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Stream bed stabilization using boulder check dams that mimic step-pool morphology features in Northern Italy

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Abstract

During the last 10 years, the check dams made of boulders have been fully employed for torrent management, particularly for high-gradient stream stabilization. The analysis of this typology is shown in relation to three aspects: building features, field of use and design according to geomorphologic principles. The "Maso di Spinelle" torrent located in the Province of Trento, Italy (North Italian Alps) is an example where a sequence of low-check dams made of boulders have been used for bed stabilization. The design criteria are taken from the step–pool morphology features and the results are encouraging for further applications. The artificial step–pool grade-control structures in the Maso di Spinelle torrent have been successfully tested by floods events with return periods of about 7–10 and 20–25 years. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Catchment management; Streambed stabilization; Boulder check dams; Step–pool morphology

1. Introduction

Torrent control requires the design of diverse interventions in the basin. Advanced technology and superior knowledge enable the construction of interventions that are increasingly appropriate to their objectives. These objectives are determined by what is to be protected, from what danger and, most importantly, to what extent.

It is undeniable that each intervention in a complex ecosystem, such as a stream, alters the balance of its biotic communities (vegetation, fauna, microfauna) and, therefore, its ecological stability. Equally undeniable, however, is the need to protect infrastructure and habitations that could be damaged by floods, which in a mountain area are absolutely "natural" and destined to reoccur cyclically (Kettl, 1994; Della Giacoma et al., 1991).

Current trends for mountain stream control, which blend in with the ecosystem as much as possible, entail the combined use of naturalistic engineering techniques and methods of morphologically "reconstructing" the stream. These should be as compatible as possible with the stream's natural tendency to reach a stable configuration over a long period (Kondolf, 1996). Such criteria should be applied with care and be accompanied by traditional structural interventions (Lenzi et al., 2000). The latter are, in fact, essential both in preventing the most severe disorders (such as rapid phases of channel erosion and incision, debris flow and near-bank landslides) and guaranteeing stability in situations where the safety of the population must be guaranteed. The two naturalistic–geomorphological

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aspects and the classic structural one must, therefore, interact, taking on different degrees of importance within the control work, according to the level of protection required, the return time of the flood and the objectives established during planning. Biological–naturalistic engineering interventions aim above all to restore the ecological functionality of the stream, essentially through the reintroduction of riparian vegetation which, once established, can effectively perform a number of functions (Schweitzer, 1995). Aspects of restoration or rehabilitation of torrents connected to a morphological "reconstruction" of the stream are, at a practical level, much less common than biological–naturalistic or engineering remedial measures (Sear et al., 1995; Newson, 1995; Knighton, 1998). Nevertheless, research intending to propose constructional variations of traditional concrete check dams and to study the conditions of formation and stability of some natural morphological units (riffle-pool, step–pool) has greatly increased within the scientific community and in some organisations with specific expertise in this sector (Brooks and Douglas Shields, 1996; Lenzi et al., 2000).

In particular, traditional check dams arranged in a cascade, which reduce gradient through a series of concrete works (Benini, 1990), have recently been constructed using large boulders. In some cases, old concrete check dams have even been converted (Fig. 1) into check dams made from boulders or ramps (Haltiner et al., 1996; Brooks et al., 1996; Lenzi et al., 2000). Reconstruction is aimed reducing the artificial effect of the concrete on the channel and, at the same time, adhere firmly to control principles and objectives. Such interventions are particularly appropriate in areas of tourist and recreational importance, but more generally, they allow a more natural control arrangement in many streams where there are already large boulders on the bed (1–1.5 m diameter). Further refinement of the planning stage for boulder check dams may be carried out, taking into account the similarity between the morphology of "step" and "pool" physiographical units and traditional stabilisation works. Indeed, the longitudinal profile of step–pool reaches resembles a series of check dams (Fig. 2). The distance between the steps in a sequence, L_s, is determined by stream slope, S, step height, H, and bed roughness as well as by the floods that formed them (Lenzi, 1999; Lenzi and D'Agostino, 1998, 2000). The channel arrangement found in step–pools appears to be the outcome of a natural evolutionary process which tends towards a certain stream stability (Lenzi, 1999, 2001). The end results of complex natural hydraulic, sedimentological and geomorphological interactions, which are characteristic aspects of step–pool morphology, may be taken as a starting point and applied appropriately to the aimed channel "reconstruction" (Lenzi, 2001).

