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DYNAMICS OF WATER AND SEDIMENTS IN MOUNTAIN BASINS

ESTRATTO

M. A. Lenzi and V. D’Agostino

Step pool in the Rio Cordon: geomorphic effectiveness of the floods occurred between 1986 and 1999
STEP POOLS OF THE RIO CORDON:
GEOMORPHIC EFFECTIVENESS OF THE FLOODS
OCURRED BETWEEN 1986 AND 1999

*M. A. Lenzi, *V. D'Agostino

Summary

The idea of formative events, punctuated by periods of evolution, recovery or even temporary periods of steady state conditions, was used in order to point out the step pool morphology evolution of the Rio Cordon streambed in the 1986-1999 period. The Rio Cordon is a small catchment (5 km²) of the Dolomites where several geomorphic and hydraulic parameters are measured. The analysis of the characteristics of both the floods and the coarse bedload recorded at the Rio Cordon experimental station, along with detailed field surveys of the step pool structures carried out before and after the September ’94 and October ’98 floods has served to illustrate the control on step pool changes by these floods. Floods were grouped into two distinct categories. The first includes “ordinary” events which are characterized by peak discharges with a return time of 1-5 years (1.8 – 5.15 m³s⁻¹) and by an hourly bedload rate not exceeding 20 m³ h⁻¹. The second refers to “exceptional” events with a return time of 30-50 years. A flood of this latter type occurred on September 14, 1994, with a 10.4 m³s⁻¹ (peak discharge) and average hourly bedload rate of 324 m³ h⁻¹. Step pool features were characterised by the steepness parameter c = (H/Ls)/S. Its evolution was measured in the field from 1992 to 1998. The steepness factor evolution proves that maximum resistance conditions are gradually reached at the end of a cycle of ordinary flood events. During this cycle, bed armouring is dominant on the sediment transport response. However, following an extraordinary flood and unlimited sediment supply conditions, the steepness factor can suddenly decrease as a result of sediment trapped in the pools and a lengthening of step spacing. The analogy of step spacing with antidune wavelength and the main destruction and transformation mechanism of the steps are also discussed: scouring processes and downstream migration are the dominant features.

Keywords: step pool morphology, steep stream, flood and sediment transport, process- form linkage, instrumented catchment, monitoring, field measurements, Alps.

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Idronomia montana  20
1. Introduction

The dominant morphology of a mountain stream is the final result of many geological, climatic, hydrological and hydraulic factors, occurring over a long period of time (even millions of years). In a certain period the channel configuration consequently reflects the tendency, the mode of combination and the weight of different physical processes. This is not necessarily a symptom of static conditions since, during exceptional flood events (return period, $T_r$, greater than 50 years), a stream can modify its course and channel geometry. Nevertheless, following ordinary flood events ($T_r$ ranging from 1 to 10 years), the stream morphology tends to assume its original dominant characteristics (D’Agostino and Lenzi 1996; Lenzi et al., 1997).

Each river bed has a peculiar dynamic that takes shape by adapting to its flow limits, to the sediment-supply regime and to the bed grain size distribution. This natural disposition to change is often neglected and the observation of evolutionary tendencies misunderstood, particularly in mountain streams (Lenzi, 1999a; Lenzi and D’Agostino, 2000).

The most common and striking morphological typologies occurring in mountain streams can be synthetically categorised as step pools (Whittaker, 1987; Chin, 1989; Grant et al., 1990; Billi et al., 1994; D’Agostino, 1996; D’Agostino and Lenzi, 1997; Lenzi, 1998; Lenzi 1999$b$) and riffle pools. The latter are rarely found when the channel gradient exceeds 2-3% (Rosgen, 1994; Montgomery and Buffington, 1997). Step pools (Fig. 1) are found within a gradient range between 3-4% and 25-30%.

![Diagram of a step pool sequence](image-url)
They can be subdivided as follows:

- Boulder steps – composed of a straight or curved line of boulders lying across the channel.
- Riffle steps – composed of imbricated rocks forming a short, possibly steep, natural slope. They may also incorporate some boulder steps along their longitudinal development.
- Rock steps – characterizing parts of the channel with bedrock outcrops. Their occurrence is influenced by geological rather than hydraulic conditions.
- Log steps – produced by vegetative debris and tree trunk obstruction. They are incorporated into the bed along with sediment, becoming an integrating part of the bed morphology.

Rock steps and log steps may be distinguished from boulder and riffle steps for a certain irregularity in their spacing (wavelength, \( Ls \); Fig. 1). Their development is likely to be isolated whilst boulder and riffle step pools tend to occur in regular, well-organised sequences.

Various theories explaining the origin, formative dynamics and evolution of step pool structures have been proposed:

