Flood-induced changes in the step-pool morphology of a steep mountain stream

P. MOLNAR[1], A. L. DENSMORE[2], B. W. McARDELL[3] & P. BURLANDO[1]

1 *Institute of Environmental Engineering, ETH Zurich, CH-Zurich Switzerland*
molnar@ifu.baug.ethz.ch

2 *Department of Geography, Durham University, Durham, UK*

3 *Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland*

Abstract The step-pool morphology of steep mountain streams is reorganized during large floods by scouring of the river bed and deposition of step-forming grains. We compare the statistical properties of step-pool sequences before and after a large flood in the Erlenbach stream, in Switzerland, to document this effect. We show that the flood has led to substantial overall erosion of the river bed. Steps were completely reorganized, although their total number did not change. More small and large steps were formed, with a wider statistical distribution of step spacing. The location of the largest steps before and after the flood remained constrained to the middle reaches of the stream where hillslope landslides are most active. We also applied scaling techniques to the increments of the longitudinal profile to detect statistical differences between the pre- and post-flood sequences. We found a multiscaling signature in the step sequences both before and after the flood, which is an indication of complex structure in the bed morphology. Overall, our results show that a large flood may reorganize the bed, build complex step risers and fill pools. Subsequent lower floods will structure and extend the pools, remove small steps and regularize the step-pool sequence.

Key words channel morphology; step-pool streams; mountain rivers; scaling processes

INTRODUCTION

Steep mountain streams with coarse bed material often develop a distinct step-pool morphology which is continuous over long reaches (Montgomery & Buffington, 1997). Step formation is generally connected with the right combination of flood magnitude, local channel width, and particle size and availability of coarse material for transport. As a result, step placement is highly variable in space along the stream and changes in time in response to flow variability. The most common mechanism for step formation in mountain streams is the deposition (jamming) of large keystone clasts that form the step riser behind which sediment accumulates to create a step, and below which plunging (nappe) flow erodes a pool (Church & Zimmermann, 2007).

The resulting step-pool morphology often appears rather organized, which has led researchers to look for regularity in the geometric structure; for example, consistent relationships between step height, spacing or step length, channel slope, etc. in field data (e.g. Chin, 1999; Zimmermann & Church, 2001; Milzow *et al.*, 2006). The physical mechanisms that lead to step formation and destruction were also investigated in flume experiments (e.g. Curran, 2007). However, comparisons of flume and river data are difficult because the scaling of flow properties, sediment size and channel geometry is not trivial. Authoritative recent reviews on the subject can be found in Chin & Wohl (2005) and Church & Zimmermann (2007).

An important aspect in step-pool systems is their evolution in time. There are very few field-based data sets that document changes in the step-pool structure in response to floods. One of the few sites where such changes have been studied is the Rio Cordon (Italy), where substantial step reorganization during and following floods was observed (Lenzi, 2001). These studies provide some evidence that large floods are responsible for macroscale changes in the step-pool sequence, while more frequent lower magnitude floods are responsible for reworking the channel, scouring pools and altering minor steps (Lenzi *et al.*, 2006).

In this paper, we add evidence of changes in the Erlenbach stream in Switzerland following the largest recorded flood in 2007. We look at changes in the statistical distributions of step heights, step spacing, and relative step steepness from pre- and post-flood surveys of the longitudinal profile. We also look for the connection between the location of large steps and hillslope landslides. Finally, we provide a new look at the pre- and post-flood step-pool profiles with a scaling approach which quantifies variability at different resolutions. We estimate and compare scaling parameters which capture the nonlinear nature and spatial organization in the longitudinal profile. Scaling methods have been successfully used to describe structure in various geophysical data (e.g. Davis *et al.*, 1994) and are also appropriate for step-pool profiles.

STUDY SITE AND DATA

The Erlenbach is a tributary of the Alp River in the northern foothills of the Alps in central Switzerland. It is a steep gravel bed stream with typical step-pool morphology and active landslides on hillslopes adjacent to the channel (Schuerch *et al.*, 2006). The study reach exits into a sediment retention basin that captures most of the sediment (Fig. 1) and is instrumented with piezoelectric bedload impact sensors to measure bedload transport rates (Rickenmann & McArdell, 2007). The study reach is about 630 m long (along the thalweg) with a vertical drop of about 95 m (i.e. average gradient about 15%).