In this article, construction designs currently used for boulder check dams will be described. An example of their planning and design according to geomorphological and stream bed stabilization criteria will be given, with reference to an artificial step–pool sequence structure constructed with large boulder in the Province of Trento, North Italian Alps.

2. Construction designs and fields of use for boulder check dams

Large boulder stabilisation works include concrete check dams covered with boulders, structures with boulders anchored to the bed by micropiles and boulder check dams either uncemented or strengthened with cement. The use of large boulders in torrent control was directed mainly at longitudinal bank protection structures (rip-rapping, deflectors, training walls). During the course of these works, it was possible to reduce labour requirements considerably, thereby cutting the costs of traditional forms of stabilisation. On the other hand, these interventions could not and, still cannot, be applied in more complex situations. For example, in steep streams where energy excesses with sudden planimetric and altimetric changes, considerable bedload or debris flows have to be dealt with. The use of these construction designs is further conditioned by technical limitations. Exceeding certain heights (2–2.5 m) is problematic even though the structure's strength is largely assured by the size of the boulders. Durability is another factor that should not be overlooked because it appears to be slightly more limited than that in traditional concrete check dam structures. To overcome some of the limitations of using uncemented or cemented boulder check dams, new construction designs have been researched which guarantee greater strength against violent floods and/or debris flows, even for high-drop structures. At the

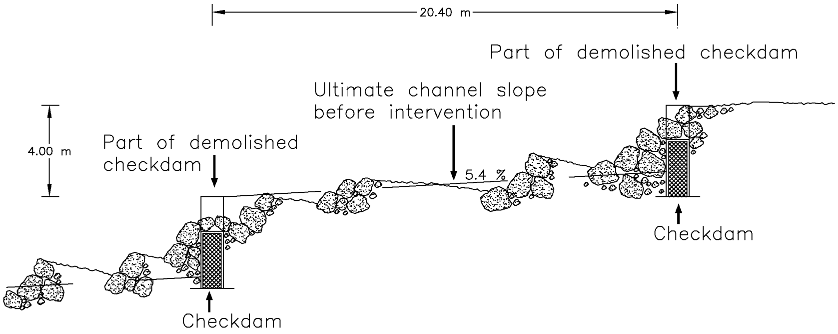

Fig. 1. Longitudinal profile showing the reconstruction of the old grade control structure (redesign on the base of a project of the Torrent Control Agency of the Autonomous Province of Trento) (source: Lenzi et al., 2000).

same time, attempts have been made to increase durability, to keep costs within limits comparable to those of traditional concrete check dams and to better conceal any concrete which may be visible through the interstices (D'Agostino et al., 1997; Lenzi, 2000).

In an attempt to combine all these objectives, the Torrent Control Agency of the Autonomous Province of Trento has been developing a design, widely used in the east of Trentino, since 1990. This involves works with a reinforced concrete framework to which very large, uncut boulders are firmly tied and anchored. This design has been subject to development, which aims to save concrete and achieve greater constructional simplicity. In the most recent works, the upstream framing has been replaced by a rudimentary baffle against the scour front. This means there is less scour, greater safety for workers and reduced construction time. This construction design is now the