- The Antidune Model (Ashida et al., 1984; Grant, 1994; Rosport, 1994; Rosport and Dittrich, 1995) – the step pool develops as an antidune in phase with a standing wave on the water surface. According to the model originally proposed by Kennedy (1963), antidunes only form from a plane bed where the Froude numbers for the flow are higher than 0.84 and less than 1.
- The Maximum Flow Resistance Model (Davis and Sutherland, 1980; Whittaker and Jaeggi, 1982; Abrahams et al., 1995) – the mean flow velocity for a step pool reach is the mini-mum attainable for assigned values of mean slope, grain size distribution and bed roughness. This condition was tested in the laboratory (Abrahams et al., 1995) for a uniform wavelength between steps, satisfying the inequality: \( S \leq H/Ls \leq 2 S \), where \( H \) is the mean step height, \( Ls \) the relative wavelength and \( S \) the mean gradient of the step pool sequence. \( H/Ls \) is defined as “steepness” (Fig. 1) and the ratio \( c=(H/Ls)/S \) is the non-dimensional steepness parameter (for \( c \geq 1 \) the bottom profile of the pools has a reverse slope). Taking into account both field and flume results, Abrahams et al. (1995) proposed \( H/Ls \approx 1.5 S \) as a more likely relation. The expression proposed has initially the mean value of the steepness \( (H/Ls) \), in place of the ratio between the average values of \( H \) and \( Ls \) per se-quence. The slight change in the equation does not actually have any notable effects in proportion to the intrinsic regularity of the sequences.
- Combination of the antidune formation mechanism with a bed armouring process – according to experiments carried out by Whittaker and Jaeggi (1982), the initial formation of antidunes, where gradients are lower than 7.5% and the influence of the grain roughness is negligible, is accompanied by the occurrence of a first step pool profile. For higher gradients (>7.5%), the effect of heterogeneous grain size distribution, and moderate flows increases the bed armouring and the definition of the step pool morphology. Both situations lead to a step pool morphology, even if the latter is closer to a natural system.
The schemes of physical modelling related to the geometric step pool pattern are mainly carried out in steady state hydraulic conditions. This hypothesis is quite simplified in comparison with the complexity of natural processes, these being mainly conditioned by the succession of exceptional and ordinary flood events. The first can disrupt the pre-existent morphological arrangement, while the second do not substantially modify the dominant bed configuration. The ordinary events produce progressive adjustments that overlap the previous configuration induced by the exceptional flood event.

Whittaker (1987), Chin (1989, 1999), Grant et al., (1990) and Wohl and Grodek (1994) all reported an inverse power law relationship between step wave length and channel slope, thus a non-linear fit was tested. In the Erlenbach stream the wave length of step pools is poorly correlated ($r^2 = 0.4$) with channel slope (Rickenmann and Dupasquier, 1995). The relationship reported by the aforementioned authors is built from clusters of data collected from several different regions which exhibit limited overlap in slopes. It is important to note, however, that these studies examine preserved step pool architecture.

Much research on step pool morphological characteristics fails to mention a temporal factor and, in particular, the elapsed time since the last extraordinary flood in the stream.

Laboratory research (Whittaker and Jaeggi 1982, Whittaker 1987) has proved that step pool sequences behave as stable structures on the occasion of floods with return times not greater than 30-40 years. For higher flow rates these sequences can collapse, reform in different reaches or partially transform. Up to now such changes are not documented in scientific literature owing to the difficulty of a prompt measurement of hydraulic and geomorphologic parameters during the flood event.

Our understanding of upland channels is far from complete. Nonetheless, these research efforts have been identified several apparent requirements for step pool development:

1. Step channel gradients, greater than 3-5% (Grant et al., 1990; Montgomery and Buffington, 1995; Billi et al., 1994; D'Agostino and Lenzi, 1997).
2. A heterogeneous bed with the largest material immobile except under step-forming conditions (Grant and Mizuyama, 1991; Billi et al., 1994; D'Agostino and Lenzi, 1997; Lenzi, 1999a).
3. High-magnitude, low frequency flow events with recurrence intervals ranging 20 to 50 years or greater (Whittaker and Jaeggi, 1982; Grant and Mizuyama, 1991; Lenzi et al., 1997; D'Agostino and Lenzi, 1997; Lenzi, 1999a; Lenzi and D'Agostino, 2000).
4. Near critical to supercritical flows (Grant and Mizuyama, 1991; Lenzi et al., 1997; D'Agostino and Lenzi, 1997; Lenzi, 1999a; Lenzi and D'Agostino, 2000).
5. Low sediment transport rate and a low sediment supply environment (Grant and Mizuyama, 1991; Grant et al., 1990).

The main aim of the study was to monitor the temporal evolution of step
pool morphology and, at the same time, the influence of steepness on the total bedload volume yielded by comparable flood hydrographs. The analogy of step spacing with antidune wavelength and the model suggests that step pools evolve toward a condition of maximum flow resistance are also discussed.

2. Study site and methods

2.1 Study basin and measuring station

The research was conducted in the Rio Cordon watershed, a small basin in the Dolomites (Eastern Italian Alps). The solid geology consists of dolomites, which make up the highest relieves in the watershed, volcaniclastic conglomerates and tuff sandstones (the Wegen Group). In the lower part of the watershed the Buchenstein Group consists of calcareous, calcareous-marly and arenaceous rock outcrops. Quaternary moraine and scree deposits are also very common. In general soils are thin and belong to three main families: a) skeletal soils, occurring on steep slopes with discontinuous vegetation cover; b) organic soils, with more continuous and dense vegetation cover than the previous group; c) brown earth soils. Vegetation cover consists mainly of herbaceous associations, including both continuous-cover mountain grass-land (43% of watershed surface) and sparse grassland (18%). Shrubs are quite widespread (18%), while forest stands consisting of spruce and larch are found only in the lower part of the watershed and occupy 7% of the total area. 14% of the catchment consists of bare land. Active sources of sediment mainly consist of bare slopes, overgrazed areas, shallow landslides, eroding streams banks and debris flow channels (Billi et al., 1998).

The climatic conditions are typical of an Alpine environment. Precipitation occurs mainly as snowfall from November to April. Runoff is usually dominated by snowmelt in May and June but summer and early autumn floods represent an important contribution to the flow regime. Usually late autumn, winter and early spring lack noticeable runoff events.

The facilities for monitoring water discharge, suspended sediment and bedload transport at the Rio Cordon experimental station have been described in detail in previous papers (Fattorelli et al. 1988; Lenzi et al., 1990; D’Agostino and Lenzi, 1996; Lenzi et al., 1999). Measurements are taken by separating coarse bedload (minimum size > 20 mm) from water and fine sediment. The measuring station consists of an inlet flume, an inclined grid, where the separation of the coarse particles takes place, a storage area for coarse sediment deposition and an outlet flume to return water and fine sediment to the stream. The volume of coarse bedload is measured at short intervals (less than 600 s) by 24 ultrasonic sensors fitted on a fixed frame over the storage area (Lenzi et al. 1999). In 1993-94 a settling basin for fine material (silt, sand and fine gravel) was built at the end of the outlet channel. Water level gauges are installed in the inlet and outlet channels and in the settling basin. Suspended sediment is measured by two turbidimeters: a Partech SDM-10 light absorption turbidime-
ter installed in the outlet flume, working since the early years of station operation, and a light-scatter turbidimeter, installed in 1994 and connected to the inlet flume (Lenzi and Marchi, 2000).

