldridge and Hickin, 2002; Nickolotsky and Pavlowsky, 2007). Many studies on step-pool streams report a strong correlation between step wavelength and channel width, but only the study of Weichert *et al*. (2008) has focussed on the role of channel width in the step formation. Other authors suggest particle size of bed material, especially the largest stones that commonly make up the steps, can play a relevant role in determining their wavelength, geometry and loci of occurrence (Zimmerman and Church, 2001; Curran, 2007; Zimmerman *et al*., 2010).

In spite of the environmental relevance of mountain streams, many questions about their geomorphic characteristics and generating processes are still open. Nevertheless, the understanding of the processes controlling the formation of step-pools is crucial to design appropriate and environmentally friendly plans for mountain stream restoration and rehabilitation and more consolidated geomorphic and hydraulics models are needed.

Aiming to contribute to improve the understanding of step-pools morphology and processes and to test and compare the most renowned findings reported in the literature, field experiments and observations on the mobility and entrainment threshold of step particle are carried out on the Aneva River, small mountain streams of the northern Apennines. Complementary field observations are also reported from two ephemeral streams/gullies in the Ethiopian Rift Valley and highlands.

MATERIAL AND METHODS

Study Area

The Aveva R. is a tributary of the Vergatello R. that joins the Reno R. near Vergato (Figure 2). The area of the Aneva catchment is 26.93 km^2, its highest mountain peak is 1003 m a.s.l., the average elevation is 663 m a.s.l and the average streambed gradient is 0.04 mm^{-1}.

In the study area there are only two rain gauges with a long data record, Raiola di Vergato and Vergato at an elevation of 623 and 195 m a.s.l., respectively (Figure 2). The annual precipitation at Raiola di Vergato is 909 mm whereas at Vergato is 809. The monthly rainfall distribution in both stations follows a typical Mediterranean pattern with a dry summer (40 and 59 mm in July and August, respectively at Raiola di Vergato; 68 and 31 mm in June and July, respectively, at Vergato) and a peak in Autumn (in November at Raiola di Vergato with 138 mm and in October at Vergato with 115 mm).

In the upper portion of the Aneva catchment, Miocene sandstones with marlstone intercalations outcrop whereas the lower part is underlain by clayey olistostromes including Jurassic ophiolites and blocks of Cretaceous limestone. Here, active landslides that in places may reach the streambed, and intensive erosion processes are very common.

About half of the catchment (52%) is covered by forest and Mediterranean bush, the remaining is taken up mainly by cropland (43%) and a small percentage of grassland (5%).

The middle reach of the Aneva has been selected for the field measurements. Its morphology consists of an alternation of step-pool and riffle-pool and lateral bars reaches. The study reach gradient varies between 0.02 and

0.04 mm^{-1}, with the riffle-pool-bar reaches occurring on the gentler and the step-pools on the steeper slopes, respectively. Such a situation is also reflected by the grain size of these geomorphic units with average D_{50} being 562, 65 and 50 mm for steps, riffles and bars, respectively.

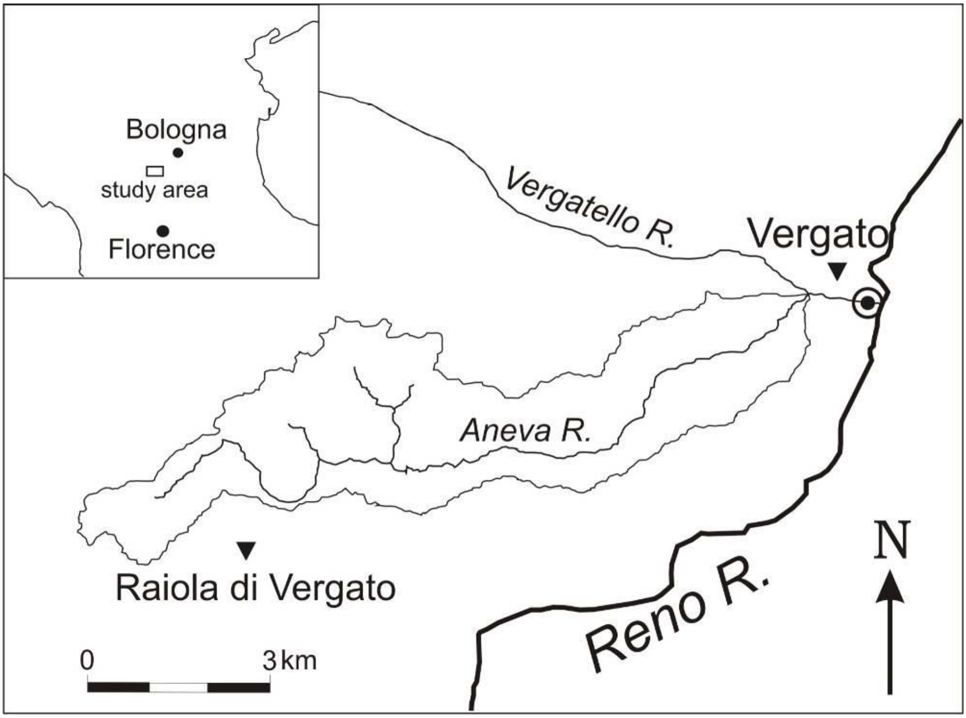

Figure 2 The Aneva River study area. Black triangles indicate the rain gauges.

Data and Methods

Eight step-pool sequences were measured in the study reach of the Aneva stream. The average values of the main geomorphic parameters of the step-pool sequences selected are reported in Table 1. For the data collected, channel width (W) refers to bankfull width in step-pool alluvial reaches or the actual channel width in bedrock confined reaches. The streambed gradient (S) was measured by a total station from the step top of the most upstream to the most downstream step of the sequence. Step spacing (L) is obtained for each sequence by averaging the individual step-to-step horizontal distances (Figure 1). A few authors (e.g. Chin, 1989) define wavelength as the horizontal distance between pool troughs. Given the small longitudinal thickness of steps (typically coinciding with one line of boulders), this difference in measuring wavelength is not expected to produce significant differences in the data. Step height (H) is the vertical distance from the step top to the pool scour at the step foot. D_{84} was obtained from measuring the intermediate diameter of all the step particles in a sequence. The transect line method (Leopold, 1970) was instead used to sample riffles and lateral bars bed material. These methods are used also in the most of the papers on step-pools though, regrettably, a few of them do not report any information about the field measurement criteria.