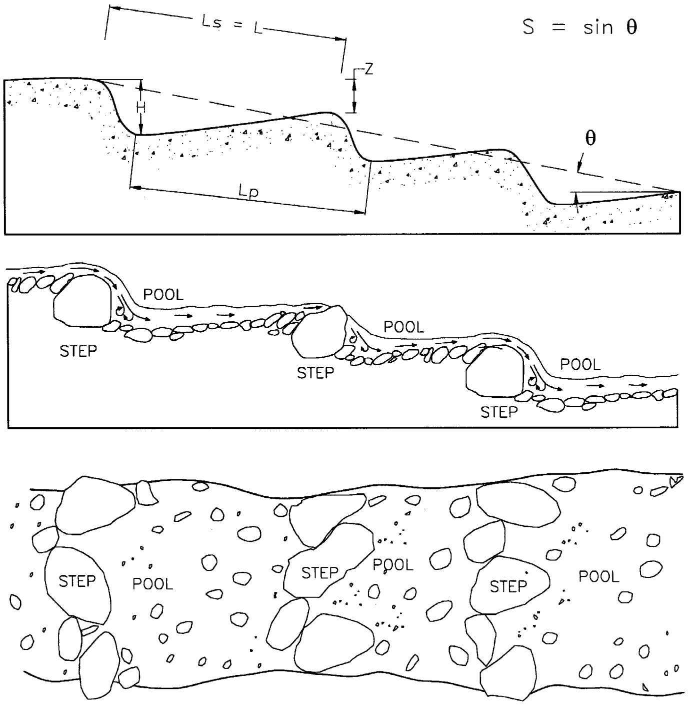

Fig. 2. Sketch of a natural step–pool sequence (L_s = step wavelength; L_p = pool wavelength; H = step height; B = width of the step riser).

most commonly used in Trento Province and results in works of considerable strength and durability (Lenzi et al., 2000). Some such stabilisation works have already been rigorously tested by floods with return intervals over 30 years and even by a debris flow.

Cemented boulder check dams are obviously a simplification of the check dams previously described: the upstream framing is rarely made, there is no reinforcement and fastening and the amounts of concrete are clearly low as the body of the construction behind the downstream face is reduced to the minimum necessary to structurally join the boulders and give the check dam a certain monolithicity. Two to four square metres of concrete are used per square metre of downstream face for tied works, but only 0.5–1.5 m^3 for works that are just cemented. Even the designs considered here have their limitations and their construction requires particular care. Their use is recommended in channels characterised by a uniform, coarse distribution of bed material. Indeed, if no large boulder is present, the control would have a completely artificial effect, which may be worse than that obtained from traditional works. In these circumstances, it would be necessary to transport blocks from other locations with a consequent increase in costs. When choosing between these different boulder check dam designs, determining factors are protection aims and the nature of what is to be protected (residential areas, infrastructure, extensive or intensive farmland, natural landscape). It is, therefore, logical to hypothesise a high degree of protection for areas of high value and a lower degree of protection for farmland and forest areas, leaving aside the now outmoded concept of a standard size for a flood with a 100-year return time (UFEA, 1995). Table 1 proposes an outline of the fields of use for the main kinds of boulder check dams, taking into account the degree of protection required, the kind of solid transport and some basic geomorphological parameters of the stream. Conditions for the construction of artificial steps (uncemented boulder check dams or check dams strengthened with cement) are as follows: (a) bed slope reach should be typical of that of step–pool sequences (5–20%); (b) sufficient availability of large boulders in the stream; (c) possi-

Table 1
Fields of use for boulder check dams

Uncemented boulder check dams (artificial steps, riffle steps)	Check dams strengthened with cement (artificial steps, riffle steps)	Check dams with reinforced concrete framework and tied boulders
Characteristics of reach where control works are to be constructed		
Gradient up to 12–14%	Gradient up to 18–20%	Gradient up to 18–20%
Grain size of surface material		
(a) Wide and complete (heterogeneous)	(a) Quite graduated	(a) Quite uniform
(b) Consistent presence of large boulders	(b) Prevalence of gravel and pebbles, but also a certain number of boulders	(b) Prevalence of sand, gravel and small pebbles; a few boulders
Morphology		
(a) Not changed by previous interventions	(a) Slightly changed by previous interventions	(a) Already changed by previous interventions
(b) Presence of step–pool and/or riffle step–pool sequences	(b) Presence in the stream and/or its tributaries of short step–pool and/or riffle step–pool sequences	(b) Not very structured channel
Sediment transport		
(a) Bedload	(a) Bedload	(a) Bedload
	(b) Hyperconcentrated flow	(b) Hyperconcentrated flow
		(c) Debris flow
Abundance of large boulders present in stream	Considerable availability of boulders in the stream	Hardly any boulders in the stream
Surrounding environment		
Natural, farmland	Natural, farmland, slight urbanisation	Built up
Degree of safety required		
Return time: 20–30 years	Return time: 30–50 years	Return time: > 50 years

