Management of Landscapes Disturbed by Channel Incision

Stabilization • Rehabilitation • Restoration

May 19-23, 1997

EFFECTS OF AN EXTREMELY LARGE FLOOD ON THE BED OF A STEEP MOUNTAIN STREAM

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Edited By:
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Published By:
THE UNIVERSITY OF MISSISSIPPI
Management of Landscapes
Disturbed by Channel Incision

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Proceedings of the Conference on Management of Landscapes
Disturbed by Channel Incision

Oxford Campus, The University of Mississippi

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The Center for Computational Hydroscience and Engineering
The University of Mississippi
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Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision held at The University of Mississippi, May 1997

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ISBN 0-937099-05-8

First published in May 1997, by:

Center for Computational Hydroscience and Engineering
School of Engineering
The University of Mississippi
University, MS 38677
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EFFECTS OF AN EXTREMELY LARGE FLOOD ON THE BED OF A STEEP MOUNTAIN STREAM

Mario A. Lenzi¹, Paolo Billi² and Vincenzo D’Agostino¹

ABSTRACT

In an instrumented, small catchment of the Dolomites several geomorphic and hydraulic parameters are monitored. The study stream, Rio Cordon, is a typical, short, high gradient (over 0.13) stream characterized by almost vertical cliffs in the headwater (over 2000 m a.s.l.) and steep slopes. The morphological structure and the sedimentology of the stream bed are closely related to its gradient and to both quantity and size of the particles supplied. Riffle-pool and lateral bar reaches alternate with the more typical step-pool reaches. In September 1994 a large flood (Q₃₀-s, the largest ever measured since the construction of the gauging facility) widely affected the streambed. A comparison of channel morphology and bed material data measured before and after such an extreme flood is presented. A lot of sediment was supplied to the stream. Although much of it was transported as bedload, as it is proved by the volume of coarse particles measured at the gauging facility, in-stream deposition prevailed on erosion. A few step-pool sequences were buried while others showed particles displacement. Other were instead destroyed and rebuilt, but their post-flood arrangement is different from the previous one. The post-flood sequences are shorter but the step length increased giving way to a lower flow resistance bed structure. The increase in bed material grain size was almost ubiquitous though the shape of the distribution curve remained approximately the same.

INTRODUCTION

Steep streams are very common in mountain areas and generally show features that are notably different from those of larger lowland rivers. Notwithstanding the relevance of the ecological and geomorphic role played by such high gradient streams in an alpine environment, the current knowledge of the main physical processes affecting them is still very limited. Steep mountain streams commonly experience an excess of energy to which they adjust through channel changes that take place during extreme floods. Such changes are not very well documented in the scientific literature since access difficulties or tough local conditions have often impeded the systematic observation of even a few basic geomorphic and hydraulic parameters. This lack of field data has been partly counterbalanced by laboratory experiments aimed to investigate the main relationship between flow, sediment transport and streambed structure. Laboratory studies provided some information on the basic hydraulic processes acting on mountain streams but the difficulty of satisfactorily simulating flood conditions on very steep and coarse-grained beds makes flume experiments only complementary to field investigations.

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Since 1986 an instrumented catchment (the Rio Cordon) run jointly by the Regione Veneto and the University of Padova, (Lenzi et al, 1990) is operating in the Dolomites. The facilities installed include a system for monitoring flow discharge and both suspended and bed sediment transport. In order to investigate the relationships among streambed morphology, bed material grain size, flow discharge and sediment transport a detailed survey of the streambed hydraulic geometry and structure was carried out during summer 1994 on the main stem of the study stream. Bed material grain-size characteristics were investigated as well by means of the pebble count method.

On September 14, 1994, a very large flood, whose return time was assessed to be between 30 and 50 years, had a great impact on the streambed and provided a unique occasion to study the effectiveness of an exceptional flood on a steep mountain stream and to investigate the adjustment to unusual higher flow energy and sediment supply. Several reaches of the Rio Cordon had a step-pool morphology and, since the September '94 flood provided the right hydraulic conditions invoked by many authors (Whittaker, 1986; Grant et al, 1990; Whol and Grodek, 1994; Abrahams et al, 1995) for their formation, a detailed survey of the stream bed was repeated after the flood in order to verify if new boulder steps were formed. In this paper the streambed adjustments induced by the September '94 flood are reported, while the factors originating the stepped morphology of mountain stream will be discussed in a companion paper, in preparation by the same authors.