Table 1. Main geomorphic parameters of the study step-pool reaches in the Aneva River (mean values in bold).

Channel width (*W*) (m)	Bed slope (*S*) (mm^{-1})	Step spacing (*L*) (m)	Step height (*H*) (m)	Step D_{84} (mm)	*L/W*	*H/L/S*
3.3	0.03	2.4	0.20	730	0.73	2.78
4.2	0.04	3.5	0.25	880	0.83	1.79
3.7	0.14	2.1	0.44	800	0.56	1.52
4.2	0.06	6.3	0.83	960	1.51	2.18
4.0	0.06	3.0	0.30	850	0.75	1.67
3.3	0.11	1.9	0.26	730	0.58	1.24
3.3	0.09	3.9	0.66	810	1.20	1.86
4.6	0.08	4.9	0.94	980	1.07	2.40
3.8	**0.08**	**3.5**	**0.48**	**842**	**0.90**	**1.93**

The field data measured on the Aneva River were compared with a large, reference data set of the main geomorphic parameters of step pool sequences including field and laboratory data reported on international journals (Chin, 1989, 1999a, 2003; Abrahams *et al.*, 1995; Chartrand and Whiting, 2000; Lenzi, 2001; Zimmermann and Church, 2001; Lenzi and D’Agostino, 1998; Wooldridge and Hickin, 2002; Donadel, 2001; Lee and Ferguson, 2002; Gomi *et al.*, 2003; McFarlane and Wohl, 2003; Wohl and Wilcox, 2005; Nickolotsky and Pavlowsky, 2007), PhD and MSc theses and unpublished data from step pool streams in the eastern Italian eastern Alps (Billi, 1999) and the Euganei plug hills in the Po Plain south-west of Padova (Preciso, 2007). These data encompass a wide range of environments, hydrological and climate conditions, geological settings and altitudes, therefore they can be considered as representative of a large variety of geographical and geomorphic settings. A summary of such large step-pool database, including the number of data, average value and range for the main geomorphic and sediment parameters are reported in Table 2.

Table 2. Characteristic values of the reference step-pool database used (several authors, see text).

	N.	Mean	Range	Stand. dev.
Channel width *W* (m)	302	4.50	0.60 – 38.00	3.98
Bed gradient *S* (mm^{-1})	324	0.12	0.01 - 0.45	0.09
Step spacing *L* (m)	295	4.29	0.90 – 17.00	2.17
Step height *H* (m)	295	0.58	0.12 - 3.32	0.41
Step D_{84} (m)	83	0.64	0.14 - 1.77	0.32
Step D_{max} (m)	66	0.72	0.17 - 2.60	0.42

RESULTS AND DISCUSSION

The Aneva River Field Experiment

Many authors (e.g., Grant *et al.*, 1990; Chin, 1999b; Halwas and Church, 2002; Wohl and Merrit, 2008) assume that step-pool sequences are originated by long return time interval (more than 50 years) floods, i.e. large floods capable to entrain the largest particles, under conditions of limited sediment supply (Grant *et al.*, 1990). In order to verify the conditions for the large step particles entrainment and dynamics in the Aneva R., seven, individual large particles the size of which is comparable to D_{50} of the step-pool sequences in the study reach (i.e. 0.33m) were selected, their position recorded by the total station and marked with acrylic paint. These particles were intended as control particles to check the entrainment, if any, of large stones and photos were taken to visualize the particles making up the steps in the study reach.

Unfortunately, there is no flow gauge on the Aneva, nor any historical record, therefore, in order to assess hydraulic characteristics of floods at peak flow, a maximum level recorder was installed. It consists of a 2.5 m high and 10 cm in diameter pipe, closed at the bottom and with several small holes near its base in order to let the water in. Inside the pipe a second, coaxial narrower pipe (5 cm in diameter) is fixed from the top. Some kind of fine powder such as ground cork, sawdust or coal dust is poured into the larger pipe. As the water rises in the pipe the powder remains stuck to the inner pipe and the maximum level of water is marked with accuracy and can be recorded by a total station. In order to avoid mistakes or malfunction of the maximum level recorders, three of them were installed in the study reach. This simple device proved to work well and provided reliable data of flood peaks.

During the study period, only three floods occurred. Two of them were characterised by a discharge just a little higher than base flow, whereas a third one was higher (about 2 m^3s^{-1}) and the stream bed reacted remarkably by changing the position of a few steps, whereas others were formed and large particles were entrained. The return time of this flood was calculated as 9.7 years. Such a figure was obtained by Preciso (2007) on the base of the frequency analysis of the rainfall that generated it and using different methods: 1) five empirical equations specifically derived for Italian rivers (Maione, 1977; Maione and Moisello, 2003); 2) the “Rational Method” (Chow *et al.*, 1988); 3) the Soil Conservation Service (SCS) method (USDA, 1972).

Since there is no flow record for the Aneva, these methods were tested against flow data of a nearby stream of almost the same catchment area and the SCS method proved to provide the most accurate results with a difference of only 0.1 m^3s^{-1} between calculated and predicted peak flow (see Preciso, 2007, for a detailed analysis of the procedure adopted).

DATA ANALYSIS

Step-Pool Morphology

Several authors (e.g., Whittaker, 1987, Grant *et al*, 1990; Wohl *et al*., 1997; Chin, 1999a; Chartrand and Whiting, 2000; Gomi *et al*., 2003) observed that step-pool spacing is related to channel width. In the reference data set 67% of the wavelength/width ratio (*L/W*) is in the 0.5 - 1.5 range, with an average value of 1.3. The Aneva conforms to the literature data since the step spacing/channel width ratio (*L/W*) ranges between 0.56 and 1.51 with an average value of 0.90 (Table 1). In the reference database *L/W* values higher than 5 are a very small percentage and may depend on the difficulty in an objective identification of individual step-pool sequences (Wooldridge and Hickin, 2002; Nickolotsky and Pavlowsky, 2007).

In the reference dataset, 90% of step height values are less than 1 m, 60% of channel gradients fall between 0.04 and 0.15 mm^{-1} and more than half of D_{84} and D_{max} are within the 0.25-0.75 m range. The Aneva data are included in the same ranges whereas D_{84} is a little coarser.