bility of basing these works on large boulders already present in stream; (d) presence of well-defined step–pool sequences in stream or in some of its tributaries.

Design criteria for these transverse works, which attempt to artificially reconstruct a natural step–pool morphology, can make use of research carried out in fluviomorphological and hydraulic fields on step–pool sequences (Lenzi, 2001).

To guarantee a wide safety margin, it is advisable to base the step on at least two of these foundation boulders whilst a suitable foundation should be laid for the rest of the structure, with boulders at least 1.5–2.0 m deep. Building the step requires careful excavator work so that the boulders anchor each other in, making the whole step stable. Except in certain cases, the step should not be higher than 2.5 m above the ground. This guarantees a more natural effect and also avoids laying more than three rows of boulders, which would make the step structurally less stable. Structural stability can be improved by slightly arching the step towards upstream or it can be supported on the banks with an open "V" shape. Even the increased stability of an arched planimetric shape can be put at risk when banks erode. In these cases, there should be both good lateral keying (4–5 m), to prevent possible turning of the step, and a continuous lateral bank protection with rootwads/boulders (D'Agostino et al., 1997; Lenzi, 2000).

A constructional precaution to increase stability can consist in creating supplementary anchoring points, such as micropiles placed upstream of the step and tied to the foundation boulders with steel cables. Torrent control works built according to the above criteria blend in well with their natural surroundings. To further reduce the impact of rip-rap on the environment, and to speed up revegetation, willow cuttings can be planted between the boulders.

3. Study area

In 1996 and 1997, the Torrent Control Agency of the Autonomous Province of Trento, with the scientific support of the University of Padua, carried out hydraulic control works on some reaches of a mountain stream, the Maso di Spinelle, using transverse boulder works for channel protection against incision. The Maso di Spinelle forms, along with the Maso di Calamento, the Maso, a tributary that flows into the River Brenta, from the left bank, near the village of Castelnuovo (Fig. 3a) in Northern Italy. The main physiographic characteristics of its basin are synthesised in Table 2. 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 rains represent an important contribution to the flow regime. Usually, late autumn, winter and early spring lack noticeable runoff events.

Soils in general are thin and belong to three main families: (a) skeletal soils, occurring on steep slopes with a discontinuous vegetation cover; (b) organic soils, with more continuous vegetation cover; (c) brown earth soils. Vegetation cover consist of herbaceous associations, including both continuous-cover mountain grassland (6% of catchment surface) and sparse grassland (5%). Shrubs are well widespread (24%), while forest stands made up of spruce and larch are found in the and lower parts of the catchment and occupy 53% of the total area; 12% of the catchment consists of bare land.

Sediment sources in the Maso di Spinelle catchment were mapped through field surveys in the summer of 1996. Area, elevation, slope and vegetation cover of sediment sources were measured in the field. Investigated areas were sketched, photographs were taken and sediment samples were collected. The resulting file includes several sediment source areas, covering 7.2% of total basin area. Active sediment sources mainly consist of stream bed incisions, eroded banks and landslides along streams, shallow landslides, bare slopes, overgrazed areas, low-order channels and debris flow tracks (Sonda, 1998). The geology of the basin has contributed consistently to such large alterations of the stream, which are also documented by aerial photographs taken after the 1966 flood (Figs. 3b and 4). The geological formations of the valley result from the great crystalline (magmatite) presence of the Cima D'Asta. Vulcanite protrudes in the lower reach (particularly on the right bank). Metamorphites (phyllites, cornubianites, paragneiss) are present in the upper reach. The channel is dominated by degraded deposits of Quaternary age, particularly in the lower reach between Pontarso and the confluence with the Rivo Caserine. Moraine and fluvioglacial deposits are highly evident close to the banks and are often covered by talus. The moraine material has led to a high percent-