Previous studies in the Rio Cordon mainly concerned the measurement and assessment of bedload (Lenzi et al., 1990; D’Agostino et al., 1994; Lenzi and D’Agostino, 1998; Rickenmann et al., 1998; D’Agostino and Lenzi, 1999; Lenzi et al., 1999), the morphological structure and sedimentology of the stream bed (D’Agostino and Lenzi, 1997; Lenzi et al., 1997; Lenzi et al., 1999; Lenzi, 1999; Lenzi and D’Agostino, 2000), and an analysis of sediment sources (Dalla Fontana and Marchi, 1998).

2.2 Floods, bedload records, channel morphology and step pool topographical survey

Twelve floods have been recorded so far (Table 1-2), ten of which are characterised by bedload transport. Bedload data reported in this paper, and already partly discussed in previous contributions (Lenzi et al., 1990, D’Agostino et al., 1994; Billi et al., 1998; Lenzi et al., 1999; D’Agostino and Lenzi, 1999), refer to the fraction coarser than 20 mm that is retained by the inclined grid and stored in the downstream trap.

All the floods recorded before September 1994 have a return time ranging from 1 to 5 years and are comparable in terms of peak discharge (1.8-5.3 m$^3$ s$^{-1}$) and mean hourly bedload transport rate not exceeding 6 m$^3$ h$^{-1}$. They are therefore defined here as “ordinary”. By contrast, the flood of 14th September 1994 (Fig. 2) can be considered “exceptional” since it has a return time falling between 30 and 50 years, a peak discharge of 10.4 m$^3$ s$^{-1}$ and a coarse bedload yield of 890 m$^3$. The mean transport rate was about 324 m$^3$ h$^{-1}$: a value larger by two orders of magnitude than that of ordinary events. Of the other three flood events recorded after the 1994 big flood, the “ordinary” flood of October 7, 1998 (Fig. 3; photo 1) is particularly interesting as its total coarse bedload (278 m$^3$, photo 2) and the mean bedload rate (16 m$^3$ h$^{-1}$) were the highest of the “ordinary” events recorded from 1986 to 1999.

The streambed of the Rio Cordon consists of three different types of channel reach: they were identified as step pool, mixed and riffle pool reaches (Billi et al., 1994, 1998). Short bed rock reaches are also presented but they are restricted to the catchment head waters and to the cascade in the gorge (Fig. 3). Step pool geometry of the Rio Cordon can be described by several morphometric features. Step risers are transversal accumulations of boulders organized into discrete channel-spanning features. Located between successive step are pools (Fig. 1). The mixed reaches are step pool sequences irregularly punctuated by small heaps of coarse material, while riffle pool reaches are characterized by lateral and central bars and are bounded by a small alluvial plain. Mixed reaches are similar to step pool reaches but with “heaps” of coarse particle deposited upstream of the boulder step, or in isolated big boulder, and over imposed on and taking up the largest part of the upstream pool. This channel type seems to
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*water runoff volume above the threshold discharge for bedload initiation in the flood hydrograph

**Table 1** – Main hydrological and hydraulic data of the floods recorded: October 11, 1987 – May 19, 1994

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*water runoff volume above the threshold discharge for bedload initiation in the flood hydrograph.

**Table 2** – Main hydrological and hydraulic data of the floods recorded: July 18, 1994 – October 7, 1998
Fig. 2a - The flood of September 14, 1994 on the Rio Cordon: water discharge, bedload transport and S.S.C. during the event

Fig. 2b - Rainfall, flood hydrograph, coarse bedload and S.S.C. during the event of 1998, October 7th
Fig. 3 - Plan view of the Rio Cordon stream and the of the surveyed step-pool sequences
Photo 1 - Rio Cordon: the October ’98 flood (Reproduced by permission of ARPAV- Avalanche Center, Arabba)

Photo 2 - Total coarse bedload accumulated during the October ’98 flood (Reproduced by permission of ARPAV- Avalanche Center, Arabba)
reflect both the description and the diagnostic features of the “cascade channel” proposed by Montgomery and Buffington (1997). Almost all the main stem is incised into Quaternary deposits.

Detailed field surveys of the stream bed structures were carried out before and after the September ’94 flood to point out the effectiveness of such a large flood in causing streambed changes (Tab. 3, Figs. 3 and 4).

Other topographic surveys were conducted after the October ’98 flood (Tab. 4). Step pool structures (geometric parameters $L_s$, $L_p$, $H$ in Fig. 1) and channel gradient, $S$, were measured along the reach using a Total Station Positioning System. Longitudinal profiles were surveyed over a length of stream comprising at least three step pool units. Channel bed elevation was measured along

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<td>0.05</td>
</tr>
<tr>
<td>SP8</td>
<td>0.72</td>
<td>1.00</td>
<td>7.21</td>
<td>0.87</td>
<td>0.68</td>
<td>6.00</td>
<td>6.43</td>
<td>0.16</td>
</tr>
</tbody>
</table>

N1,N2,N4,N6 = New step pool reaches developed over part of the mixed reaches M2,M3,M5,M7, upstream of step pool sequences SP1,SP2,SP4,SP6, during the September '94 flood

Table 3 - Main characteristics of step pool sequences before and after the September 1994 flood (see Fig.1)
Fig. 4. Longitudinal profiles of the stream reach (distance in meters vs. altitude in meters a.s.l.).
the channel centreline at each step crest and at four or more locations in each pool. The elevation of the step crest was neither the highest nor lowest point on the step, but rather a visually approximated median elevation. Step pools channel width was measured directly over step crests. Channel gradient was calculated by regression. The superimposition and the comparison between post-flood longitudinal profiles (Fig. 4) and the previous ones allowed the identification of the main morphological changes in the river bed.