Although the contributing catchment area is small (0.74 km^2), floods can be extreme because of shallow loamy soils with low infiltration capacity. The flood on 20–21 June 2007 was the largest one recorded, with an estimated peak discharge of 14.5 m^3/s. The bulk sediment volume trapped in the retention basin was ~1650 m^3 and does not contain fine sediment; the fines were flushed downstream. The deposits in the basin contained grains of step-forming size (d_s > 50 cm) and substantial amounts of woody debris (Fig. 1). For comparison, the second largest flood in 1984 had a peak ~12 m^3/s, while the long-term mean annual flood is only 3.1 m^3/s (1980–2004).

Fig. 1 Debris mound deposited in the retention basin after the flood on 20–21 June 2007 (photo by Patrick Schleppi, WSL Birmensdorf, used with permission).

The longitudinal profile of the study reach, starting at the retention basin, was surveyed after a long period of low/medium flow conditions in summer 2004 (Schuerch *et al.*, 2006) and then resurveyed after the flood in August 2007 (J. Turowski, unpublished data). The surveys were used to automatically extract steps using the method of Milzow *et al.* (2006), where a measurement segment slope larger than a critical value b_c is used to define a step. The critical slope b_c = 0.5 was estimated from the segment slope distributions. Every step was assigned a height H and length (step spacing) L which is the distance to the next downstream step. A representative bed slope S was computed for every step from the profile measurements, with a moving window of 30 m centred at the step. Basic reach and step information is given in Table 1.

Table 1 Basic statistics and estimated scaling parameters of the studied step-pool sequences (see text for the explanation of the parameters and their estimation).

	Erlenbach 2004	Erlenbach 2007	Change from 2004 to 2007
Basic reach statistics			
Length of reach (along thalweg), L_t (m)	627.9	651.9	+24
Total elevation drop, Z_t (m)	95.3	94.6	–0.7
Overall gradient, Z_t/L_t (m/m)	0.152	0.145	–0.07
Bed grain diameter, d_{90} (cm)	~ 40*	~ 40–90	
Basic step-pool statistics			
Number of steps (with b_c = 0.5)	84	82	–2
Total step height, H_t (m) (% of Z_t)	57.4 (60%)	55.8 (59%)	–1.6
Mean (st. deviation) step height, H (m)	0.68 (0.33)	0.68 (0.42)	0 (+0.09)
Mean (st. deviation) step length, L (m)	7.5 (5.0)	7.9 (7.5)	+0.4 (+2.5)
Scaling parameters			
Intermittency β for steps (pools)	0.06 (0.48)	0.06 (0.48)	no change
Scaling parameter σ^2 for steps (pools)	0.21 (0.26)	0.22 (0.05)	change in pools

*Rickenmann (2001)

RESULTS

Changes in step-pool geometry

The 2007 flood led to a slight increase in total channel length (by about 24 m) due to lateral erosion and channel shifting (Table 1). Steps generate about 60% of the vertical drop in the stream; the rest is covered by sloping treads. Interestingly, the total number of steps and their mean height remained practically the same pre- and post-flood (Table 1). However, the statistical distribution of H in Fig. 2(a) shows that step variability has changed substantially, in particular there are many more both smaller and higher steps in the post-flood sequence. Changes in the statistical distribution of L are less pronounced (Fig. 2(b)), with again a slight prevalence of both short and long step lengths after the flood. The result is that the step steepness $c_s = H/L$ distribution does not change considerably (Fig. 2(c)) with the exception of some low c_s values after the flood.

In Fig. 2(d) we plot the relative step steepness, which is defined as $c = c_s/S$ (Lenzi, 2001), as a function of step spacing. Figure 2(d) illustrates that well-developed pools with reverse slope (c > 1) are not the norm in the steep Erlenbach stream. There are many steps which have a downstream sloping pool and tread. In summary, the 2007 flood resulted in the formation of more small and large steps, with a wider statistical distribution of step spacing.