THE STUDY CATCHMENT AND ITS MEASURING FACILITY.

The Rio Cordon is located in the Dolomites (Fig. 1) and is a small catchment with characteristics typical of the region. The main features of the watershed are listed in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1. Main characteristics of the Rio Cordon catchment</th>
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<tbody>
<tr>
<td>Basin area (km$^2$)</td>
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<tr>
<td>Maximum elevation (m a.s.l.)</td>
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<tr>
<td>Measuring station elevation (m a.s.l.)</td>
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<tr>
<td>Average slope gradient</td>
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<tr>
<td>Main stream length (km)</td>
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<tr>
<td>Mean stream gradient</td>
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<td>Annual precipitation (mm)</td>
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<td>Average annual temperature ($^\circ$C)</td>
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The solid geology consists of dolomites, which make up the highest relieves in the watershed, volcaniclastic conglomerates and tuff sandstones; in the lower part of the basin calcaeous and arenaceous rocks outcrops. Quaternary moraine and scree deposits are also very common. Herbaceous associations cover 61% of the watershed surface, while shrubs are relatively widespread (18%). Forest stands are found only in the lower part of the watershed occupying 7% of its area; 14% of the catchment consists of bare land.

The climate is typical Alpine with precipitation occurring mainly as snow from November to April. Runoff is usually dominated by snow melt in May and June, but also summer and early autumn floods, triggered by cloudbursts, are common.

In the Rio Cordon, water and sediment discharges are measured by a specifically designed facility (Lenzi et al., 1990, Bili et al., 1995). The gauging station consists of: 1) an inlet flume, where flow discharge is measured by standard water level recording systems; 2) a downstream inclined grid retaining particles coarser than 20 mm; 3) a storage area for coarse sediment deposition; and 4) an outlet flume to return water and fine sediment to the stream. Coarse sediment exceeding 20 mm slides along the grid and accumulates in the storage area, where its volume is
measured every 15 - 60 minutes by means of ultrasonic probes on a fixed frame. Water and fine sediment pass through the grid and are directed to the outlet channel where flow and turbidity are automatically recorded (Lenzi et al., 1990, Billi et al., 1995).

THE SEPTEMBER 14, 1994, FLOOD

The flood of September 14, 1994, followed a rainstorm that lasted a few hours and whose intensity increased progressively to a maximum of 20.5 mm h⁻¹. Peak discharge was 10.4 m³ s⁻¹ (2.08 m³ s⁻¹ km⁻²) (Fig. 2) and it was calculated to have a return time between 30 and 50 years. To peak flow are associated the maximum values of Froude number, shear stress and unit stream power that were 1.7, 53 kg m⁻² and 182 watt m⁻² respectively. During the flood a large quantity of sediment was entrained and conveyed in the gauging station sediment trap where 900 m³ of particles larger than 20 mm accumulated. Peak coarse bedload rate was about 0.09 m³ s⁻¹ (0.018 m³ s⁻¹ km⁻²), i.e. 50 times that measured during the previous floods that, for this reason, were defined as “ordinary” (D’Agostino and Lenzi, 1996). Bed material entrainment was observed to start at a discharge of 1.8 m³ s⁻¹ (0.36 m³ s⁻¹ km⁻²) that is very close to the critical discharge value of 2 m³ s⁻¹ (0.4 m³ s⁻¹ km⁻²) measured for the previous floods (D’Agostino and Lenzi, 1996).

During the September ’94 flood a larger than usual quantity of sediment was supplied to the stream network. A number of sediment sources displayed evidence of reactivation, while slope instability phenomena were rather limited and mainly consisted of small debris flows and shallow landslides in grass-covered colluvium. The Rio Cordon streambed was likely the principal sediment source, but several minor eroded banks and bank failures were also observed on the main stem and some tributaries (Billi et al, 1995).

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Fig. 1 Location map of the Rio Cordon

Fig. 2 Hydrograph of September 14, 1994, flood

STREAMBED ADJUSTMENTS

Detailed field surveys of the streambed structure and grain-size characteristics were carried out before and after the September ’94 flood in order to point out the effectiveness of a large flood such as this in causing streambed changes.