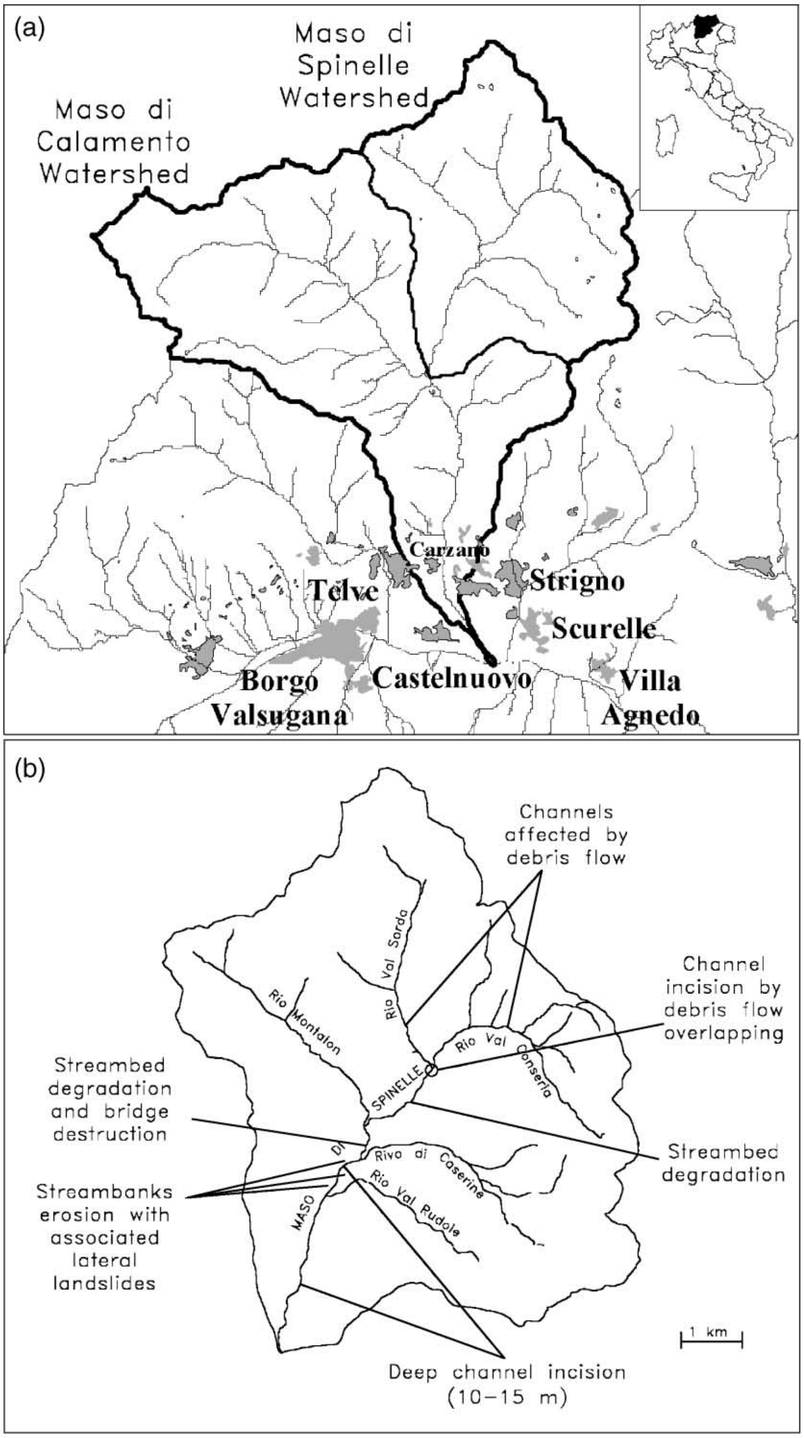

Fig. 3. (a) Location map of the Maso di Spinelle catchment. (b) Erosion processes on the main stem.

