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STEP–POOL EVOLUTION IN THE RIO CORDON, NORTHEASTERN ITALY

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ABSTRACT

The principle that formative events, punctuated by periods of evolution, recovery or temporary periods of steady-state conditions, control the development of the step–pool morphology, has been applied to the evolution of the Rio Cordon stream bed. The Rio Cordon is a small catchment (5 km^2) within the Dolomites wherein hydraulic parameters of floods and the coarse bedload are recorded. Detailed field surveys of the step–pool structures carried out before and after the September 1994 and October 1998 floods have served to illustrate the control on step–pool changes by these floods. Floods were grouped into two categories. The first includes ‘ordinary’ events which are characterized by peak discharges with a return time of one to five years (1·8–5·15 $m^3\ s^{-1}$) and by an hourly bedload rate not exceeding 20 $m^3\ h^{-1}$. The second refers to ‘exceptional’ events with a return time of 30–50 years. A flood of this latter type occurred on 14 September 1994, with a peak discharge of 10·4 $m^3\ s^{-1}$ and average hourly bedload rate of 324 $m^3\ h^{-1}$. Step–pool features were characterized primarily by a steepness parameter $c = (H/L_s)/S$. The evolution of the steepness parameter was measured in the field from 1992 to 1998. The results indicate that maximum resistance conditions are gradually reached at the end of a series of ordinary flood events. During this period, bed armouring dominate 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.

KEY WORDS: step–pool morphology; mountain stream; floods; sediment transport; antidunes; Alps

INTRODUCTION

The morphology of a mountain stream is the result of many geological, climatic, hydrological and hydraulic factors, occurring over a long period of time (even millions of years). In a given period, the channel configuration consequently reflects the trend, the mode of combination and the relative influence of different physical processes. This does not necessarily result in static conditions because, 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 one to ten years), the stream morphology tends to consistently maintain largely invariant characteristics (Lenzi *et al*., 1997). Each river bed has site-specific dynamics, the morphology of which is adapted to the peculiar flow, to the sediment-supply regime and to the bed grain size distribution. This natural disposition to systematic change is often neglected and the observation of evolutionary tendencies misunderstood, particularly in mountain streams (Lenzi, 1999).

The most common and striking morphological typologies occurring in mountain streams can be categorized as step–pool sequences (Whittaker, 1987; Chin, 1989; Grant *et al*., 1990; Billi *et al.* 1998; Lenzi, 1999) and riffle–pool sequences. The latter are rarely found when the channel gradient exceeds 3–5 per cent (Rosgen, 1994; Montgomery and Buffington, 1997). Step–pool sequences (Figure 1) are found within a gradient range between 3–5 per cent and 25–30 per cent. Steps are typically formed from accumulations of boulders and cobbles, which span the channel in a more or less continuous line and separate a

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backwater pool upstream from a plunge pool downstream. The risers of individual steps are generally composed of several large boulders that act as a framework against which smaller boulders and cobbles are imbricated, creating a tightly interlocking structure with considerable stability (Knighton, 1998). Although steps composed of boulders are the most common type, they can also form in bedrock (Hayward, 1980; Wohl and Grodek, 1994, Duckson and Duckson, 1995) and through accumulations of large woody debris (Keller and Swanson, 1979). Step–pool sequences have been reported from a wide range of humid and arid environments (Chin, 1989), and analogous forms have even been observed in supraglacial streams (Knighton, 1981).

Various theories explaining the origin, formative dynamics and evolution of step–pool structures have been proposed. It is widely recognized that step–pool sequences form at high discharges, but the process whereby they form remains controversial. Ashida *et al.* (1984), Grant (1994) and Rosport (1994) argued on the basis of flume studies that step–pool originate as antidunes in phase with standing waves on the water surface. Ashida *et al.* displayed their step–pool data on Kennedy's (1963) diagram of F against kh, where F is the Froude number, k is the wave number $2\pi/L_b$, h is the mean flow depth, and L_b is the wave form wavelength. These data fell either within or close to the domain for antidunes. Similar results were obtained by Grant (1994) and Rosport (1994); thus these comparisons between the properties of flume step–pools and antidunes tend to support the antidune model.

The maximum flow resistance model, first advanced by Davis and Sutherland (1980), and re-proposed by Whittaker and Jaeggi (1982) and Abrahams *et al.* (1995), means that the mean flow velocity for a step–pool reach is the minimum 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 $S \leq H/L_s \leq 2S$, where H is the mean step height, L_s the relative wavelength and S the mean gradient of the step–pool sequence. H/L_s is defined as 'steepness' (Figure 1) and the ratio $c = (H/L_s)/S$ is the non-dimensional steepness parameter (for $c > 1$ the bottom profile of the pools has a

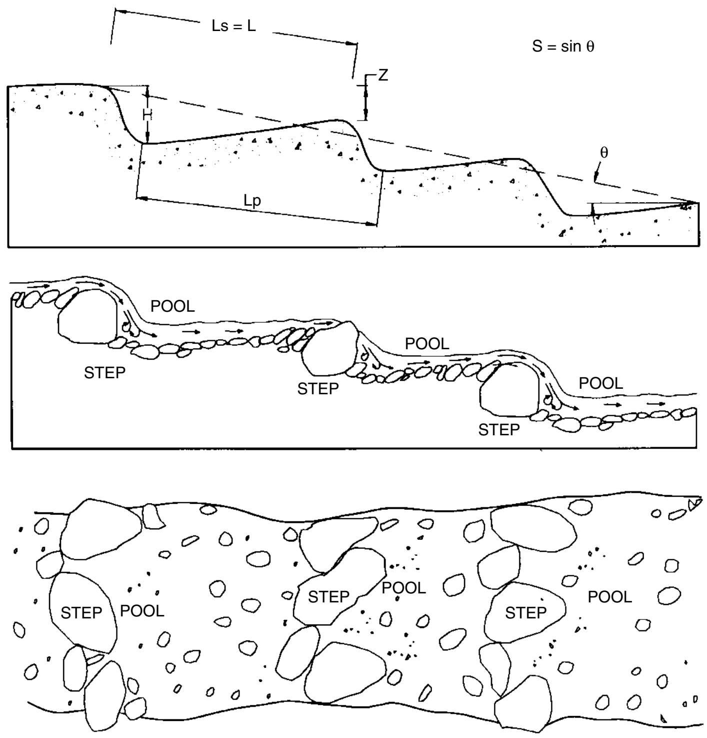

Figure 1. Sketch of a step–pool sequence

reverse slope). Taking into account both field and flume results, Abrahams *et al*. (1995) proposed $H/L_s \cong 1{\cdot}5S$ as an explanatory function. The expression proposed:

$$\overline{H/L_s} \cong 1{\cdot}5S \quad (1)$$

has initially the mean value of the steepness ($\overline{H/L_s}$), in place of the ratio between the average values of H and L_s per sequence:

$$\overline{H}/\overline{L_s} \cong 1{\cdot}5S \quad (2)$$

The differences in these equations do not have any notable effect in predicted steepness given the intrinsic regularity of the downstream sequences.