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One of the salient features of the Rio Cordon is its stepped morphology. Since the shear stress experienced by the bed at peak discharge was close to the critical value, calculated by the equation of Baker and Ritter (1975), for the entrainment of the boulders making up the steps, it was reasonable to expect some modification of the bed or the formation of new step-pool sequences as envisaged by a few authors (Whittaker, 1986; Grant et al, 1990; Whol and Grodek, 1994; Abrahams et al, 1995).

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 II, while those relative to the streambed survey carried out after the September '94 flood are reported in Table III. A comparison of the two tables reveals that many changes have occurred. Almost all the mixed reaches (step-pool reaches with some depositional features - Billi et al, 1995) 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.

The step-pool reaches that survived (SP1, 2, 4, 7 and 8) underwent a remarkable length contraction as now they are shorter by 42%, on average a general shortening of 28% results as well considering all the sequences including also the newly formed ones. This reflects the main adjustment of the streambed that after the flood assumed a riffle-pool and bar configuration due to main channel filling by the large volume of sediment supplied. Peak discharge, though very high for the Rio Cordon, lasted only a few minutes; probably a too short time to let the flow to remove the material supplied.

| TABLE II | Main characteristics of the step-pool reaches before the September '94 flood. |
|----------|-----------------|-----------------|----------------|-----------------|-----------------|-----------------|
|          | X               | Lr              | W              | S               | Ls              | H               | Lp              | Hp              |
| SP1      | 653.5           | 9.61            | 6.60           | 0.221           | 5.66            | 1.283           | 5.51            | -0.220          |
| SP2      | 519.5           | 13.38           | 4.76           | 0.174           | 4.46            | 1.053           | 4.50            | -0.277          |
| SP3      | 450.5           | 58.73           | 6.19           | 0.118           | 6.52            | 1.004           | 6.62            | -0.234          |
| SP4      | 339.5           | 19.25           | 6.23           | 0.141           | 6.42            | 1.157           | 4.92            | -0.253          |
| SP5      | 282.0           | 25.33           | 4.96           | 0.120           | 4.22            | 0.850           | 4.21            | -0.343          |
| SP6      | 203.5           | 11.85           | 4.87           | 0.119           | 3.95            | 0.827           | 4.12            | -0.357          |
| SP7      | 166.0           | 12.95           | 6.12           | 0.094           | 6.47            | 0.655           | 6.54            | -0.045          |
| SP8      | 121.0           | 26.13           | 5.92           | 0.117           | 5.23            | 0.846           | 5.05            | -0.236          |

X = distance from the gauging station of the reach most upstream step (m); Lr = reach length (m); W = mean channel width (m); S = reach gradient; Ls = mean step wave length (m); H = mean step height measured from the deepest point of the downstream pool (m); Lp = mean pool deepest point wave length (m); Hp = mean difference in elevation between the deepest point of a pool and the downstream step (m); negative values indicate a reverse slope of the pool bottom.

| TABLE III | Main characteristics of the step-pool reaches after the September '94 flood. |
|-----------|-----------------|-----------------|----------------|-----------------|-----------------|-----------------|
|           | X               | Lr              | W              | S               | Ls              | H               | Lp              | Hp              |
| SP1       | 653.5           | 18.95           | 5.62           | 0.201           | 6.32            | 0.940           | 6.33            | 0.206           |
| SP2       | 519.5           | 11.19           | 5.01           | 0.198           | 5.59            | 0.940           | 5.53            | -0.125          |
| SP4       | 339.5           | 12.78           | 7.05           | 0.210           | 11.03           | 1.930           | 7.98            | 0.220           |
| SP7       | 166.0           | 7.56            | 8.19           | 0.046           | 7.56            | 0.810           | 10.79           | -0.460          |
| SP8       | 121.0           | 12.86           | 7.21           | 0.159           | 6.43            | 0.675           | 6.00            | 0.190           |
| N1        | 703.0           | 40.80           | 7.99           | 0.223           | 6.80            | 1.278           | 6.65            | 0.011           |
| N2        | 556.0           | 16.21           | 7.30           | 0.183           | 8.10            | 1.025           | 8.88            | -0.205          |
| N4        | 377.0           | 12.45           | 4.69           | 0.146           | 6.22            | 0.485           | 6.76            | -0.015          |
| N6        | 233.0           | 13.51           | 5.19           | 0.157           | 4.50            | 0.754           | 4.82            | -0.240          |