Before the September '94 flood particle size was characterized at seven selected sites (Lenzi, 1992). After this flood, in step pool reaches, pebble counts were conducted in a manner similar to that of Wolman (1954). Ten particles were selected at random from each riser and each pool within a sequence of step pools, the b-axis measured, and the value recorded. Totals of 60, 80, and 100 grains were counted for step pool reaches which consisted of six or more step pool units.

<table>
<thead>
<tr>
<th>Code</th>
<th>Mean step width</th>
<th>Mean step drop</th>
<th>Mean step pool height</th>
<th>Mean pool spacing</th>
<th>Mean step spacing</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W (m)</td>
<td>Z (m)</td>
<td>H (m)</td>
<td>Lp (m)</td>
<td>Ls (m)</td>
<td>S (-)</td>
</tr>
<tr>
<td>N1</td>
<td>7.99</td>
<td>1.16</td>
<td>1.23</td>
<td>4.93</td>
<td>5.40</td>
<td>0.22</td>
</tr>
<tr>
<td>SP1</td>
<td>5.62</td>
<td>0.71</td>
<td>0.88</td>
<td>4.19</td>
<td>4.31</td>
<td>0.16</td>
</tr>
<tr>
<td>N2</td>
<td>7.30</td>
<td>0.54</td>
<td>0.81</td>
<td>3.82</td>
<td>3.90</td>
<td>0.14</td>
</tr>
<tr>
<td>SP2</td>
<td>5.00</td>
<td>0.46</td>
<td>0.72</td>
<td>3.59</td>
<td>3.59</td>
<td>0.13</td>
</tr>
<tr>
<td>SP3</td>
<td>7.99</td>
<td>0.50</td>
<td>0.66</td>
<td>4.60</td>
<td>4.53</td>
<td>0.11</td>
</tr>
<tr>
<td>N4</td>
<td>4.69</td>
<td>0.84</td>
<td>0.88</td>
<td>5.48</td>
<td>6.68</td>
<td>0.13</td>
</tr>
<tr>
<td>SP4</td>
<td>7.05</td>
<td>0.80</td>
<td>0.82</td>
<td>5.96</td>
<td>6.67</td>
<td>0.12</td>
</tr>
<tr>
<td>M6</td>
<td>7.30</td>
<td>0.33</td>
<td>0.63</td>
<td>3.36</td>
<td>3.39</td>
<td>0.10</td>
</tr>
<tr>
<td>SP5</td>
<td>5.62</td>
<td>0.47</td>
<td>0.64</td>
<td>4.25</td>
<td>4.22</td>
<td>0.11</td>
</tr>
<tr>
<td>M7</td>
<td>5.01</td>
<td>0.28</td>
<td>0.42</td>
<td>2.23</td>
<td>2.32</td>
<td>0.12</td>
</tr>
<tr>
<td>N6</td>
<td>5.19</td>
<td>0.53</td>
<td>0.79</td>
<td>3.75</td>
<td>3.80</td>
<td>0.14</td>
</tr>
<tr>
<td>SP7</td>
<td>8.10</td>
<td>0.92</td>
<td>1.15</td>
<td>5.94</td>
<td>5.82</td>
<td>0.16</td>
</tr>
<tr>
<td>SP8</td>
<td>7.20</td>
<td>0.38</td>
<td>0.70</td>
<td>2.83</td>
<td>2.84</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 4 – Geometric characteristics of the step pool sequences after the October 1998 flood (see Fig.1).

In Sept. 1998 fourteen crest stage gauges has been installed in natural cross sections; this instrumentation consented the acquisition of the maximum flow depth in different discharge conditions (from 0.1 to 4.7 m³ s⁻¹). The reaches investigated have been selected in consideration of their morphological characteristics and in particular their stability conditions (Scussel et al., 1999). The flow conditions were very variable due to the hydraulic jumps and direction changes of the flow; the crest stage gauges have been installed in the main discontinuity point of the flow: the head of the step; the deeper point of the pool;
and the gushed back final point. Afterwards, a topographic survey of the fourteen cross sections and flow velocity and discharge measurements on selected four transversal sections located between reaches SP3 and M7 (Figs. 3 and 4) have been made. Total streambed reach is 250 m. long and the terminal part of it is located 150 m. upstream the instrumented station of the Rio Cordon.

Velocity were measured both with Siap, model 611046, electronics meters with digital readout and accuracy 2% for high parameters values, and with MicroSeba, model 501, for lower one. Depth was measured with a stadia road calibrated and read to the nearest 0.5 cm.; velocities were measured at almost four-five verticals, at 1, 2 or 3 points in each vertical in function of the depth of flow.

<table>
<thead>
<tr>
<th>Year of survey</th>
<th>Mean step spacing $L_s$ (m)</th>
<th>Mean pool spacing $L_p$ (m)</th>
<th>Step height $H$ (m)</th>
<th>Flood event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992-93</td>
<td>5.37</td>
<td>5.18</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>1995-96</td>
<td>6.95</td>
<td>7.08</td>
<td>0.98</td>
<td>1994</td>
</tr>
<tr>
<td>Variation</td>
<td>+ 1.58</td>
<td>+ 1.90</td>
<td>+ 0.02</td>
<td></td>
</tr>
<tr>
<td>1998-99</td>
<td>4.42</td>
<td>4.22</td>
<td>0.79</td>
<td>1998</td>
</tr>
<tr>
<td>Variation</td>
<td>- 2.53</td>
<td>- 2.86</td>
<td>- 0.19</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 – Mean geometric characteristics of the step pool sequences before and after 1994 and 1998 floods

Preliminary values of water discharge associated at each of the four transversal sections were compared with the values obtained at the instrumented station; first one were generally greater than the second but the major differences were always inferior to the 5%. After these tests was possible to obtain mean flow velocity values on the reaches SP6-N6 and M7-SP5, corresponding to the following different water discharge stage: 0.25, 0.50, 0.90, 1.00, 1.60, and 2.00 m$^3$ s$^{-1}$ (Tab. 6).