Table 2
Main physiographic and climatic characteristics of the Maso di Spinelle catchment

Catchment area (km^2)	45.0
Average elevation (m.a.s.l.)	1860.0
Minimum elevation (m.a.s.l.)	909.7
Maximum elevation (m.a.s.l.)	2561.6
Mean slope gradient (%)	50.3
Length of the main stem (km)	10.0
Mean gradient of the main stem (%)	13.8
Mean annual precipitation (mm); mean annual temperature (°C)	
✎Pontarso station	1100–7.7
✎Costa Brunella station	1300–3.4

age of sandy and sandy–gravelly banks on which there are large boulders of various shapes. Some of these boulders, which range up to some hundreds of cubic metres, caused huge flow diversion during the 1966 and 1993 floods, leading to bank slides (Sonda, 1998; Cerato, 1999).

The streambed of the Rio Maso di Spinelle consists of five different types of channel reach: they were identified during summer 1996 as step–pool, cascade–pool (step–pool–cascade), pool–riffle and riffle step (plane-bed–step–pool) (Lenzi et al., 2000). Short bedrock reaches are also present but they are restricted to the catchment headwaters and tributaries. Step–pools reaches of the Maso di Spinelle showed a disorganized pattern, associated with steep gradients ($10\% < S < 15\%$), and confinement by the valley walls. The cascade–pool reaches are step–pool sequences irregularly punctuated by small heaps of ill-formed gravel bars of coarse material, while pool–riffle reaches are characterized by well defined lateral and central bars and are bounded by a small eroded alluvial plain. Cascade–pool 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. This latter

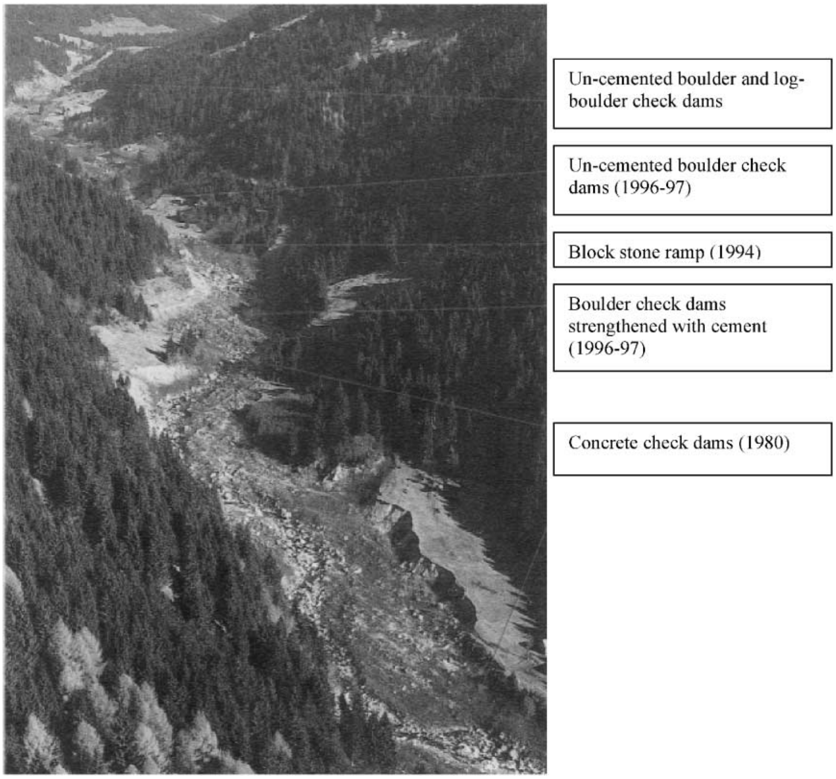

Fig. 4. Aerial photograph taken after the 1966 flood showing the location of the different types of protective structure built since 1980 (photograph courtesy of the Torrent Control Agency of the Autonomous Province of Trento).