Erosion and step location

We determined the overall vertical erosion dz between the 2004 and 2007 profiles by normalizing the total stream length and resampling the measured heights z onto a regular grid. The result in Fig. 3(a) shows that erosion of up to 2–3 m locally, was possible. The total change was about 770 m^3 per metre of eroded channel width, which could easily supply the sediment volume in the retention basin. Little vertical change was observed at the bottom of the reach and about midway along the reach. Similar observations were made by Schuerch *et al.* (2006).

The cumulative step height along the stream thalweg in Fig. 3(a) shows that steps are distributed rather evenly throughout the profile. Figure 3(b) shows the 10 largest steps in 2004 and 2007. Although it is difficult to assess exactly which steps remained in place after the flood, it is evident that many of the largest steps have been mobilized by the flood.

We also looked at the location of steps in connection to mapped landslides on channel banks, which directly influence sediment supply and channel morphology locally (Schuerch *et al.*, 2006). Notably, the largest steps in Fig. 3(b) are found in the central part of the study reach, where landslide activity is also most pronounced. We cannot at this stage confirm whether landslides

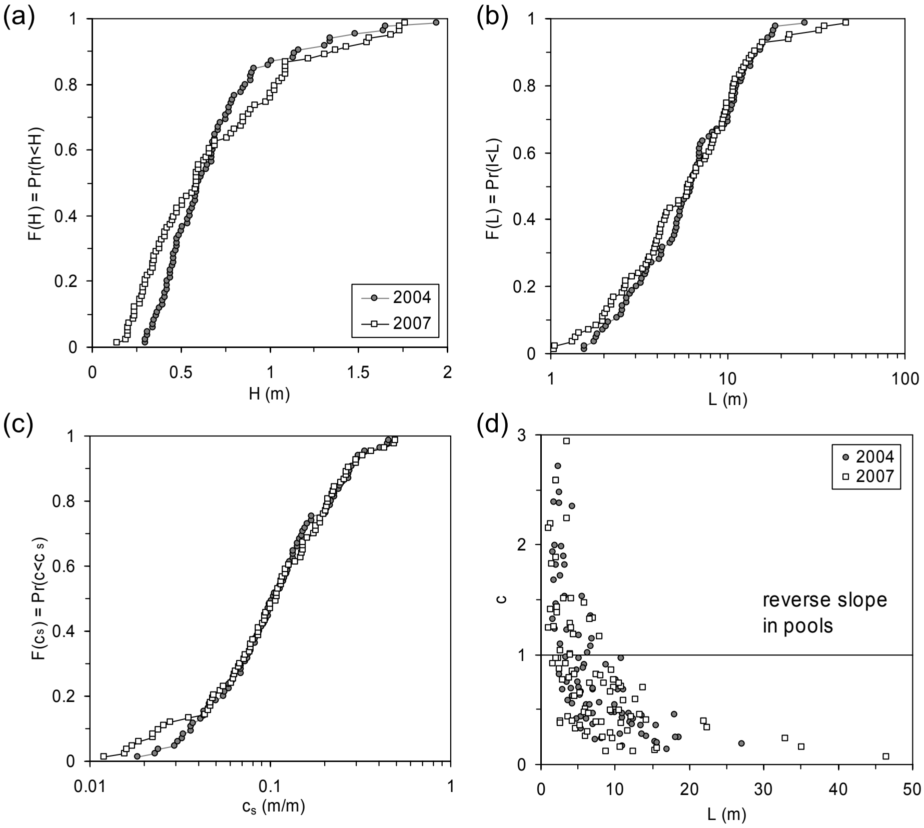

Fig. 2 The empirical cumulative distribution functions for: (a) step height H, (b) step spacing L, (c) step steepness c_s, and (d) the relative step steepness c as a function of L for the studied profiles.