Other surface velocities measurements, corresponding to a water discharge values of 4.00 m$^3$ s$^{-1}$ at the measuring station, have been made by using floats in the reaches N6 (Photo 3) and SP3 (Photo 4, 5 and 6). Based on the water level depth measured, on the average depth and surface velocity and assuming that the average cross-section velocity was 80% of the surface velocity (Mathes, 1956), average Froude number were also calculated for this water discharge value.

Maximum water level registered by the crest stage gauges located on the cross-sections 2 and 12 (reaches N6 and SP3) allowed to estimate mean flow depth, average velocity and Froude number related with the peak discharge (4.7 m$^3$ s$^{-1}$) of the October '98 flood (Tab. 6)
Table 6 – Hydraulic conditions corresponding to different water discharge values of the October '98 flow at the crest stage gauges N° 2 (reach N6) and N° 12 (reach SP3)

Other value of average cross-section velocity and Froude number were estimated for the peak water discharge (10.4 m³ s⁻¹) of the September '94 flood, using both a synthetic cross-section schematized following the procedure of the U.S. National Weather Service (Lenzi et al., 1999) and a flow resistance equation proposed by Bathurst (1987). These equations were checked assumed uniform flow conditions.

3. Step pool morphology evolution of the Rio Cordon stream after the September '94 and October '98 floods

Before the September '94 flood, eight step-pool reaches were identified. The main characteristics of these reaches, numbered as SP1-8, are reported in Table 3, together with those relative to the streambed survey carried out after the September '94 flood. A comparison of the geometric features reveals that many changes have occurred. Almost all step pool reaches with some depositional features and three step pool reaches (SP3, SP5 and SP6) were turned into riffle-pool and bar reaches, while four new reaches formed. These are numbered as N1-2-4 and 6 since they are located upstream of SP1-2-4 and 6, respectively, corresponding to the mixed reaches previously identified as M1, M3, M5 and M7.

The total length of the step pool sequence reaches that survived (SP1, 2, 4, 7 and 8) were shortened by 42% on average. A general increase (25-30%) in the
Photo 3 – Four crest stage gauges in the reach N6 (Reproduced by permission of ARPAV-Avalanche Center, Arabba)

Photo 4 – Three crest stage gauges in the reach SP3 during the October ’98 flood (Reproduced by permission of ARPAV-Avalanche Center, Arabba)
Photo 5 - The downstream part of the reach SP3 (Reproduced by permission of ARPAV- Avalanche Center, Arabba)

Photo 6 - The reach SP3 after the flood (Reproduced by permission of ARPAV- Avalanche Center, Arabba)
average single spacing between consecutive steps (step wavelength) results when taking into account all the sequences including the newly formed ones. This reflects the main adjustment of the streambed which, after the flood, assumed a riffle pool and bar configuration due to main channel filling by the large volume of sediment supplied. Peak discharge of 10.4 m$^3$s$^{-1}$, though very high for the Rio Cordon, lasted only a few minutes, probably too short a time to let the flow remove the material supplied (D’Agostino and Lenzi, 1996, Lenzi et al., 1997).

Channel geometry and profile also changed remarkably (Fig. 4). Post flood channel widening was observed in the downstream reaches as a response to higher than usual flow discharge that may have caused bank erosion.

After the October ’98 flood (peak water discharge equal to 4.7 m$^3$s$^{-1}$), a new streambed survey was made. A comparison of these results with those obtained after the September ’94 flood reveals that further changes have occurred (Tab. 4 and Fig. 4).

The large amount of sediment deposited on the streambed in 1994 caused the burial of cross structures and filled the pools with sediments. On the other hand, the October 7th 1998 event mainly induced a more pronounced polishing process along the pools. Therefore the noteworthy accumulations of sediments in the coarse bedload trap recorded by the measuring station during the last two events (’96 and ’98; Tab. 2) could be seen as a result of the considerable availability of material in the riverbed.

The step and pool wavelength ($L_s$, $L_p$) of the reaches that survived the September ’94 flood increased (Table 5) and the step steepness ($c$ parameter) decreased. The October 7, 1998 event had a different effect from the 1994 flood, mainly causing a better definition of the step pool profile (Fig. 4), a general shortening (~2.53 m) of the average step spacing (Table 5), and a reduction in step height (~0.19 m).

The main morphological changes induced by the October ’98 flood can be summarized as follows: a) peak discharge (4.7 m$^3$s$^{-1}$) was inferior to the competent discharge for moving the large boulders constituting the steps; consequently no downstream migration or destruction of step pools occurred; b) pools became deeper and induced the formation of a negative bed slope between step; c) there was a modelling of poorly formed cross-step structures (sequences SP3 and SP5; Tab. 4).

4. Discussion

Abrahams et al. (1995) hypothesise that step pools in mountain streams may be the result of a natural tendency of water channels to maximise resistance to flow. They found that flow resistance is maximised when the extreme values of the quotient of the mean values of the relation between the height of the step pools ($H$) and their wavelength ($L$) are between one and two times the mean channel slope ($S$), with a more likely average value of 1.5.