According to flume experiments carried out by Whittaker and Jaeggi (1982), the initial formation of antidunes, where gradients are lower than 7·5 per cent and the influence of the grain roughness is negligible, is accompanied by the first development of a step–pool profile. For higher gradients (>7·5 per cent), the effect of heterogeneous grain size distribution and moderate flows increases the degree of bed armouring and the definition of the step–pool morphology is enhanced. Both formative processes lead to a step–pool morphology, and the latter is close to a natural system.

Physical modelling related to the geometric development of step–pool patterns is mainly carried out in steady-state hydraulic conditions. This scenario is simplified in comparison with the complexity of natural processes, these being mainly conditioned by the succession of exceptional and ordinary flood events. The first may disrupt the pre-existent morphological arrangement, while the second do not substantially modify the dominant bed configuration. The ordinary events produce progressive adjustments that modify 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 wavelength and channel slope, thus a non-linear function seems appropriate. However in the Erlenbach stream (Switzerland) the wavelength of step–pools was reported to be poorly correlated with channel slope (Rickenmann and Dupasquier, 1995). However, the reported relationship was derived from clusters of data collected from several different geographical regions which exhibit limited overlap in the range of slope data. It is important to note, however, that all these studies examined well-preserved step–pool architecture. Thus, 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 shown that step–pool sequences behave as stable structures on the occasion of floods with return times not greater than 30–40 years. For higher discharges these sequences can collapse, reform in different reaches, or partially transform. Up to now such changes are not documented for natural river floods owing to the difficulty of prompt measurement of hydraulic and geomorphologic parameters during or inmediately after the flood event.

Research has identified several apparent requirements for step–pool development, considering that the steps are boulder steps in the classification by Hayward (1980):

1. step channel gradients, greater than 3–5 per cent (Grant *et al*., 1990; Montgomery and Buffington, 1997; Billi *et al*., 1998);
2. a heterogeneous bed with the largest material immobile except under step-forming conditions (Grant and Mizuyama, 1991; Billi *et al*., 1998; Lenzi, 1999);
3. high-magnitude, low-frequency flow events with recurrence intervals ranging from 20 to 50 years or greater (Whittaker and Jaeggi, 1982; Grant and Mizuyama, 1991);
4. near-critical to supercritical flows (Grant and Mizuyama, 1991);
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 suggestions that step–pools evolve towards a condition of maximum flow resistance are also discussed.

STUDY SITE AND METHODS

Study basin and measuring station

The research was conducted in the Rio Cordon watershed, a small basin in the Dolomite (eastern Italian Alps). The solid geology consists of dolomites, which make up the highest relief in the watershed, volcaniclastic conglomerates and tuff sandstones (the Wengen 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; (b) organic soils; (c) brown earth soils. Vegetation cover consists mainly of herbaceous associations with forest found only in the lower part of the watershed. Fourteen per cent of the catchment consists of bare land. Thus 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 rainfall-induced 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 previously (Fattorelli *et al*., 1988; D'Agostino and Lenzi, 1999; Lenzi *et al*., 1999). Bedload 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). 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 and a light-scatter turbidimeter (Lenzi and Marchi, 2000).

Previous studies in the Rio Cordon mainly concerned the measurement and assessment of bedload (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 (Lenzi *et al*., 1997, 1999; Lenzi, 1999), and an analysis of sediment sources (Dalla Fontana and Marchi, 1998).

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

Twelve floods have been recorded (Tables I and II), ten of which are characterized by bedload transport. All the floods recorded before September 1994 have a return time period of one to five 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 were defined by Lenzi *et al*. (1999) and by D'Agostino and Lenzi (1999) as 'ordinary'. By contrast, the flood of 14 September 1994 (Figure 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 (D'Agostino and Lenzi, 1999). Of the other three flood events recorded after the 1994 big flood, the 'ordinary' flood of 7 October 1998 (Figure 3) is particularly interesting as its total coarse bedload yield (278 m^3) and the mean bedload yield (16 $m^3 h^{-1}$) were the highest of the 'ordinary' events recorded from 1986 to 1999 (Lenzi, 2000).

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*., 1998). Short bedrock reaches are also present but they are restricted to the catchment headwaters and to the cascade in the gorge (Figure 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

Table I. Main hydrological and hydraulic data of the floods recorded 11 October 1987–19 May 1994

	11/10/87	3/7/89	17/6/91	5/10/92	2/10/92	19/5/94
Runoff volume* (10^3 m^3)	79·9	103·36	57·89	21·52	30·69	5·41
Peak discharge (m^3 s^{-1})	5·15	4·40	4·00	2·90	4·30	1·80
Return time (years)	4.0–5.0	3·0	2.0–3.0	1.0–2.0	3·0	1·0
Total bedload volume (m^3)	50·0	85·0	39·0	9·3	10·2	1·0
Duration of bedload transport (h)	8·00	27·00	20·00	10·00	6·00	12·00
Mean bedload rate (m^3 h^{-1})	6·25	3·15	1·95	0·93	1·70	0·08
Max. suspended sediment. Conc. (g l^{-1})	–	–	–	1·20	1·70	0·10

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

Table II. Main hydrological and hydraulic data of the floods recorded 18 July 1994–7 October 1998

	18/7/94	14/9/94 (1)	14/9/94 (2)	13/8/95	15/10/96	7/10/98
Runoff volume* (10^3 m^3)	0·0	4·71	21·93	1·81	21·99	91·75
Peak discharge (m^3 s^{-1})	1·80	3·74	10·40	2·72	2·96	4·73
Return time (years)	1·0	2·0	30–50	1.0–2.0	1.0–2.0	4·0
Total bedload volume (m^3)	0·0	10·0	890·0	6·2	57·0	278·1
Duration of bedload transport (h)	0·00	1·42	2·75	1·00	22·00	17·00
Mean bedload rate (m^3 h^{-1})	0·00	7·00	323·6	6·18	2·59	16·36
Max. suspended sediment. conc. (g l^{-1})	7·80	30·00	57·90	6·60	15·50	5·00

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

(Figure 1). The mixed reaches are step–pool sequences irregularly punctuated by small heaps of ill-formed gravel bars of coarse material, while riffle–pool reaches are characterized by well-defined lateral and central bars and are bounded by a small alluvial plain. Mixed reaches are similar to step–pool reaches but with coarse particle bars deposited upstream of the boulder steps, or adjacent isolated big boulders, and largely infilling the upstream end of pools (Billi *et al*., 1998). This latter channel type seems to reflect both the description and the diagnostic features of the 'cascade channel' proposed by Montgomery and Buffington (1997).