Chartrand and Whiting (2000) report a significant relationship between step spacing and step height. This finding is not confirmed by the analysis of the reference database, though the data from Idaho rivers of these authors are included as well. The same inconsistency is reported also by Wooldridge and Hickin (2002) and Nickolotsky and Pavlowsky (2007). The Aneva data show a correlation coefficient (R^2 = 0.67) higher than the reference database and appear to support Chartrand and Whiting (2000) conclusion (Figure 3).

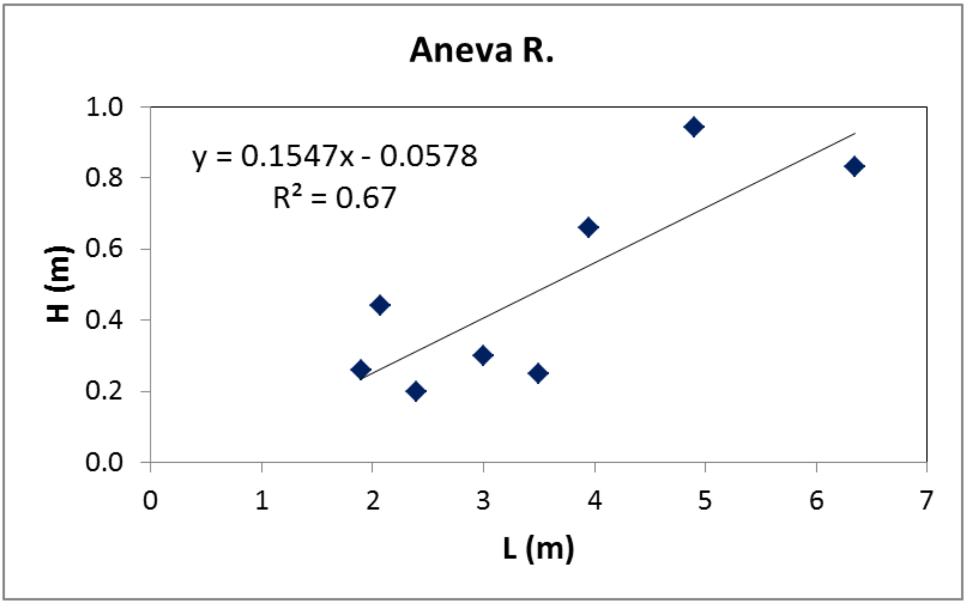

Figure 3. Correlation between step spacing (*L*) and step height (*H*).

Step height seems to be someway influenced by the size of the coarser step particles (D_{84}), as observed also by Curran and Wilcock (2005) in their flume experiments. The reference database shows some correlation (R^2 = 0.64), whereas a weaker correlation (R^2 = 0.59) characterises the Aneva data (Figure 4) as found also by Nickolotsky and Pavlowsky (2007).

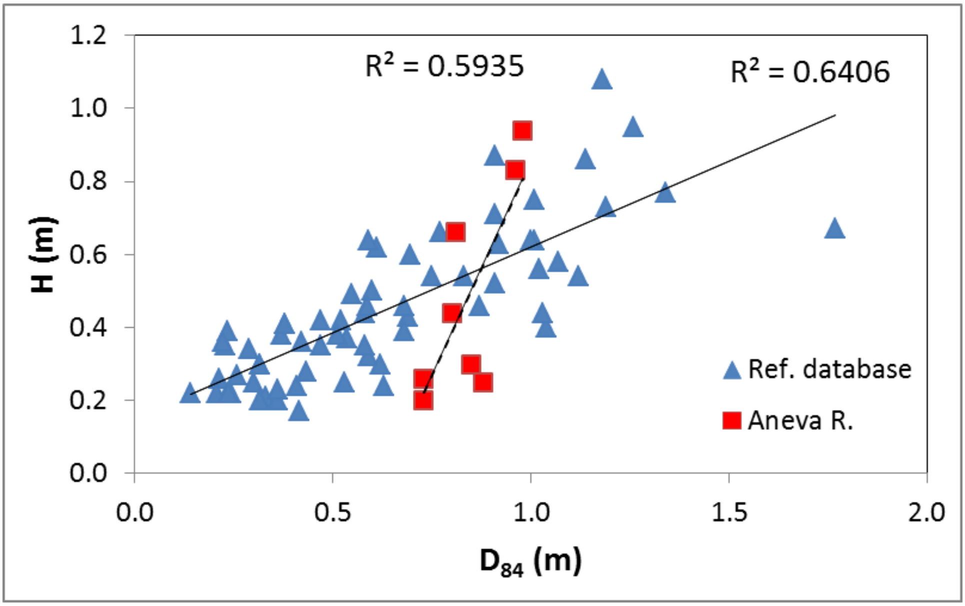

Figure 4. Plot diagram of step D_{84} versus step height (H).
R^2 = determination coefficient.

In their study on bedrock step-pools, Duckson and Duckson (2001) report that step height is proportional to slope, whereas Nickolotsky and Pavlowsky (2007) observe a weak relationship in their headwater study stream of the Boston Mountains in Arkansas. Nevertheless, the plot of both the reference database and Aneva data indicates that such relationship is inconsistent.

Slope is considered by several authors (Whittaker, 1987; Grant *et al.*, 1990; Wohl *et al.*, 1997; Chin, 1999; Chartand and Whiting, 2000) to exert a strong control on step spacing and Chin and Wohl (2005) and Chin and Phillips (2007) indicate the inverse relationship between wavelength and slope as a consolidate finding. According to all these authors, the negative exponential relation takes the forms of Judd's expression (Judd, 1964):

$$L = K/aS^{b} \qquad [1]$$

where L is step spacing; S is channel gradient; K is a representative bed element height (typically step height - Chartrand and Whiting, 2000) and a and b are empirically determined constants.

The distribution of step spacing of both the reference database and the Aneva data do not show any relationship with bed gradient (Figure 5) and also Chin's data (1999a) show a very poor correlation coefficient ($R^2 = 0.33$).