Assuming that the mean value of $H/S$ is equal to the relation between the mean values $H$ and $S$, data from the Rio Cordon step pools taken prior to the
September 1994 flood (Fig.5) confirm Abrahams' claims. However, the values of mean geometric parameters of the step pools taken after the flood, including those relative to the four new sequences, do not correspond to the maximum resistance model, since the values $H/L$ are often less than $S$ (Fig. 5). The data in Table 3 show the change from $H/L=1.30$ $S$ before the flood to $H/L=0.79$ $S$ afterwards (Fig. 5). There had not been such a large flood in the Rio Cordon for 15 years before that of September 1994 (with a maximum discharge of 10.4 m$^3$s$^{-1}$) – only floods not exceeding 5 m$^3$s$^{-1}$ with a return period of less than five years. The well-organized and stable step pool sequences measured on the Rio Cordon in 1992 and 1993 seems to reflect a period of substantially steady-state morphological conditions.

The steepness parameter $c$ changed suddenly from a value of 1.30 ($R^2=0.33$) before the September 14, 1994 event to 0.79 ($R^2=0.16$) after this "extreme" flood (Fig. 5). This transformation was associated with a more disorganized pattern of the step pool morphology.

![Graph showing Channel gradient S versus the mean steepness H/Ls (Rio Cordon)](image)

Due to the "ordinary" floods (with a return period from 1 to 5 years) which occurred on 13/08/1995, 15/10/1996 and, in particular, on 07/10/1998, the morphological features of the step pool sequences tended to re-establish the geometrical characteristics existing before 1994. Fine and medium-sized sediments, eroded from the hillslope source areas, supplied to the stream network and stored in the pools during the decreasing limb of the hydrograph of the September 14, 1994 flash flood, were removed and transported by the long "ordinary" flood of 07/10/1998. Step pool sequences are still not well organised; but due to the fact that bed erosion processes and pool scouring prevailed over deposition the relationship $c=(H/Ls)/S$ assumed a value of 1.33 ($R^2=0.036$) after the 07/10/1998 flood underlying the evolution of step pool structures.
The processes are supported both by a low sediment supply to the stream network from the sediment source areas and by the surface sediment cleaning in the bed caused by the “ordinary” floods.

The evolution over time of the $c$ parameter affects the trend of the measured bedload rate for different flood events. Before 1994 the $c$ parameter close to 1.5 represented a developed “macro-armouring” of the bed. The bedload rate was therefore almost two orders of magnitude less than the transport capacity computable from bedload formulas (D’Agostino and Lenzi, 1996). The decrease of $c$ during the September ’94 flood was accompanied by the break up of macro-armouring, the “equal mobility” of the transported sediment grain size (Lenzi and D’Agostino, 1998) and bedload rates close to those expressed by the Schoklitsch (1962) formula (D’Agostino and Lenzi, 1999). Successive ordinary events took the bedload rate back towards the values recorded before 1994. Nevertheless, these values (Table 2) are slightly increased by an excessive supply of sediment already present on the bed (Lenzi, 1999).

The described time evolution of step pool sequence geometry in the period 1986-1999 is outlined in Figure 6 along with the values for the total coarse bedload volume transported, peak flood discharge and duration of the coarse bedload transport for each flood.

The studies confirm what Whittaker and Jaeggi (1982) and Whittaker (1987) suggest in their laboratory tests. They highlight a certain stability in step pool structures where floods have a return period of 30-40 years, either a tendency for the sequences to be destroyed and then reformed in other reaches of the channel by even stronger flows or to transform themselves slightly.

The variation in wavelength in the same stream without substantial change in hydraulic gradient makes one cautious about expressions that determine

![Graph showing hydrological and sedimentological data for the floods recorded in the Rio Cordon: time evolution of the $c$ parameter of the step pool sequences in the period 1986-1999](image)
wavelength in correlation only to gradient or to gradient and step height. Indeed they express more the schematisation of a particular “historic” moment in the stream rather than the absolute evolutionary tendency of the step pool structure. It is more likely that the expected wavelengths of the step pool sequences lie within a range of values in which they may vary in proportion to the entity of the various flows that formed them.

The analysis of the changes in the Rio Cordon step pools generally seem to correspond to the results of laboratory tests carried out by Rosport (1994) and Rosport and Dittrich (1995). It has been possible to verify that the dominating transformation mechanism is erosion at the foot of the step with a resulting undermining from downstream (Fig. 7-a). The erosive action progresses upstream leading to the collapse of the structure (Fig. 7-b) whereupon the rocks fill the pool below. The pool silts up and a rock alignment reforms further down (Fig.7-c). The step pool formation, therefore, is redefined by the effect of erosion and the formation of new pools (as in 7-a, but further downstream).

A second means of transformation identified in the Rio Cordon steps after the September '94 flood, though a less frequent occurrence than undermining, is the partial breaking up of a step through the sinking of the rocks joining the step to the banks. This case can easily be seen in the field. There is a clear trace of the niche left by the rock on the banks, while the “wings” of the step have shifted downstream from the central part of the step itself. When both “wings” have been eroded, a step pool often has a typical planimetric V shape pointing upstream. In the Rio Cordon, the downstream migration after the September '94 flood is particularly clear and uniform in the SP2 sequence (Fig. 4). However, in the SP6, SP7 and SP8 reaches, the downstream movements concern only some steps of each sequence. This produces transformations that are less well articulated and uniform and, as a whole, more chaotic.
On the other hand, reaches SP, SP and SP showed, after the September '94 flood, above all, partial or total deformation of the step pools, with the formation of some riffle reaches combined with irregular accumulations or the establishment of lateral bars. According to the results of laboratory study (Ashida et al., 1984, 1986; Whittaker, 1987), the above morphological transformations should be supported by a loss in gradient. Such a situation is found in the data taken after the September 1994 flood, since the gradients of reaches SP, SP and SP were lower than or equal to previous ones. A general leveling of the whole reach, occurring after the widening of the section and the filling of existing pools with very fine sediment transported by the flow, may also be noted. Sequences SP and SP (Fig.4) are a case in point. Here the higher gradient of the step pools along with the high overall channel roughness is replaced by a morphological configuration with a flatter profile and reduced channel roughness (even though there may be isolated steps or riffles and lateral bars). This transition from a step pool profile (Fig.7-a) to a plane bed profile (Fig.7-d), is clearly more attributable to the downstream transportation of solid materials than the erosion process in pools (Fig.7-b) and causes a sort of “burying” of the transversal structures. Another factor in this process is the widening of the channel which, by reducing the flow and the kinetic energy of the flow, favours depositing over erosive processes.