Detailed field surveys of the stream bed structures were carried out before and after the September 1994 flood to determine the effectiveness of such a large flood in causing stream bed changes (Table III, Figures 3 and 4). Other topographic surveys were conducted after the October 1998 flood (Table IV). Step–pool structures (geometric parameters L_s, L_p, H in Figure 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 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–pool channel width was measured directly over step crests. Channel gradient was calculated by regression. The superimposition and the comparison between post-flood longitudinal profiles (Figure 4) and the previous ones allowed the identification of the main morphological changes in the river bed.

Before the September 1994 flood particle size was characterized at seven selected sites (Billi *et al*., 1998). 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 step–pool sequence, 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.

In September 1998, 14 crest stage gauges were installed in natural cross-sections; this instrumentation permitted the acquisition of the maximum flow depth for different discharge conditions (from 0·1 to 4·73 m^3 s^{-1}).

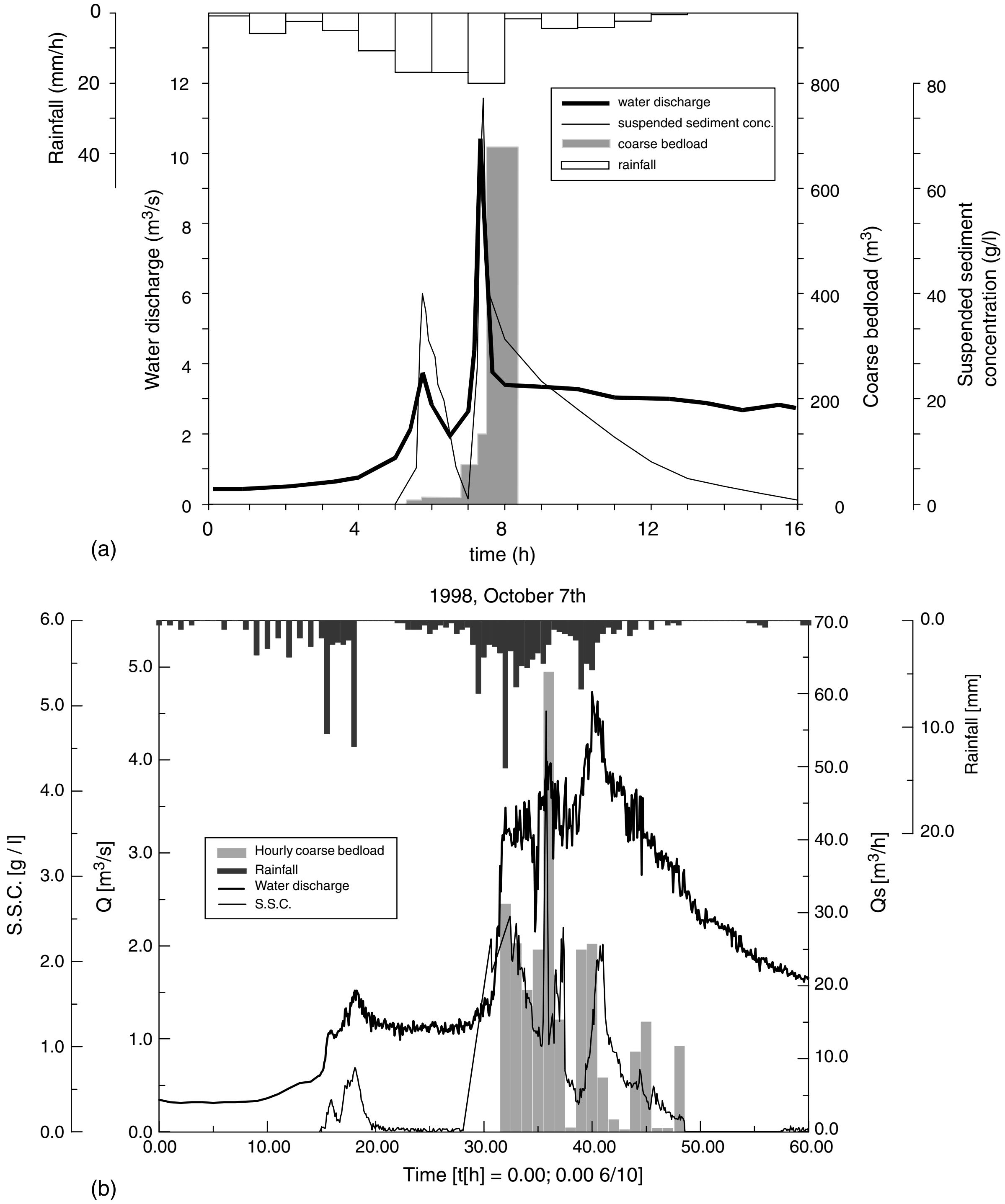

Figure 2. (a) The flood of 14 September 1994 on the Rio Cordon: water discharge, bedload transport and suspended sediment concentration during the event. (b) Rainfall, flood hydrograph, coarse bedload and suspended sediment concentration during the event of 7 October 1998