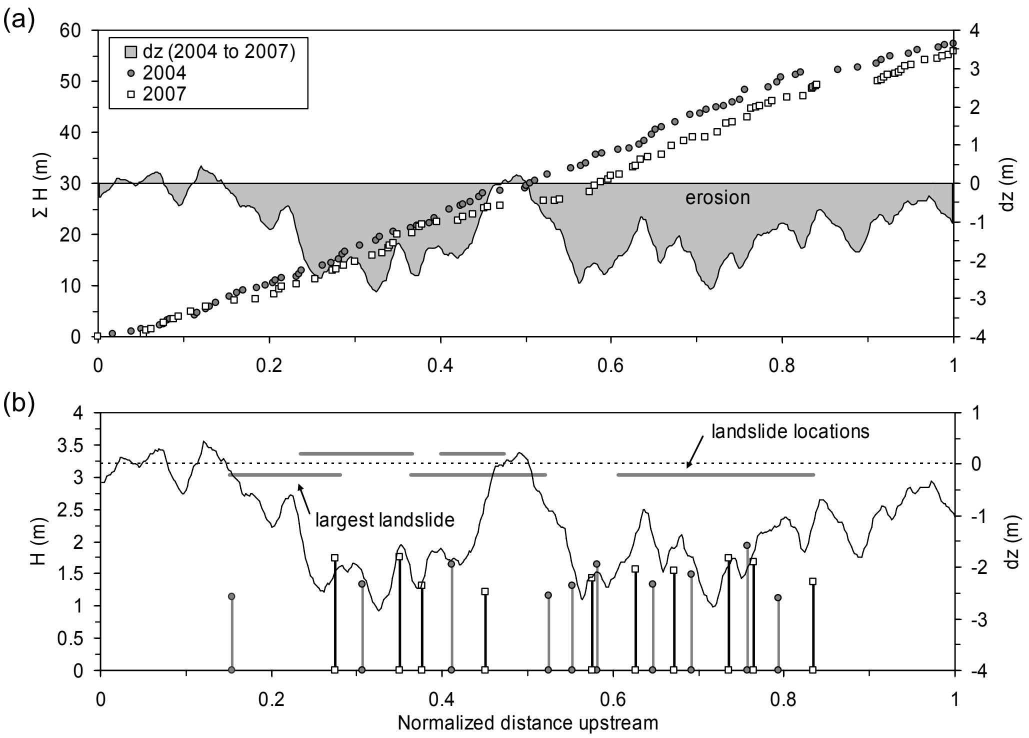

Fig. 3 (a) The cumulative step height along the Erlenbach stream with estimated depth of erosion, dz, between 2004–2007; (b) location of the 10 largest steps in 2004 and 2007 and main mapped landslide locations on both banks of the stream (dashed line) from Schuerch *et al.* (2006).

contributed to step formation; however, it is very likely that landsliding activity will increase following the widespread erosion and rearrangement of steps which buttressed the hillslopes.

Scaling analysis of the longitudinal profile

Attempts to search for structure in step-pool morphologies, for instance by spectral analysis (e.g. Chin, 2002), are problematic because correlation in space is weak and the usual record lengths are short. A more promising way to look for structure in the data is to examine the scaling properties of the longitudinal profile.

In our case the variable of interest is the height increment of the measured long profile, which we compute as $e_s = |z(i + 1) – z(i)|$. We do this separately for steps if $z(i + 1) > z(i)$, and for pools if the increment has a negative gradient or lies in a pool behind a step riser. An example of e_s for steps is shown in Fig. 4.

For a scaling variable, its statistical moments change with scale (resolution) λ as:

$$M_e(\lambda, q) \sim \lambda^{-\tau(q)} \qquad (1)$$

where M_e is the qth order statistical moment defined here as $M_e(\lambda,q) = \sum e_s^{\,q}$. The spectrum of exponents $\tau(q)$ indicates the nature of the scaling: simple scaling if $\tau(q)$ is a linear function of q, or multiscaling (multifractal) if it is nonlinear. A random field is simple scaling, while a complex structure with variabilities at different scales will tend to multiscaling (e.g. Davis *et al.*, 1994).

In order to estimate $\tau(q)$, we resampled the longitudinal profiles onto a regular grid, computed the moments M_e at doubling scales from λ = 1 to 32 m, and finally estimated $\tau(q)$ from the log–log plot of M_e *versus* λ (see Fig. 4(a)). The $\tau(q)$ exponents are shown in Fig. 4(b) and (c) for steps and pools. For some scaling models, such as the log-normal intermittent multiplicative random cascade, we know the analytical relation for $\tau(q)$ which we can use to estimate scaling parameters:

$$\tau(q) = (\beta - 1)(q - 1) + \sigma^2 \ln 2(q^2 - q)/2 \qquad (2)$$

The parameter β quantifies intermittency (β = 0 for continuous data and β > 0 for intermittent data). This parameter is important for identifying the extent of pools. The second scaling parameter, σ^2, determines the multifractality of the field (if $\sigma^2 = 0$ the field is simple scaling).