Newly formed step pool configurations have resulted, after the September '94 flood, in a higher mean sequence gradient, for all reaches, than in reaches of mixed origin. The formation of the four new step pool sequences (N, N, N, N, N) occurred upstream from the SP, SP, SP and SP sequences in parts of reaches previously classified as mixed (M, M, M, M). These reaches, as has already been mentioned, are characterised by irregular accumulations of material of which the larger particles form barely visible steps, not yet organised in continuous transverse alignments (Fig.8-a). Before the September 1994 flood, along with step pools, mixed reaches represented a relatively stable bed configuration (that is, they were not altered by ordinary floods). During the 1994 flood, parts of some mixed reaches became step pool reaches through a progressive “trapping” process. This is caused by the largest rocks trapping smaller pieces, and then even finer particles (Fig. 8-b). The biggest rocks in mixed reaches may be considered static or pseudo-static foundation elements, thanks to which a new step pool reach is formed (Fig. 8-b, c).

Some researchers (Ashida et al., 1984; Grant, Mitzumaya, 1991; Grant, 1994; Whittaker, 1987) affirm that step pool morphology originates in antidune formation in phase with the standing wave on the water surface. Others, including Wohl and Grodek (1994) as well as Abrahams et al. (1995), cast doubt on the theory that step pool formation is connected with antidunes. The latter plotted data from the laboratory experiments in Kennedy's (1963) diagram. Correlating the Froude number (Fr) of the flow with the wave number (k h = 2 π h / L), where h is the mean depth of flow and L the wavelength of the antidunes) enables the identification of the formation region of the antidunes. The data, plotted by the authors in this diagram, could not be collocated within, or in direct proximity to, the antidune region.
Field data from the Rio Cordon September 1994 flood enable the association of the mean wavelength of the step pools \( (L_b = L_s \equiv L_p = 7 \text{ m}, \text{ Tab. 5}) \) with the mean flow velocity \( (V=3.37 \text{ m s}^{-1}) \) at maximum discharge \( (Q_p=10.4 \text{ m}^3\text{s}^{-1}) \). These values, shown in Fig. 9 (Allen, 1982) which includes Kennedy’s as well as other researchers’ results, show that the formation of step pools falls within the antidune region \( (Fr=1.7, kh=0.36) \), even if they are close to an area characterised by a flatter profile (Fig. 9).

It is also interesting to observe how the expression used to calculate the antidune wavelength, defined by the equation \( L_b = 2\pi V^2/g \), gives a wavelength of 7.3 m if applied to velocity at the height of the flood \( (V=3.37 \text{ m s}^{-1}) \). Such a value correctly interprets the data given as representative of the average pool-pool distance of the newly formed sequences \( N_1, N_2, N_4, N_6 \) \( (L_p = 6.8 \text{ m}) \), of pre-existing ones rearranged after the flood \( (L_p=7.3 \text{ m}) \) or even of both typologies \( (L_p=7.08 \text{ m}, \text{ Tab. 5}) \).

In order to analyze where step pools plot relative to the stability field of antidunes, the hydraulic conditions associated with the formation of step pool (for the September ’94 flood) can be also estimated following Grant (1997). The existence field is defined by Froude number and wavenumber. The Froude number is:

\[
Fr = \frac{V}{(gh)^{0.5}} \tag{1}
\]

Where \( V \) is the average velocity, \( g \) is the gravitational acceleration and \( h \) is flow depth. From the definition of shear velocity

\[
V^* = (ghS)^{0.5},
\]
Fig. 9 - Geometry of step pools relative to the stability field for their existence: a) for the data of October '98 flood; b) for the data of D’Agostino and Lenzi (1997); c) for the data from the Rio Cordon (1994) with $kh = 2\pi D_{50} / L_b$.

Equation (1) is rewritten:

$$Fr = \frac{V}{V^* S^{0.5}}$$

(2)

Flume and field experiments by Bathurst (1985) have shown that in step, hydraulically rough channels, the flow resistance is given by the following relation:

$$V/V^* = (8/f)^{0.5} = 5.62 \log (h/D_{84}) + 4$$

(3)

Also critical dimensionless shear stress, $\tau^*_{cr}$, is given by the Shields relation (Shields, 1936):

$$\tau^*_{cr} = \frac{hS}{(\gamma_s - \gamma_w)D}$$

(4)

where $\gamma_s$ and $\gamma_w$ are the specific weights of the water and sediment respectively,
and \( \tan \theta = S \), channel slope. Assuming \( \gamma_s = 2.65 \), (4) can be rearranged as relative roughness equation:

\[
\frac{h}{D} = 1.65 \frac{\tau^*_{cr}}{S} \tag{5}
\]

By setting \( D = D_{84} \) and substituting (5) into (3) and (2), is possible to calculate Froude number at incipient motion for a given slope as:

\[
Fr = [5.62 \log (1.65 \frac{\tau^*_{cr}}{S}) + 4] S^{0.5} \tag{6}
\]

The grains making up the steps are thought to move only during formative events (Grant and Mizuyama, 1991), so a lower estimate of the Froude number associated with formative flows can be calculated for the incipient motion movement \( \tau^* = \tau^*_{cr} = 0.045 \).