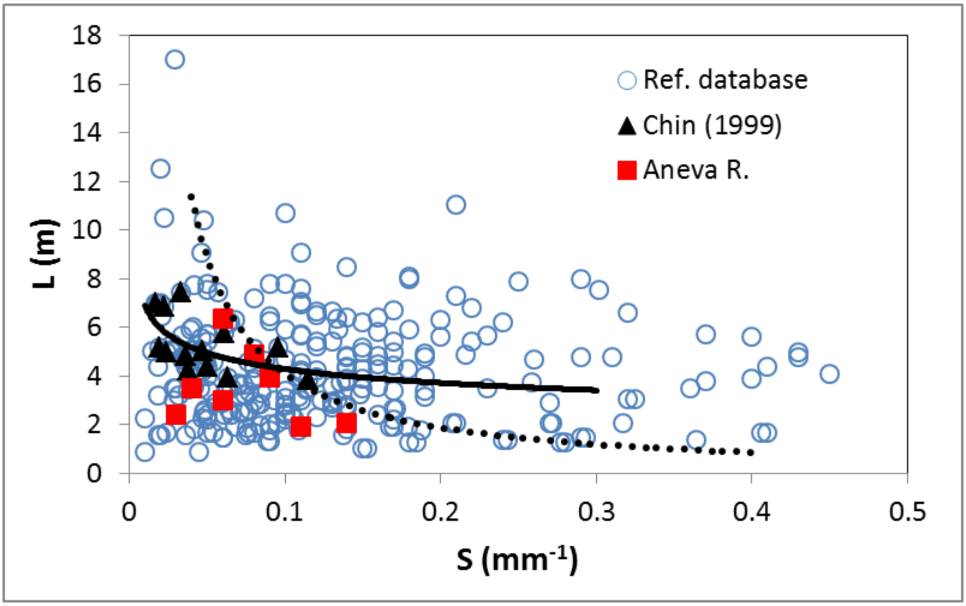

Figure 5. Bed gradient versus step wavelength. Interpolation lines are: solid ($R^2 = 0.33$), Chin (1999); dotted ($R^2 = 0.68$), Wittaker (1987).

Other authors (see Weichert *et al*., 2008 for a review and their figure 2) found that bed gradient (*S*) is inversely correlated with step steepness (step height/step spacing ratio, *H/L*). The flume experiments of Abrahams *et al*. (1995) have shown that the maximum flow resistance in step-pool reaches is obtained when the ratio is between 1 and 2. In the Aneva the average (*H/L*)/*S* ratio is 1.93 with five data out of eight in the 1-2 range that includes also more than 60% of the reference database values (Figure 6).

Particle Mobility

The highest flow recorded during the study was assessed to have a return time in the 5-10 years range, i.e. a little larger than bankfull discharge, and proved to be able to entrain large particles in the D_{84}-D_{100} range. During this flood, a few steps were completely removed and new ones were formed as shown by figure 7 in which at least a few large boulders were dislodged and formed a new step during moderate floods. This observation is corroborated also by the painted particles experiment (0.3 - 0.6 m in mean diameter, i.e. intermediate between step D_{50} and D_{84}) that were all entrained by a relatively moderate flood the peak flow of which was calculated to have exerted a boundary shear stress of 60Nm^{-2}.

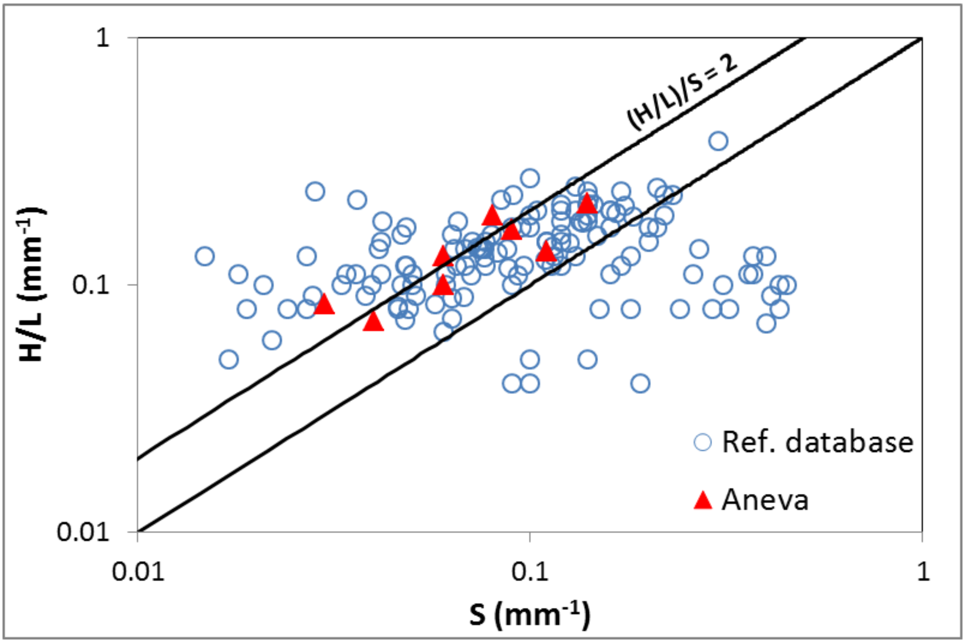

Figure 6. Plot diagram of step steepness (*H/L*) versus bed gradient (*S*). *H* = step height; *L* = step wavelength; *S* = bed gradient.

In Table 3, the shear stress required entraining particles in the 0.3 – 0.6 m range is calculated by different equations (Shields, 1936; Baker and Ritter, 1975; Costa, 1983, Williams, 1983) and compared with the field data. Costa (1983) and Williams (1983) equations provide good predictions, at least for the entrainment of particles of 0.3 m in mean size. Shields' criterion (1936) and Baker and Ritter (1975) equation predict a critical shear stress by far higher than the measured value of 60Nm^{-2} which was able to entrain the large particles of the Aneva step-pool study reach.

Table 3. Measured and calculated critical shear stress (Nm^{-2}) capable to entrain particles in the 0.3 - 0.6 m range in intermediate diameter (*D*).