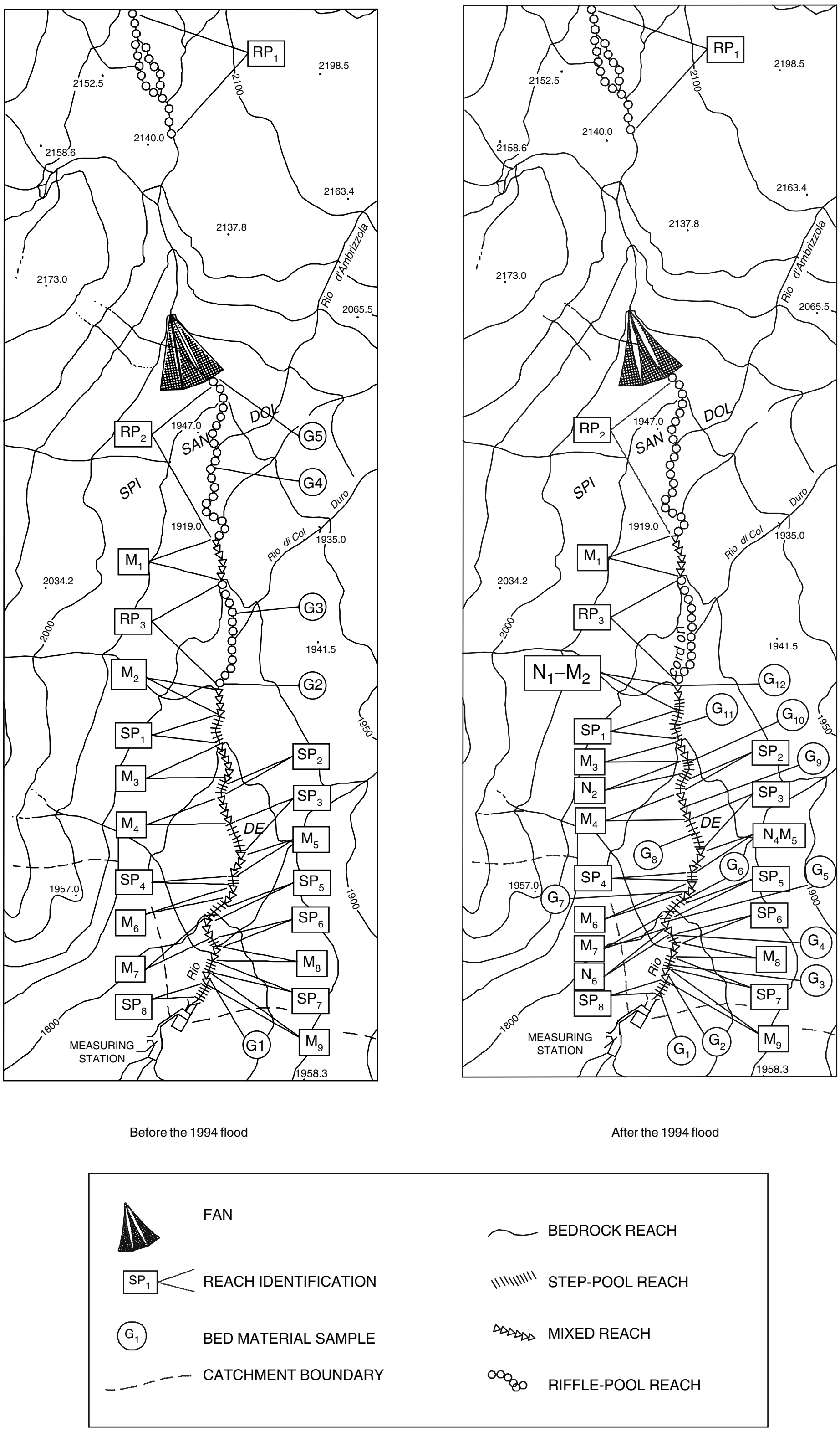

Figure 3. Plan view of the Rio Cordon stream and the reaches of the surveyed step–pool sequences

Table III. Main characteristics of step–pool sequences before and after the September 1994 flood (see Figure 1)

Code	Grain size of of riser, D_{50} (m)	Grain size of riser, D_{84} (m)	Mean step width, W (m)	Mean step–step drop, Z (m)	Mean step–pool height, H (m)	Mean pool spacing, L_p (m)	Mean step spacing, L_s (m)	Slope, S (−)
Before the flood of 14 September 1994								
SP1			6·60	1·06	1·28	5·51	5·66	0·22
SP2			4·76	0·78	1·05	4·50	4·46	0·17
SP3			6·19	0·77	1·00	6·62	6·53	0·12
SP4			6·23	0·91	1·16	4·93	6·42	0·14
SP5			4·96	0·51	0·85	4·21	4·22	0·12
SP6			4·87	0·47	0·83	4·12	3·95	0·12
SP7			6·12	0·61	0·66	6·54	6·48	0·09
SP8			5·92	0·61	0·85	5·05	5·23	0·12
After the flood of 14 September 1994								
N1(M2)	0·72	1·16	7·99	1·29	1·28	6·65	6·80	0·22
SP1	0·69	1·15	5·62	1·15	0·94	6·33	6·32	0·20
N2(M3)	0·62	0·95	7·30	0·78	1·03	8·88	8·11	0·18
SP2	0·65	0·99	5·01	1·05	0·94	5·54	5·60	0·20
N4(M5)	0·60	0·65	4·69	0·47	0·49	6·76	6·23	0·15
SP4	0·64	1·12	7·05	2·15	1·93	7·98	11·03	0·21
N6(M7)	0·66	1·10	5·19	0·51	0·75	4·82	4·50	0·16
SP7	0·80	1·01	8·19	0·35	0·81	10·79	7·56	0·05
SP8	0·72	1·00	7·21	0·87	0·68	6·00	6·43	0·16

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 1994 flood.

The flow conditions are very variable due to the hydraulic jumps and direction changes of the flow. Consequently the crest stage gauges have been installed at critical points to define the profile of maximum flood elevation: the head of the step, the deepest point of the pool, and the pool exit slope. Afterwards, a topographic survey of the 14 cross-sections and flow velocity and discharge measurements on four selected transversal sections located between reaches SP3 and M7 (Figures 3 and 4) was made. The total stream bed reach is 250 m long and the downstream end is located 150 m upstream from the instrumented station.

Velocities were measured with a Siap model 611046 electronic current meter with digital readout and accuracy >2 per cent for higher velocities, and with a MicroSeba model 501 meter for lower current velocities. Velocities were measured at four to five verticals, and at one, two or three points in each vertical. Depth was measured with a stadia rod calibrated and read to the nearest 0·5 cm.

Preliminary values of water discharge associated at each of the four transversal sections were compared with the values obtained at the instrumented station; the former were generally greater than the latter but the major differences were always less than 5 per cent. After these calibration exercises, it was possible to obtain section-mean flow velocities on the reaches SP6–N6 and M7–SP5, for a range of water discharges (Table V), using rating curves derived at the instrumented station. Other surface velocity measurements, corresponding to a water discharge value of 4·00 $m^3 s^{-1}$ at the measuring station, have been made by using floats in the reaches N6 and SP3. Based on measured depths, the average depth was calculated and the average cross-section velocity determined as equal to 80 per cent of the surface velocity (Mathes, 1956). The average Froude number, $F = V/(gh)^{0.5}$, was calculated for each discharge. Maximum water levels registered by the crest stage gauges located on cross-sections 2 and 12 (reaches N6 and SP3) allowed estimations to be made of mean flow depth, average velocity and Froude number for the peak discharge (4·73 $m^3 s^{-1}$) of the October 1998 flood (Table V).