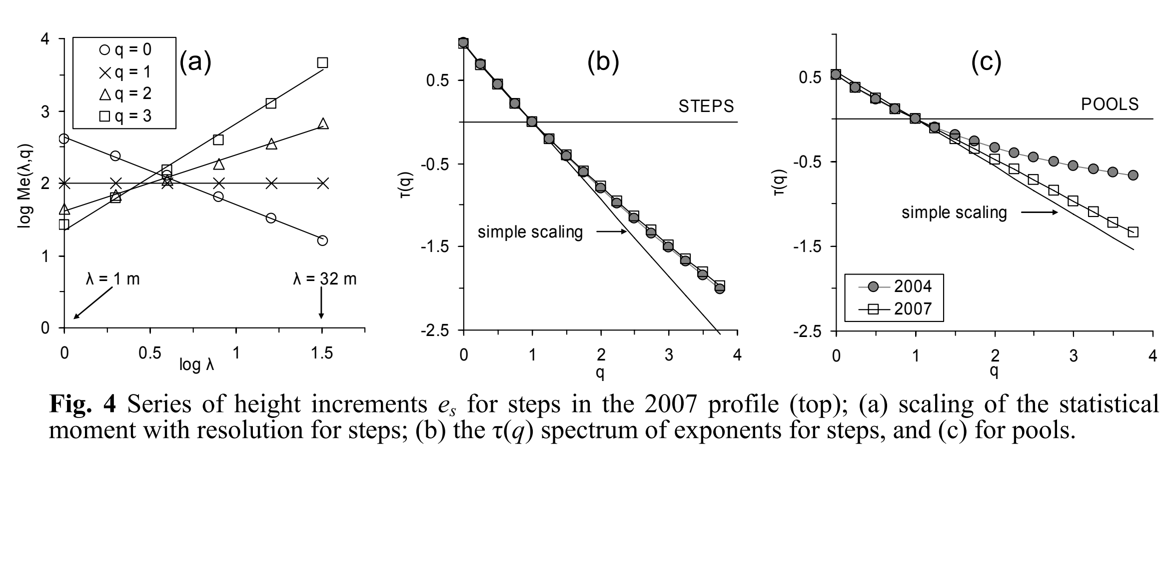

Fig. 4 Series of height increments e_s for steps in the 2007 profile (top); (a) scaling of the statistical moment with resolution for steps; (b) the $\tau(q)$ spectrum of exponents for steps, and (c) for pools.

The estimated scaling parameters are listed in Table 1. We can see that the step increments indicate a complex structure ($\sigma^2 > 0$), with slightly higher multifractality in the post-flood profile. We think this is due to the complex construction of the newly formed step risers. On the other hand, pools are most structured in the pre-flood profile, where they have been scoured and shaped over a longer period, while in the post-flood situation the pool profile is close to random ($\sigma^2 \sim 0$).

The results are intuitively correct and appealing. However, to assess the true discriminatory power and statistical significance of the difference in the scaling exponents before and after the flood in the Erlenbach, additional streams will have to be analysed. This will allow us to compare the changes in the Erlenbach with the scaling properties and parameters of other streams where step-pool sequences were formed under different flow conditions and geological settings.

CONCLUSIONS

The step-pool morphology of steep mountain streams is reorganized during large floods by scouring of the river bed and deposition of step-forming grains. In this paper we compared the statistical properties of step-pool sequences before and after a large flood in the Erlenbach stream in Switzerland to illustrate the effects on step placement. We found that the flood has led to substantial overall erosion of the river bed. Steps were completely reorganized, although their total number did not change. More small and large steps were formed, with a wider statistical distribution of step spacing. The location of the largest steps before and after the flood remained constrained to the middle reaches of the stream where hillslope landslides are most active.

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