Criterion	*D* = 0.3 m	*D* = 0.6 m
Highest flood measured	60	60
Shields (1936)	214	428
Baker and Ritter (1975)	144	405
Costa (1983)	55	129
Williams (1983)	50	100

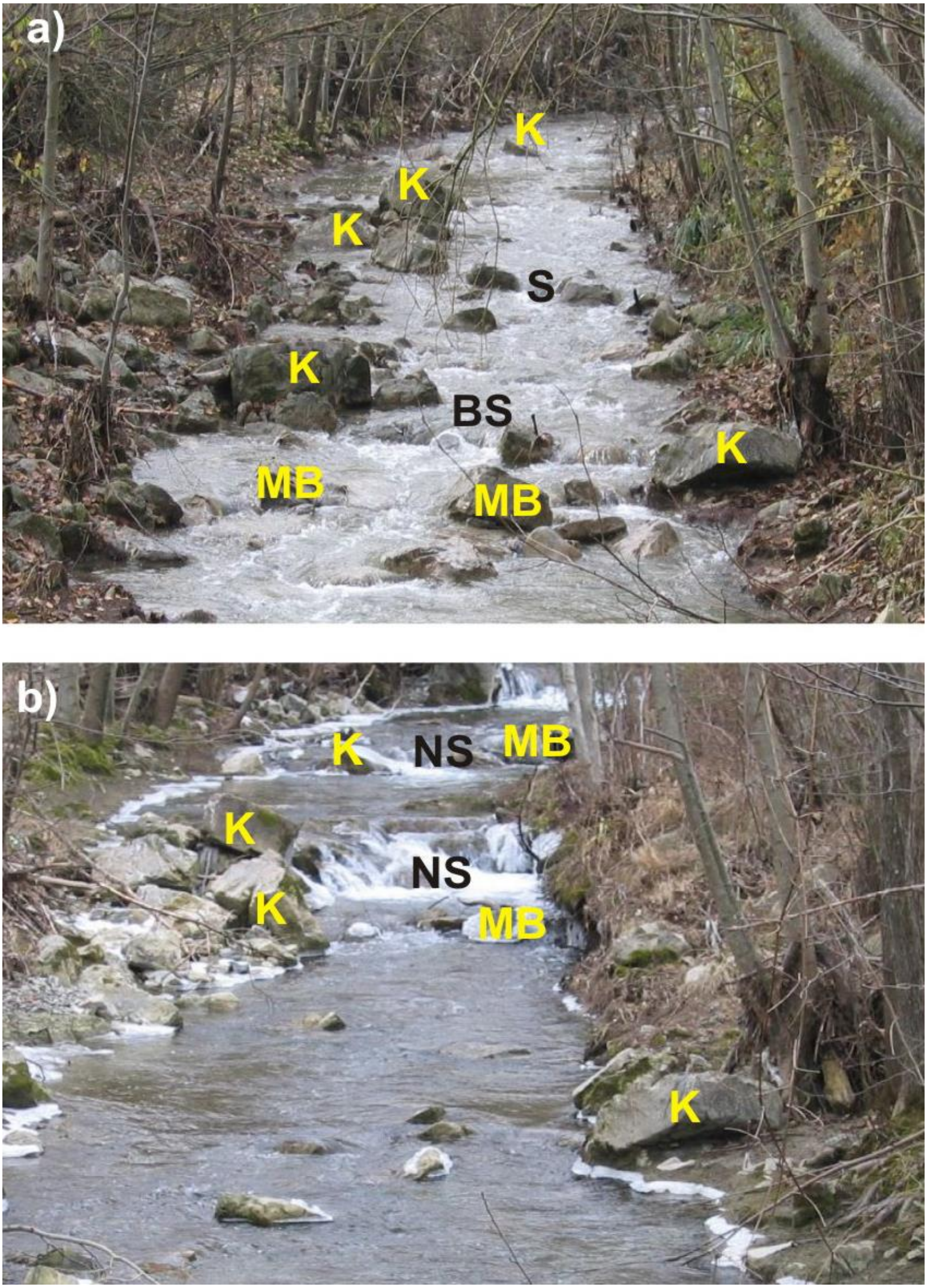

Figure 7. Streambed changes of a study reach on the Aneva R., Northern Apennines, Italy: a) bed morphology at the beginning of the study; b) the same reach after a moderate flood with 5-10 years return interval. K = keystone; MB = mobile boulder; S = step; BS = breached step; NS = newly formed step.

DISCUSSION

Since the very first studies on step-pool morphology, the step wavelength has commonly been considered as a main geomorphic parameter to be investigated in relation to channel gradient in order to uncover the main processes capable to generate them. In spite of more than two decades of field and laboratory studies, several questions are still open.

Chin and Wohl (2005) and Chin and Phillips (2007) affirm that the early observation that step-pool frequency increases with increasing slope has been demonstrated and supported by numerous field datasets from a variety of geographical settings, e.g. in New Zealand (Hayward, 1980), Israel (Wohl and Grodek, 1994), Canada (Wooldridge and Hickin, 2002) and the western United States (Heede, 1972, 1981; Grant *et al*., 1990; Wohl *et al*., 1997; Chin, 1999a; Gomi *et al*., 2003; Chin and Phillips, 2007). This convincement, however, is not shared by an almost equivalent number of authors (e.g., Lenzi *et al*., 1997; Billi *et al*., 1998; Duckson and Duckson, 2001; Lenzi, 2001; Zimmerman and Church, 2001; Comiti *et al*., 2005; Church and Zimmerman, 2007; Curran, 2007; Nickolotsky and Pavlowsky, 2007; Weichert *et al*., 2008). Our figure 5 that includes the reference database, the Aneva data and the interpolating lines obtained by Whittaker (1987) and Chin (1999) shows that the Judd type inverse relation is more an exception rather than a consolidated finding and that Whittaker and Chin expressions have different coefficients and exponents. In spite of that, Chin and Wohl (2005) still affirm that the general relation between channel gradient and step wavelength may be true and account for such inconsistency by channel size and flow disparities differences among streams in different environments resulting in a family of curves, specific for different physiographic regions (Heede, 1972). However, for most of our subsets of homogeneous data, no significant relation was found between L and S.

According to Abrahams *et al*. (1995), step pool sequences are expected to form during bankfull or higher flows, capable of entraining large particles and trigger bed armouring processes leading to the formation of transverse roughness elements the spacing of which determines the maximum flow resistance. This model, initially proposed by Davies and Sutherland (1980) and Whittaker and Jaeggi (1982), and then substantiated by the flume experiments of Abrahams *et al*. (1995), implies that the stream bed adapts its morphology to maximise flow resistance. The flume experiments of Abrahams *et al*. have shown that the maximum resistance is obtained when the $(H/L)/S$ ratio is between 1 and 2. This is an important finding that is confirmed by more than 60% or our data but, as Abrahams *et al*. state, does not provide information about the mechanisms involved in the formation of step-pool sequences. Nevertheless, this result indicates that slope has some hydraulic role, at least in the determination of wavelength as soon as a first step is formed