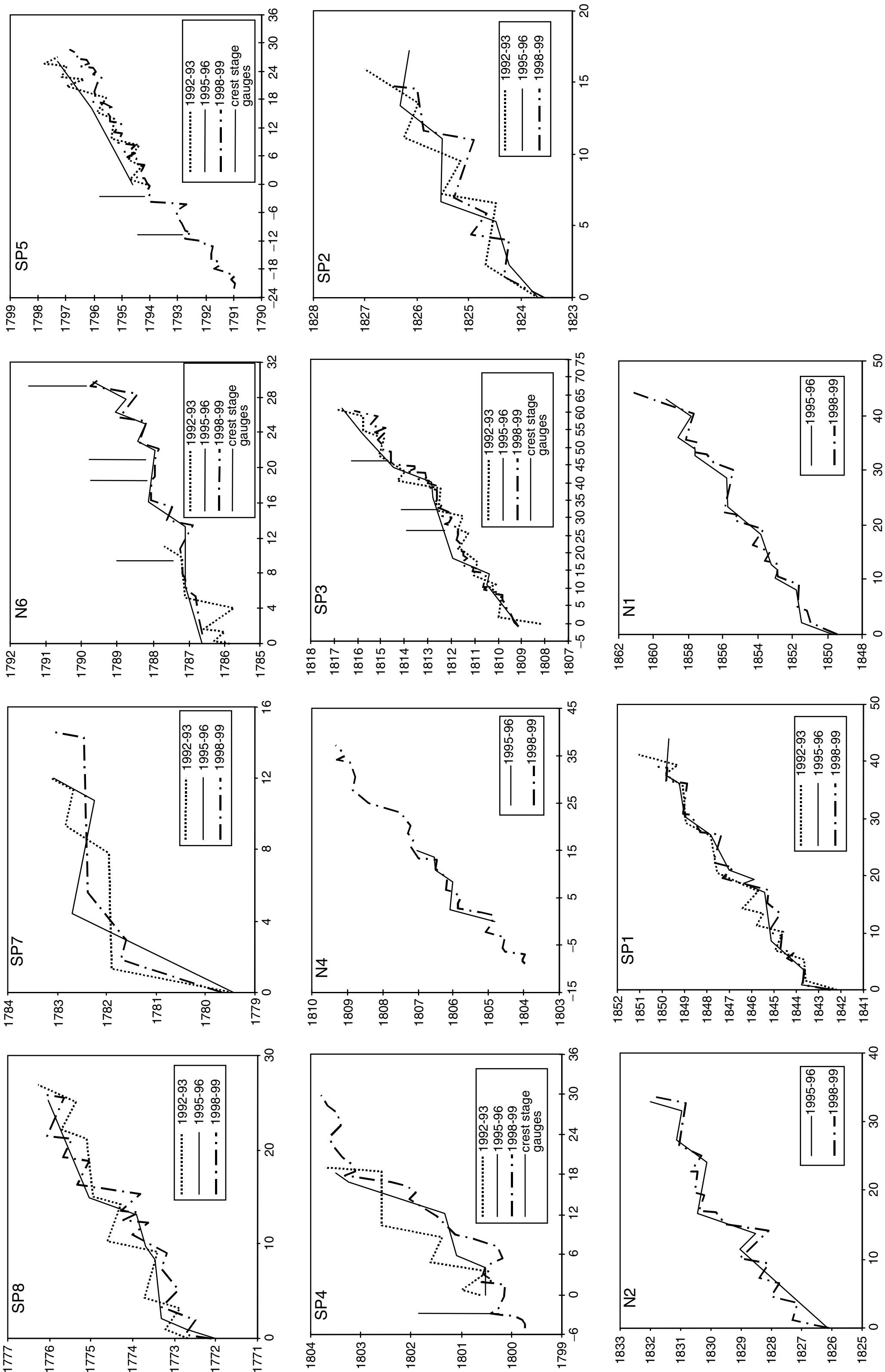

Figure 4. Longitudinal profiles of the step–pool reaches (distance in metres versus altitude in metres a.s.l.

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

Code	Mean step width, W (m)	Mean step–step drop, Z (m)	Mean step–pool height, H (m)	Mean pool spacing, L_p (m)	Mean step spacing, L_s (m)	Slope, S (−)
N1	7·99	1·16	1·23	4·93	5·40	0·22
SP1	5·62	0·71	0·88	4·19	4·31	0·16
N2	7·30	0·54	0·81	3·82	3·90	0·14
SP2	5·00	0·46	0·72	3·59	3·59	0·13
SP3	7·99	0·50	0·66	4·60	4·53	0·11
N4	4·69	0·84	0·88	5·48	6·68	0·13
SP4	7·05	0·80	0·82	5·96	6·67	0·12
M6	7·30	0·33	0·63	3·36	3·39	0·10
SP5	5·62	0·47	0·64	4·25	4·22	0·11
M7	5·01	0·28	0·42	2·23	2·32	0·12
N6	5·19	0·53	0·79	3·75	3·80	0·14
SP7	8·10	0·92	1·15	5·94	5·82	0·16
SP8	7·20	0·38	0·70	2·83	2·84	0·13

Table V. Hydraulic conditions corresponding to different water discharge values of the October 98 flow at the crest stage gauges no. 2 (reach N6) and no. 12 (reach SP3)

Water discharge, Q (m^3 s^{-1})	Cross-section number No.	Mean flow depth, h(m)	Average velocity, ν (m s^{-1})	Froude number, Fr	Wave-length, L_b (m)	Step–pool length, L_p (m)	Reach code	Wave-number, kh
1·00	2	0·15	1·23	1·00	0·97	3·75	N6	0·25
1·00	12	0·22	1·24	0·84	0·98	4·60	SP3	0·30
2·00	2	0·26	1·57	0·98	1·58	3·75	N6	0·43
2·00	12	0·32	1·24	0·70	0·98	4·60	SP3	0·44
4·00	2	0·42	1·95*	0·96	2·29	3·75	N6	0·70
4·00	12	0·48	1·93*	0·89	2·14	4·60	SP3	0·66
4·73	2	0·50	2·50†	1·00	4·00	3·75	N6	0·84
4·73	12	0·53	2·18†	0·96	3·04	4·60	SP3	0·72

* Average velocity calculated based on surface velocity using floats.
† Average velocity estimated assuming uniform flow condition.

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

Year of survey	Mean step spacing, L_s (m)	Mean pool spacing, L_p (m)	Step height, H (m)
1992–93	5·37	5·18	0·96
1995–96	6·95	7·08	0·98
Variation	+1·58	+1·90	+0·02
1998–99	4·42	4·22	0·79
Variation	−2·53	−2·86	−0·19

STEP–POOL MORPHOLOGY EVOLUTION AFTER SEPTEMBER 1994 AND OCTOBER 1998 FLOODS

Before the September 1994 flood, eight step–pool reaches were identified. The main characteristics of these reaches, numbered as SP1–SP8, are reported in Table III, together with those relative to the stream bed survey carried out after the September 1994 flood. A comparison of the geometric features reveals that many changes occurred. Almost all mixed reaches and three step–pool reaches (SP3, SP5 and SP6) were turned into riffle–pool reaches, while four new step–pool reaches formed. These are numbered as N1, N2, N4 and N6 since they are located upstream of SP1, SP2, SP4 and SP6, respectively, corresponding, in terms of location, to the mixed reaches previously identified as M1, M3, M5 and M7.