Notation as in Table II but for the newly formed step-pool reaches, numbered N1-6 according to their position upstream of the step-pool reaches surveyed before September '94 flood.
Channel geometry and profile also changed remarkably. 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. Changes in reach gradient were also recorded but their pattern is irregular without any clear streamwise trend. By contrast step length increased in all reached independently of the gradient variations confirming what found by Abrahams et alii (1995) for a few steep streams of Adirondack Mins., New York, and Lake District, England. These authors investigated the hypothesis that the stepped morphology of mountain streams can be accounted for by the tendency of natural channels to maximize flow resistance. From laboratory experiment and field data they found that flow resistance is maximized when step steepness (H/Ls) ranges from S and 2S. This relation is well fitted by the Rio Cordon step-pool data relative to the situation before the flood. On the contrary, post flood data, including also those of the newly formed step-pool sequences, do not follow the model of Abrahams et alii (1995), as H/Ls is normally less than S. This is probably due to the general increase in the step length observed for post flood data with step height not changing significantly.

Grant and Mizuyama (1991) pointed out that the formation of step-pools requires near-critical to supercritical flow conditions and postulate that step-pool originates as antidunes in phase with standing waves. Both Whol and Grodek (1994) and Abrahams et alii (1995) reject the antidune hypothesis providing good arguments. The latter authors plotted their laboratory data on Kennedy's (1963) diagram of Froude number against $kh = \frac{2\pi h}{Lp}$, where $h$ is flow depth and $Lp$ is the pool wave length, and found that all their points fall outside of the antidune field. By contrast, the post flood data of the Rio Cordon are well included within the antidune field. This is probably due to the high Froude numbers occurred during the September '94 flood, but it is not enough to support the antidune hypothesis. Further investigation is therefore needed to get light on the step-pool origin.

The streambed changes that occurred on the Rio Cordon during the September '94 flood were only at a lesser extent directed towards the formation of step-pool sequences as the majority of the channel acquired a more typical alluvial morphology with well developed riffle-pool and bar reaches. The reverse slope of the pools, very common in the stepped streams (Abrahams et alii., 1995) and in the Rio Cordon as well before the September '94 flood, give way to downstream dipping pool bottom in about half of the post flood sequences. A comparison of the longitudinal profiles show a clear flattening and smoothing. Once again, this can be accounted for by the large rate of sediment supply and deposition. Because of that the stream was unable to develop the typical step-pool structure which will be probably achieved through the next "ordinary" (shorter return interval) floods.

Changes in the grain size of bed material were remarkable. Data were collected from pebble count at seven selected sites. The coarseness of bed material and the small width of the channel did not allow to get more samples. The post flood data show a clear increase of bed material grain size. Such increase is evident for any characteristic diameter (from $D_{10}$ to $D_{90}$) and can be explained by the large supply of coarse material from slopes and, subordinately, from the breaking of steps. Other grain-size distribution parameters such as standard deviation and skewness did not vary significantly.

CONCLUSIONS

The streambed of the Rio Cordon, a typical steep mountain streams with a step-pool morphology, was largely affected by the flood of September '94 (30-50 years return interval). A few of the former step-pool reaches were turned into riffle-pool and bar reaches, while only four short sequences were formed. The step length of those reaches that survived the flood increased and the step steepness decreased. Flow resistance was therefore reduced and, though the flow energy was enough to entrain boulders as large as those making up the steps, deposition prevailed. Part of the
step-pool sequences (including those of the mixed reaches) were washed out by the flood flow while others could have been buried by the very large quantity of coarse sediment supplied from slopes. It is possible that smaller flood flows with a reduced supply of sediment will be able to resume the former step-pool structure. Plots of Froude number versus pool wavelength fall within the antidune field but doubts about this hypothesis for step-pool formation still remain.

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ACKNOWLEDGEMENTS

This research was supported by the European Commission, DGXII, Environment and Climate Programme, Climatology and Natural Hazards Unit, in the framework of the contract ENV4-CT96-0247.