A few authors (Whittaker and Jaeggi 1982; Ashida *et al*., 1984; Grant and Mizuyama, 1991; Grant, 1994; Chin, 1999; Rosport and Dittrich, 1995; Chartrand and Whiting, 2000; Lenzi, 2001; Weichert *et al*., 2008), on the base of laboratory and field data analysis, suggest that step-pool are simply the coarse grained analogous of antidunes in sand bed rivers. Kennedy (1961) has shown that antidune wavelength depends on flow velocity and it is coupled to flow depth (see Allen, 1982, his figures 10-18). Weichert *et al*. (2008), using the field and flume data of Whittaker and Jaeggi (1982), Rosport (1997), Chin (1999) and Chartrand and Whiting (2000), plotted the Froude number (*Fr*) and the dimensionless wave number ($kh = 2\pi d/L$, in which d is flow depth and L is wavelength or step spacing) on a diagram including also the region of antidune formation observed by Kennedy (1963). Most of these data fall close to the antidune region but the coupling of Froude number with flow characteristics generating step-pool is not straightforward. Chin (1999), in fact, observed that 'the role of discharge is difficult to discern in the field because the high-magnitude processes associated with step–pools are almost impossible to measure directly' and 'there is no direct evidence to show that the calculated discharges are the actual flows that generated the observed wavelengths in the channels'.

Chartrand and Whiting (2000), in order to test the consistency of the antidune model for step-pool formation, adopted the criterion of minimum estimate of antidune wavelength proposed by Allen (1982) and based on the work of Peterson and Mohanty (1960). The relation $L >= 0.15\ D_{50}/S$ is indicated as the discriminate function. Almost all the step-pool data of Chartrand and Whiting (2000, their figure 10) lie above the equality line and that, according to these authors, is enough to confirm the analogy between antidunes and step-pools. However, the original equation reported by Allen (1982) does not include D_{50} but h_2, i.e. the flow depth at the transverse clast array. Allen observes that h_2 can be of the same order of magnitude of the coarsest bed particles, hence, instead of D_{50}, we used D_{84} and/or D_{max} from our data sets (reference database and Aneva) and found results similar to those of Chartrand and Whiting (2000) (Figure 8). Actually, Allen (1982) did not apply the Peterson and Mohanty (1960) equation to step-pools but to explain the formation of transverse ribs (McDonald and Banerjee, 1971; Koster, 1978) and stated that these coarse grained bedforms can exist only within a given range of sediment and flow conditions. Though transverse ribs recall a smaller scale replica of mountain streams steps, the former typically develop on secondary channels free to adapt their depth and width to the forming flow. By contrast, step-pool channels are commonly laterally confined and larger than average flood flows are necessary for their formation. So the association of step-pools with antidunes is not straightforward. Furthermore, in a field study on coarse grained bedforms in the Derek Wenz, a step-pool, boulder bed stream on the Ethiopian highlands, Billi (2000) found that Allen's criterion is matched only for flow depths equivalent to $D_{84\text{-}100}$, whereas when higher flow depth are simulated, i.e. flow conditions typically more consistent with the formation of antidunes rather than step-pools, the data clearly depart from the discriminating function (Figure 9).

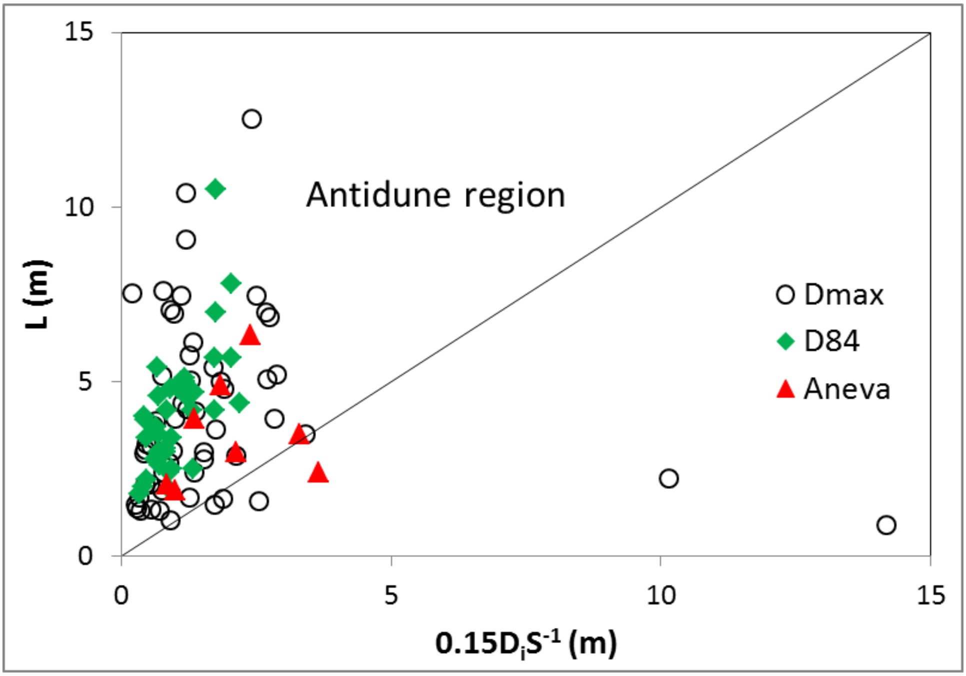

Figure 8. Minimum estimate of antidune wavelength according to Allen's (1982) criterion in which D_i is a reference grain size of steps (D_{84} and D_{max} of the reference database; Aneva is D_{84} of Aneva R.), *S* is bed gradient and *L* is wavelength.

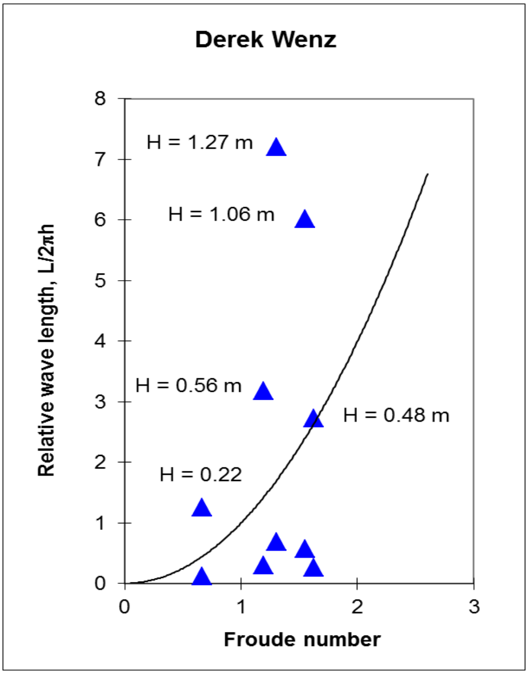

Figure 9. The average relative wavelength of a step-pool sequence measured on the Derek Wenz, Ethiopian highlands, plotted against the Froude number calculated for different flow depths. Only the flow depth of 0.48 m matches Allen's (1982) criterion for antidune, whereas for deeper flows, more consistent with the conditions of antidune formation, the data depart from it.