The total length of the step–pool reaches that survived (SP1, SP2, SP4, SP7 and SP8) was shortened by 42 per cent on average. A general increase (25–30 per cent) in the average single spacing between consecutive steps (step wavelength) results when taking into account all the sequences including the newly formed ones. This constitutes the main adjustment of the stream bed which, after the flood, largely assumed a riffle–pool configuration due to the channel having been filled by the large volume of sediment supplied. The peak discharge of 10·4 m^3 s^{-1}, though very high for the Rio Cordon, lasted only a few minutes, too short a time to allow the bed sediment wave to pass through the study reaches (Lenzi *et al*., 1997). The channel geometry and profile also changed remarkably (Figure 4). Post flood channel widening was observed in the downstream reaches as a response to higher than usual flow discharge.

After the October 1998 flood, a new stream bed survey was made. A comparison of these results with those obtained after the September 1994 flood reveals that further changes have occurred (Table IV and Figure 4). Whereas the large amount of sediment deposited on the stream bed in 1994 caused the burial of cross-structures and filled the pools with sediments, the 7 October 1998 event scoured out loose sediment from pools. Therefore the unusually large accumulations of sediments in the bedload trap during the most recent flood events (1996 and 1998; Table II) can be seen as a result of the considerable availability of material in the river bed.

The step and pool wavelength (L_s, L_p) of the reaches that survived the September 1994 flood increased (Table VI) and the step steepness (c parameter) decreased. The 7 October 1998 event had an effect which differed from the 1994 flood, mainly causing a better definition of the step–pool profile (Figure 4), a general shortening (−2·53 m) of the average step spacing (Table VI), and a reduction in step height (−0·19 m).

The main morphological changes induced by the October 1998 flood can be summarized as follows: (a) the peak discharge (4·73 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–pool sequences occurred; (b) pools became deeper and induced the formation of a negative bed slope between steps; (c) there was a remodelling of the risers of individual steps (sequences SP3 and SP5; Table IV).

DISCUSSION

Abrahams *et al.* (1995) hypothesize that step–pool sequences in mountain streams may be the result of a natural tendency of water channels to maximize resistance to flow. They found that flow resistance is maximized when Equation 1 is satisfied. The extreme values of the quotient $\overline{H}/\overline{L_s}$ were reported as being one and two times the mean channel slope.

Assuming that the mean value $\overline{H/L_s}$ is equal to the relation between the mean values $\overline{H}$ and $\overline{L_s}$, data from the Rio Cordon step–pool sequence taken prior to the September 1994 flood (Figure 5) conform to Equation 1. However, data taken after the flood, including those relating to the four new sequences, do not correspond to the maximum resistance model, because the values $\overline{H}/\overline{L_s}$ are often less than S (Figure 5). The data in Table III show the change from $H/L = 1{\cdot}30S$ before the flood to $H/L = 0{\cdot}79S$ afterwards (Figure 5). This transformation was associated with a more disorganized pattern of the step–pool morphology.

There had not been such a large flood in the Rio Cordon for 15 years before that of September 1994, only floods not exceeding 5 m^3 $s^{-1}$with a return period of less than five years.

After 1994, ‘ordinary’ floods slowly re-established the morphological features of the step–pool. Fine- and medium-sized sediments, eroded from the hillslope source areas, supplied to the stream network and stored

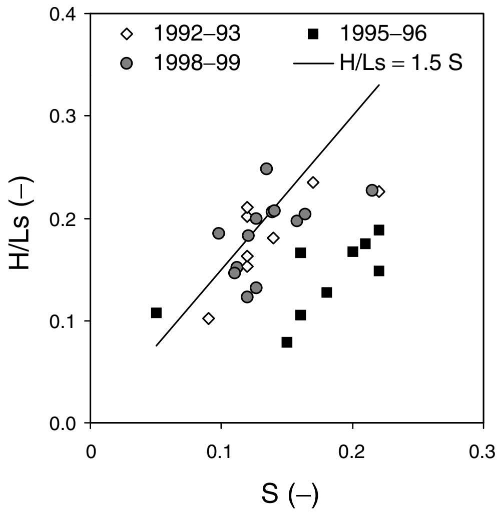

Figure 5. Channel gradient S versus the mean steepness H/L_s (Rio Cordon)

in the pools during the decreasing limb of the hydrograph of the September 1994 flash flood, were removed and transported by the long duration 'ordinary' flood of October 1998. Step–pool sequences are still not well organized; but due to the fact that bed erosion processes and pool scouring prevail over deposition the relationship $c = (H/L_s)/S$ assumed a value of 1·33 after the October 1998 flood reflecting the evolution of new step–pool structures. The process is supported both by a low sediment supply to the stream network and by the 'flushing out' of the bedload wave by the 'ordinary' floods.

The evolution over time of the c parameter mimics the trend of the measured bedload rate for different flood events. Before 1994 the c parameter close to 1·5 reflects a stable bed and well developed coarse armour. The bedload rate was therefore almost two orders of magnitude less than the transport capacity computable from bedload formulae (D'Agostino and Lenzi, 1999). The decrease of c during the September 1994 flood was accompanied by the break-up of coarse armour, the 'equal mobility' of the transported sediment grains (Lenzi and D'Agostino, 1998) and bedload rates close to those predicted 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, most recent values (Table II and Figure 6) are slightly increased owing to the excessive supply of fine sediment present in the bed (Lenzi, 1999).

The studies conform to Whittaker and Jaeggi (1982) laboratory tests. They highlighted a temporal instability in step–pool structures controlled by floods having a return period of 30–40 years. For this return period the sequences are either destroyed and then reformed in other reaches of the channel or are modified to the same degree.

The variation in wavelength in the same stream without substantial change in hydraulic gradient makes one cautious about applying expressions such as Equation 1 that determine wavelength from only gradient or gradient and step height. Indeed, Equation 1 applies to an equilibrium condition, a particular 'historic' moment in the stream, and does not apply to non-equilibrium step–pool units. The actual wavelengths of the step–pool sequences lie within a range of values which reflect the sequence of historical flows.