As noted by Lenzi and D'Agostino (1998), boundary shear stress in boulderbed streams (like Rio Cordon) can reach 1.55 \( \tau^*_{cr} \): an upper estimated of the Froude number associated with formative flows \( (Q = 6.0 - 10.0 \text{ m}^3 \text{s}^{-1}) \).

The wavenumber \( kh \) associated with formative conditions is taken as \( kh = 2 \pi D_{50} / L_N \). Flow depth was estimated (for the September '94 flood) following Allen (1982) assuming that particle size on the steps is on the order of flow depth (Tab. 3). Wavelength of topography generated by antidune were assumed those observed in the field after the formative flood of 1994 (Table 3). Using Equation (6), the potential range of \( \tau^* \), the measured wavelength of the step pools after September '94 flood and the assumed depth, the step pools observed in the Rio Cordon (1994) are compared to the stability field for antidunes (Fig. 9). One interpretation of the field results coming from the Rio Cordon catchment is that step pool forms in association with antidunes with the wave train giving rise to not perfectly and regular spacing of step pool. In the Rio Cordon stream bed this not regular spacing may be ascribe at the short duration of water discharge at higher flow for the extraordinary "flash flood" of the September '94. The different flow conditions associated to the ordinary floods of 1995, 1996 and mainly to the October '98 long duration flood, cause subsequent erosion, altering the topography somewhat such derived features may not longer plot in the stability field of antidunes. The analysis of the field hydraulic conditions measured during the October '98 flood at the crest stage gauges 2 (reach N6, Table 4) and 12 (reach SP3, Table 6), corresponding to different discharge values, confirms this hypothesis. In Fig. 9, the final geometry of reaches N6 and SP3 is not consistent with the hypothesis that they formed in association with antidunes. Dimensionless wavenumber \( kh = 2 \pi h / L_N \) and Froude number related to water discharge conditions equals to 1.00, 2.00, 4.00 and 4.70 \text{ m s}^{-1} \), plotted in Fig. 9 fall at the border or outside the stability field for antidunes.

Despite these objective correspondences, an element of doubt still surrounds the step pool formation model supported by the antidune theory. Indeed, according to this model large sediment should be completely sub-
merged by the flow conditioning the formation of the structure. This occurred in the reaches studied in the Rio Cordon characterized by narrow transversal sections. Therefore, it is possible that the antidune model accounts for the new step pool reaches developed during the September ‘94 flood. The model may satisfy better the hypotheses of various researchers (Ashida et al., 1984; Grant, Mizumaya, 1991; Grant, 1994; Whittaker, 1987) for peak flood discharges close to that observed during the September ‘94 event, but having a duration time greater (almost 10-15 hours) than that measured for this “flash flood”.

5. Conclusions

In Alpine streams, adjustment commonly occurs during large hydrological events and both channel morphology stability and sediment transport can be regarded as components of a complex system in which several processes are active.

The idea of formative events, punctuated by periods of evolution, recovery or even temporary periods of steady-state conditions, has been used in order to point out the step pool morphology evolution of the Rio Cordon streambed in the 1986-1999 period. The analysis of the characteristics of the floods and coarse bedload recorded at the Rio Cordon experimental station, along with detailed field surveys of the step pool structure, illustrates the effect of these floods on step pools.

The stream bed changes during the September ‘94 flood pointed to a lesser extent towards the formation of step pool sequences since most of the channel acquired a more typical alluvial morphology with well developed riffle-pool and bar reaches. The reverse slope of the pools, (steepness parameter \( c = (H/L_s)/S > 1 \) - very common in stepped streams and in the Rio Cordon before the September ‘94 flood) gives way to the downstream dipping of the pool profile in about half of the post-flood sequences. A comparison of the longitudinal profiles (Fig. 4) shows a clear flattening and smoothing that can be accounted for by the large rate of sediment supply and deposition. The morphological changes in Rio Cordon during the September ‘94 flood, did not imply maximum flow resistance. Even the values of the mean geometric parameters of the only four newly formed step pool sequences after the September ‘94 flood do not correspond to the model proposed by Abrahams et al. (1995), since the relation \( H/L \) is usually less than \( S \).

The complex mechanism of formation and of partial or total transformation of the step pool structures outlined in this article suggests that the theory of maximum flow resistance can only be interpreted as the possible outcome of a process of progressive step adjustment.

The channel seems to have a tendency towards this, after the event leading to the formation of new step pool sequences and thanks to the following ordinary floods which “scour” it from sediments.

The steepness factor evolution proves that maximum resistance conditions are gradually reached at the end of a cycle of ordinary flood events. During this
cycle, bed armouring is dominant on the sediment transport response. However, following an extraordinary flood and unlimited sediment supply conditions, the steepness factor can suddenly decrease as a result of sediment trapped in the pools and a lengthening of the single step spacing.

Analyzing the Rio Cordon field data, two aspects of September '94 post-flood bed instability appear: step destruction normally starts downstream of the "structure", by scouring the large elements, less developed bed forms successively disappeared; the distance between single steps increased and the coarse material forming a minor structure was partly incorporated into the major one.

Hydraulic conditions, water discharges and bed load monitored on the Rio Cordon catchment have been helpful to underline that the measured geometry of the step pools can be consistent with the hypothesis that step pools are formed by antidunes

The morphometric and sedimentological studies carried out on the Rio Cordon before and after the September 1994 and the October 1998 floods undoubtedly provide a useful comparison between different evolutionary phases in step pool sequences. However, further research still needs to be carried out supporting these studies with the surveying of hydraulic parameters (distribution of flow velocity in various sections, flow-field turbulence) which occur in such a morphological unit. Only in this way, and in conjunction with laboratory tests prepared *ad hoc*, will it be possible to understand through an increasingly quantitative approach the origins of step pool structures and the conditions that influence their stability and evolution.

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**References**