In the flume experiment of Abrahams *et al*. (1995), step pools are reported to begin as antidunes and to evolve to their final form as the bed degraded, implying a reduced sediment supply, i.e. a condition that several authors (e.g. Grant *et al*., 1990; Chartrand and Whiting, 2000; Wohl and Merrit, 2008), simply on the base of field observations on their study rivers, consider a prerequisite for the formation of step-pools. This condition is not present in the Aneva, in which sediment supply is expected to be very high because of the widespread slope degradation processes all across the catchment and close to the stream channel. Step-pools were observed by the first author (Billi, unpublished) in several small stream with high sediment supply in semi-arid environments of the Ethiopian and Eritrean highlands and on the bottom of ephemeral gullies incised in slope deposits in the Ethiopian Rift Valley. These small channels have a boxlike morphology with a few meters high, sub-vertical slopes subjected to recurrent failure and hence very high sediment supply (Figure 10).

Also Weicher *et al*. (2008) did not find any obvious influence of antidune on the formation of step-pool sequences in all their flume experiments, but observed that steps formed when particles were entrapped by large immobile keystones. Zimmerman and Church (2001) were the first to suggest that the random occurrence of large particles controls the location of steps, acting as keystones for the development of strong, imbricate structures. This hypothesis is confirmed by Curran and Wilcock (2005) flume experiments in which steps form in association with the deposition of a larger grain whereas any strongly coupled interaction between the bed surface and the free surface of the stream was not observed, as it is instead normally expected for the formation of antidunes.

All these findings suggest rejecting the antidune hypothesis, whereas the Aneva field data support the role of large size particles in the formation of step-pools. Additional flume experiments results of Curran (2007) support the keystone hypothesis and point out the role of large particles in triggering the formation of steps as the deposition of other particles around the large keystone determines the formation of a step and the downstream scour establishes the spacing between the two steps (Comiti *et al*., 2005). This view is shared also by Zimmerman and Church (2001) and Moses and Lower (2003). In fact, as a step is established, it locally affects the flow hydraulics, a hydraulic jump and a plunging jet develop, a pool is scoured with expenditure of a large proportion of the stream energy and, hence, flow resistance is maximised as postulated by Abrahams *et al*. (1995).

The keystone theory is supported by the Aneva experiment and data since a relatively small flood (with a return time of less than 10 years) was capable to entrain particles of the same size of those making up the steps (Tab. 1), new steps were formed and others were removed or breached (Figure 7). This result contradicts the convincement, not supported by any field evidence or data however, that step-pool sequences are formed only during large floods with 50-200 years of return time (e.g., Grant *et al*., 1990; Chin, 1989).

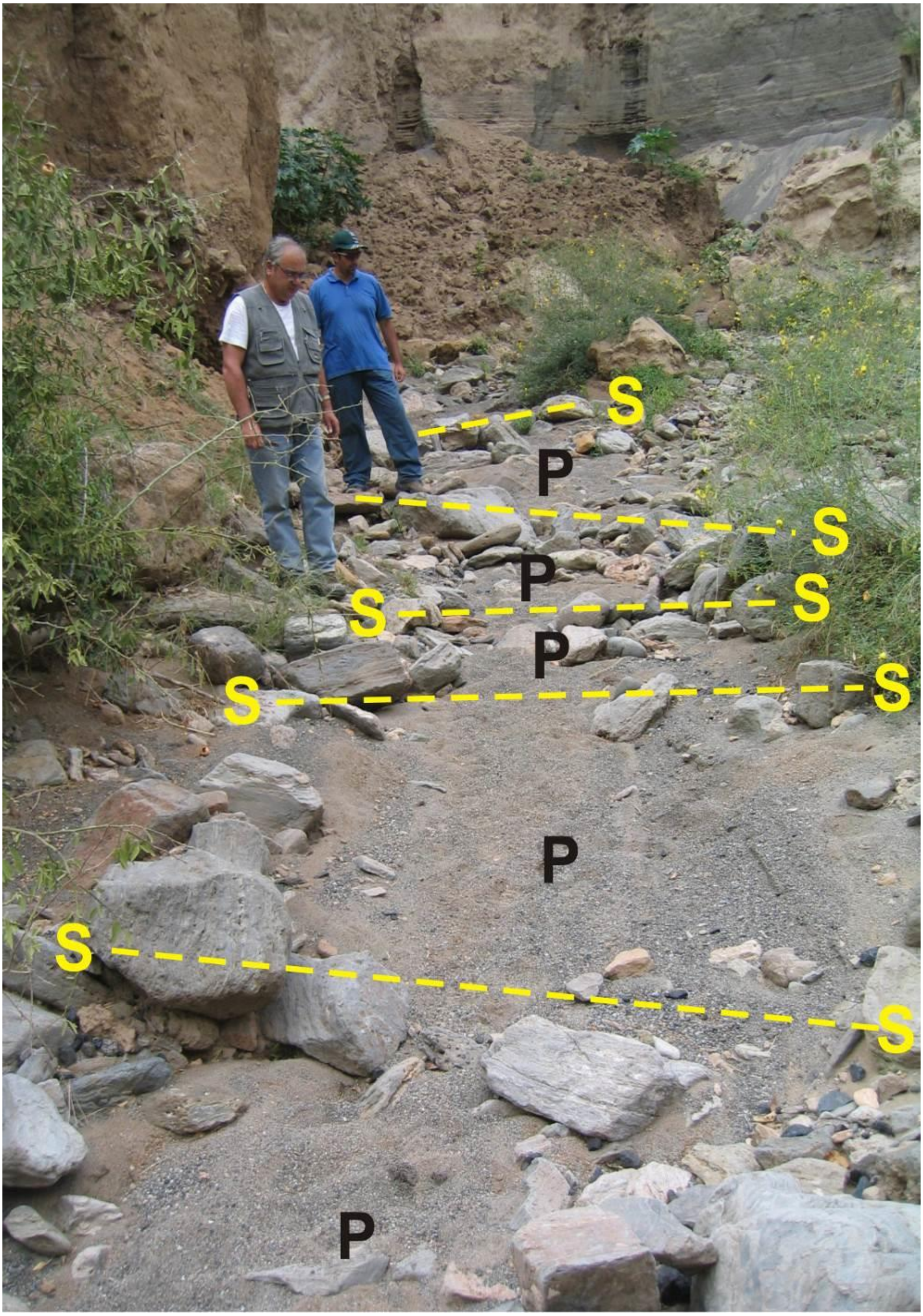

Figure10. The dry streambed of an ephemeral gully incised into Quaternary, unconsolidated slope deposits on the rim of a caldera in the Lakes Region, Main Ethiopian Rift Valley. S = step; P = pool. Notice the high sediment supply from bank collapse.