The analyses of the changes in the Rio Cordon step–pool sequences generally seem to correspond to the results of laboratory tests carried out by Rosport (1994). It has been possible to verify (from photos, topographic surveys and field observations of the movements of some steps' marked boulders) that the dominating transformation mechanism is erosion at the foot of the step with a resulting undermining from downstream. The erosive action progresses upstream leading to the collapse of the structure whereupon the rocks fill the pool below. The pool silts up and a rock alignment reforms further down. The step–pool formation, therefore, is redefined by the effect of erosion and the formation of new pools.

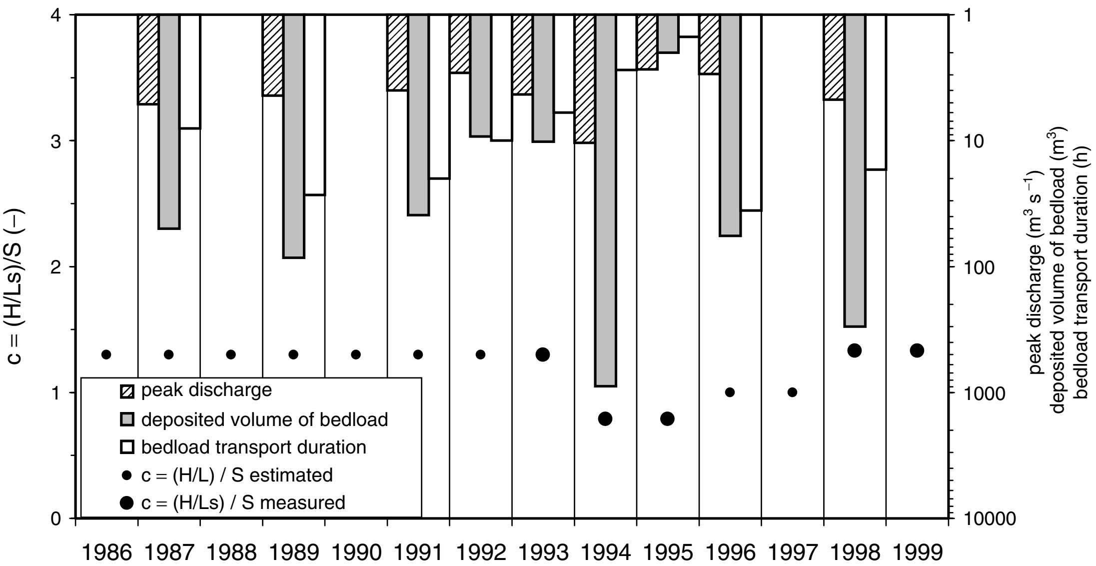

Figure 6. Main hydrological and sedimentological data of the floods recorded in the Rio Cordon: time evolution of the *c* parameter of the step–pool sequences, 1986–1999

A second means of transformation identified in the Rio Cordon steps after the September 1994 flood, though a less frequent occurrence than undermining, is the partial breaking up of a step through the removal 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 planimetrical V-shape pointing upstream. In the Rio Cordon, the downstream migration after the September 1994 flood is particularly clear and uniform in the SP2 sequence (Figure 4). However, in the SP6, SP7 and SP8 reaches, the downstream movements concern only some steps within each sequence. This produces transformations that are less well defined and, as a whole, more ill-defined. Downstream-pointing V-shaped standing waves (as reported by Croning *et al*., 1999) occurred in SP2, SP6, SP7 and SP8 reaches during the 1994 flood, where the flow was less than 1 m deep. Boulders up to 0·70 m in diameter were transported as bedload.

On the other hand, reaches SP1, SP3 and SP5 showed, after the September 1994 flood, above all, partial or total deformation of the step–pool sequences, 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 SP1, SP3 and SP5 were lower than or equal to previous ones. A general levelling 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 SP5 and SP3 (Figure 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 to a plane bed profile is clearly more attributable to the downstream transportation of solid materials than the erosion process in pools, and causes the burial of 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 deposition over erosive processes.

Newly formed step–pool configurations have resulted, after the September 1994 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 (N1, N2, N4, N6) occurred upstream from the SP1, SP2, SP4 and SP6 sequences in parts of reaches previously classified as mixed (M2, M3, M5, M7). These reaches, as has already been mentioned, are characterized by irregular accumulations of material of which the larger particles form barely visible steps, not yet organized in continuous transverse alignments. Before the September 1994 flood, along with step–pool sequences, 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. 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. Downstream-pointing V-shaped standing waves developed when the flows travelled through broad, shallow channel reaches.

Some researchers (Ashida *et al*., 1984; Grant and Mitzumaya, 1991; Grant, 1994; Whittaker, 1987) affirm that step–pool morphology originates in antidune formation in phase with a 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 ($kh = 2\pi h/L_b$, where h is the mean depth of flow and L_b is the bed form wavelength) enables the identification of the formation region of the antidunes. The data, plotted by Abrahams *et al*. (1995) in this diagram, could not be collocated within, or in direct proximity to, the antidune region.

Ashida *et al*. (1984) displayed their step–pool data on Kennedy's (1963) diagram of (Fr) against kh; these data fell either within or close to the domain for antidunes. Grant and Mizuyama (1991) plotted the measured step lengths against the corresponding minimum antidune wavelengths obtained from the expression (Kennedy, 1963):

$$L_b = 2\pi V^2/g \tag{3}$$

where V is the mean flow velocity and g is the acceleration due to gravity. The graph reveals that the measured step lengths tend to be similar to the minimum antidune wavelengths. Thus this comparison between the properties of flume step–pools and antidunes supports the antidune model.

Field data on step–pool sequences from the Rio Cordon presented herein can be used to evaluate further points raised by various authors. In order to analyse where step–pool sequences plot relative to the stability field of antidunes, the hydraulic conditions associated with the formation of step–pool sequences (for the September 1994 flood) can also be estimated following Grant (1997). The existence field is defined by Froude number and wavenumber, as suggested by Chartrand and Whiting (2000). The Froude number is:

$$Fr = V/(gh)^{0\cdot5} \tag{4}$$

where V is the average velocity, g is the gravitational acceleration and h is flow depth. From the definition of the mean shear velocity:

$$V^* = (ghS)^{0\cdot5} \tag{5}$$

Equation 4 is rewritten:

$$Fr = (V/V^*)S^{0\cdot5} \tag{6}$$

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

$$V/V^* = (8/f)^{0\cdot5} = 5\cdot62\ \log(h/D_{84}) + 4 \tag{7}$$

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

$$\tau^*_{cr} = \frac{hS}{\left(\frac{\gamma_s}{\gamma_w} - 1\right)D} \tag{8}$$

where γ_s and γ_w are the specific weights of the water and sediment respectively, and $\tan\theta = S$, channel slope. Assuming $\gamma_s = 2{\cdot}65$, Equation 8 can be rearranged as a relative roughness equation:

$$h/D = 1{\cdot}65\tau^*_{\mathrm{cr}}/S \tag{9}$$

By setting $D = D_{84}$ and substituting Equation 9 into Equations 7 and 6, it is possible to calculate the Froude number at incipient motion for a given slope as:

$$Fr = [5{\cdot}62 \log\ (1{\cdot}65\tau^*{}_{\mathrm{cr}}/S) + 4]S^{0{\cdot}5} \tag{10}$$

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 $\tau^* = \tau^*_{\mathrm{cr}} = 0{\cdot}045$.

As noted by Lenzi and D'Agostino (1998), boundary shear stress in boulder-bed streams (like Rio Cordon) can reach 1·55 $\tau^*{}_{\mathrm{cr}}$: an upper estimate of the Froude number associated with formative flows ($Q \approx$ 6·0–10·0 m^3 s^{-1}).

The wavenumber kh associated with formative conditions is taken, following Kennedy (1963), as $kh = 2\pi h/L_b$, with L_b given by Equation 3.

A crude estimate of the flow depth during formative conditions for the Rio Cordon September 1994 flood, can be made following Allen (1982) assuming that particle size on the steps (D_{50}) is on the order of flow depth (h = D_{50}), (Table III). Setting depth (h) equal to D_{50} was decided after the reconstruction of maximum water level depths in two cross-sections, from video-camera images relating with the maximum discharge of the 1994 flood. Other two flow depth values were obtain from two crest stage gauges installed before the 1994 flood in two cross-sections located 40 m and 90 m upstream from the station, respectively (Lenzi *et al.*, 1999). Chin (1989) also wrote that the coarsest particles were about equal to the flow depth on the step–pool reach of Santa Monica Mountains of southern California.

Minimum and maximum antidune wavelengths, L_b, were calculated using Equation 3, assuming that the mean flow velocity, V, can be estimated on the base of the upper and lower Froude number values calculated from Equation 10.

Using Equation 6, the potential range of τ^*, the maximum and minimum antidune wavelengths and the assumed depth, the step–pool sequence observed in the Rio Cordon (1994) is compared to the stability field for antidunes (Figure 7). One interpretation of the field results coming from the Rio Cordon catchment is that step–pool sequences form in association with antidunes, with the wave train giving rise to imperfect and irregular spacing of step–pool sequences. In the Rio Cordon stream bed this irregular spacing may be ascribed to the short duration of water discharge at higher flow for the extraordinary 'flash flood' of the September 1994.

The different flow conditions associated with the ordinary floods of 1995, 1996 and mainly to the October 1998 long duration flood, cause subsequent erosion, altering the topography somewhat such that bed features may no longer plot within the stability field of antidunes. The analysis of the field hydraulic conditions measured during the October 1998 flood at the crest stage gauges 2 (reach N6, Table IV) and 12 (reach SP3, Table V), corresponding to different discharge values, confirms this hypothesis. In Figure 7, the final geometry of reaches N6 and SP3 is consistent with the hypothesis that they formed in association with antidunes only for the highest water discharge values. Dimensionless wavenumber $kh = 2\pi h/L_b$ and Froude number related to water discharge conditions equal to 4·00 and 4·73 m s^{-1}, plotted in Figure 7, fall within or at the border of the stability field for antidunes, while the other values fall near the border or outside.

Despite these doubts the antidune theory may still be applicable. Indeed, according to this model large sediment should be completely submerged, but only shallowly, by the flow conditioning the formation of the structure. The explanation of step–pool topography as stabilized antidunes caused by a reduction in sediment supply originally offered by Whittaker and Jaeggi (1982), and confirmed by Ashida *et al.* (1986), Grant and Mizuyama (1991) and Parker (1996), appears to be the correct one.

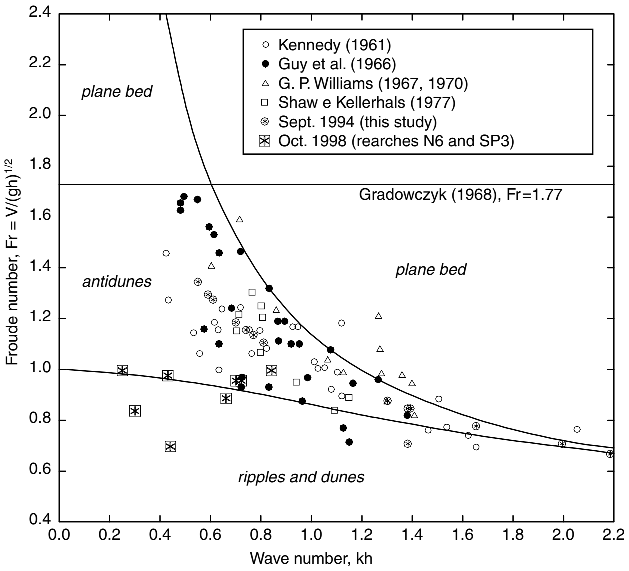

Figure 7. Geometry of step–pools relative to the stability field for their existence for the data of the October 1998 flood and for the data from the Rio Cordon (1994) with $kh = 2\pi D_{50}/L_b$. Source Allen, 1982; Elsevier

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 and temporary periods of steady-state conditions, has been used in order to explain the evolution of step–pool morphology in the Rio Cordon stream bed. The analysis of the characteristics of the floods and coarse bedload recorded at the experimental station, along with detailed field surveys of the step–pool structure, illustrates the effect of these floods on step–pool sequences. The stream bed changes during the September 1994 flood led to breakdown of step–pool sequences, and most of the channel developed riffle–pool and bar reaches. The reverse bed 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 1994 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 (Figure 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 1994 flood do not lead to maximum flow resistance. The values of the geometric parameters of the newly formed step–pool sequences after the September 1994 flood do not correspond to the model proposed by Abrahams *et al.* (1995), because 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, ordinary floods scour fine sediments from pools. The steepness factor evolution demonstrates that maximum resistance conditions are gradually reached at the end of a cycle of ordinary flood events. During this cycle, bed armouring is the dominant sediment transport response. However, following an extraordinary flood and unlimited sediment supply, the steepness factor can suddenly decrease as a result of sediment trapped in the pools and a lengthening of the step spacing.

Two aspects of post-flood bed instability appear: step destruction normally starts downstream of the 'structure' by undermining the large elements, and 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 in underlining that the measured geometry of the step–pools can be consistent with the hypothesis that step–pools are formed by antidunes. The development of V-shaped downstream-pointing standing waves and the formation of upstream-pointing steps, a common morphological response to standing waves, give additional evidence that the new steps formed during the September 1994 flood are antidunes.

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