In their British Columbia step-pool study stream, Zimmerman and Church (2001) observed that large particles did not move during a bankfull flood whereas, according to their calculations based on the overall channel slope, particles in the 0.25-0.5 m range (i.e. between loose cobbles and the smaller keystones, their figure 5) were predicted to be entrained.

To account for such a discrepancy between predicted and observed size of particles entrained, these authors suggest to consider a higher values (> 0.06) of Shields dimensionless parameter (Shields, 1936), given the structurally constrained state of the bed, and to use the pool gradient to predict the movement of smaller particles (around 0.1 m in mean diameter). Zimmerman and Church (2001) conclude that Shields' equation, based on channel gradient, gives unrealistically large estimates for the size of boulders that could be transported during a high flow, whereas competence estimates based on flow resistance equations yield somewhat smaller sizes, which are consistent with the low flow observed. However, using a Shields' number of 0.045 (a typical value for coarse-grained streams - Komar, 1987), Zimmerman and Church (2001, their table 4) calculate that at least the smaller of what they consider 'stable boulders' (the size of which ranges between 0.45 and 0.6 m) can be entrained by a bankfull flood. This result is confirmed by the Aneva field data as a little higher than bakfull flood was capable to appreciably affect the study reach step-pools but, differently from what reported by Zimmerman and Church (2001), the Shields' criterion was found to over predict the threshold for medium to large particle entrainment (Table 3) (not an unexpected result, however, since Shields' criterion was developed in a laboratory flume experiment with uniform granular material).

The observations and results of the Aneva field investigation seem to confirm the high mobility of large bed particles also with low flows and support the keystone hypothesis of Zimmerman and Church (2001) shared also by Weichert *et al*. (2008) and confirmed by the flume experiments of Zimmerman *et al*. (2010).

CONCLUSIONS

Step-pools are a very common morphological feature of mountain streams and are found almost everywhere in the world whenever a steep gradient, a very coarse-grained streambed with large keystones and some lateral confinement are present.

From the comparison of the field data measured in the Aneva River (northern Apennines, Italy) with a reference database including a large set of field and laboratory data derived from the literature, the following conclusion can be drawn:

1) The Aneva River data confirm that in mountain streams with step-pool morphology, channel width is an important parameter in controlling step spacing. The average value of the *L/W* ratio is 0.9 in the Aneva and 1.3 for the reference database. This indicates that in mountain streams with boulder steps the central tendency of pool plan geometry is a square with about one channel width side.

2) The analysis of our data sets indicates that the inverse relation between channel gradient (*S*) and step wavelength (*L*) is more an exception rather than a consolidated finding since no significant relation between *L* and *S* was found.

3) 60% of the (*H/L*)/*S* ratio (step steepness) values of our data set are within the 1-2 range, thus confirming the hypothesis of Abrahams *et al*. (1995) that the development of steps maximises flow resistance.

4) Though our data set matches Allen's (1982) criterion of minimum estimate of antidune wavelength, a criterion, however, that this author developed to explain the formation of transverse ribs, the association of step-pools with antidunes is not straightforward. In fact, field measurements in a step-pool, boulder bed stream of the Ethiopian highlands indicate that step-pool sequences do not match Allen's (1982) minimum wavelength criterion whenever flow depths consistent with the formation of antidunes are considered.

5) The keystone hypothesis of Zimmerman and Church (2001) and Weichert *et al*. (2008) is confirmed by the field measurements in the Aneva R. Our field data demonstrated that the larger bed particles have a high mobility and steps can be completely removed or new ones formed with flood flows close to or just a little larger than bankfull (5-10 years). These results suggest to reject the hypothesis forwarded by few authors that step-pools can be formed only by floods with a long return time of 50-200 years.

6) The prerequisite of little sediment supply, postulated by a few authors for the formation of step pools, is rejected since well-developed step-pool sequences were observed in the Aneva and other small streams in the highland of Ethiopia and Eritrea and in the Ethiopian Rift Valley characterised by a very high sediment supply.

ACKNOWLEDGEMENTS

The research was financially supported by the University of Ferrara and by the Reno River Authority, Emilia-Romagna Regional Government.

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Paolo BILLI
Emanuele PRECISO, Enzo SALEMI

TERENSKA ISTRAŽIVANJA MORFOLOGIJE STEP-POOL AKUMULACIJA I PROCESA U STRMIM PLANINSKIM POTOCIMA

SAŽETAK

Osnovni cilj ovog rada je uporedjivanje podataka mjerenja na nekoliko pozicija toka rijeke Aneva na Sjeveru Apenina sa referentnom bazom podataka, uključujući tu i veliki broj rezultata terenskih i laboratorijskih istraživanja brojnih literatururnih izvora o stepenica-akumulacija tokovima (*step-pool streams*), a sve u cilju boljeg opisivanja njihove geomorfologije i generalnog razumijevanja ovih procesa. Terenska istraživanja, korišćenjem bojenih čestica, vršena su na rijeci Aneva, istražujući granične uslove veličine čestica, kao štu su one koje formiraju stepenice, formirajući nove uklanjanjem starih stepenica. Teorije o faktorima koji kontrolišu razvoj ovog grubog rečnog nanosa uporedjivane su i diskutovane u odnosu na dostupne podatke. Podaci uzeti iz referentnih baza i oni dobijeni tokom istraživanja na rijeci Aneva potvrđuju osnovnu hipotezu koja objašnjava stepenica-akumulacija sekvence (*step-pool sequence*).

Ključne riječi: vodne stepenice, antidine, planinski potoci, rijeke šljunčanog korita