channel type generally occurs in the Maso di Spinelle torrent on step slopes (S>12–14%) and seems to reflect both the description and the diagnostic features of the "cascade channel" proposed by Montgomery and Buffington (1997). Riffle step reaches occur in the Maso di Spinelle torrent at moderate to high slopes (7% < S < 10%) in relatively straight reaches and unconfined by valley walls. They are composed of boulder grain sizes, but are dominantly gravel to cobble bedded. Tributaries of the Maso di Spinelle stream: Rivo di Caserine, Rio Montalon, Rio Val Sorda and Rio Val Conseria are characterised by prevailing well organised step–pool reaches sequences.

Channel reaches 10–15 channel widths in length were surveyed throughout the Maso di Spinelle drainage basin. Each reach was classified into one of the above-defined channel types. Reach slopes were surveyed using either a total station positioning system or a clinometer, a meter tape, a laser diastimeter and a stadia rod. Topographic surveys and channel-spanning pebble counts of 100 grains (Wolman, 1954) were conducted at representative cross-sections. Reach slopes were determined from topographic maps for some additional reaches where morphologies were mapped, but slope and grain-size measurements were not collected (Lenzi and D'Agostino, 1998).

Particular attention was paid to the analysis of the geometric relationships of the step–pools reaches surveyed on the Maso di Spinelle tributaries, due to their use in the torrent control designs.

4. Channel stabilization according to morphological criteria

The Maso di Spinelle's bed, especially the middle-lower part, was subject to considerable incision and deepening during the historic flood of 3–4 November 1966 ($100 < T_r < 200$ years). To give an idea of the degree of disorder of the channel, the average width of the bed downstream of the Rivo di Caserine (Figs. 3 and 4) increased from 6–7 to 35–50 m after the flood, while the bed profile went down by about 10–15 m in some reaches. Similar results, though not so accentuated, were recorded more recently following the flood event of 2 October 1993 ($50 < T_r < 75$ years).

One reach of the Maso di Spinelle, near the confluence with the Maso di Calamento, was subject to a classic intervention with concrete check dams during the 1980s (Fig. 4). As a result of the incision caused by the 1966 flood, these dams were about 7 m high. Following the 1993 flood event, further intervention was deemed necessary to stabilise the worst affected reaches of the channel. Within the framework of the Maso di Spinelle Watershed Master Plan, proposed activities and priorities of measures (Action plans) were elaborated taking into consideration a geomorphological approach at catchment scale and the most important objectives of flood protection and ecology. The procedure used for linking both the catchment analysis to planning and the researches at catchment-reach scale is reported on Fig. 5. A broader catchment-scale perspective which emphasizes the physical integrity of the drainage basin and the close links between catchment and channel dynamics was adopted. Catchment response to catastrophic flooding (1982, 1966 and 1993) was reconstructed from historical documents and field evidence in order to indicate spatial variations in geomorphological effectiveness. The role played by events of different magnitude and frequency and the conditions which can lead to instability of the main channel were also analysed. Upstream-progressing degradation as response to a fall in base-level at the confluence with the Brenta River was identified as the main dominant erosion processes. Degradation processes became more complex because interaction between a main stream and its tributaries was also deected. Channel confinement, due to the narrow valley morphology, accelerates the incision and inhibits gradient adjustment through a change in sinuosity and roughness characteristics.

Maso di Spinelle Master Plan highlights the necessity of preserving stable stream environments which means preserving the long term stability of factors that influence stream dynamics and evolution. To enable this, the Maso di Spinelle torrent was divided into characteristic reaches to be preserved or rehabilitated while recognizing that these reaches are parts of a continuum of flow and sediment transfer (Fig. 5). This plan adopts a geomorphological approach, which both complements and supplements that of river engineering, as underlined by Sear et al. (1995), Thorne et al. (1997) and by Knighton (1998), as well as applying some of the principles of "engineering geomorphology" developed by Bravard et al. (1999). Complete restoration to a predisturbance state was not considered

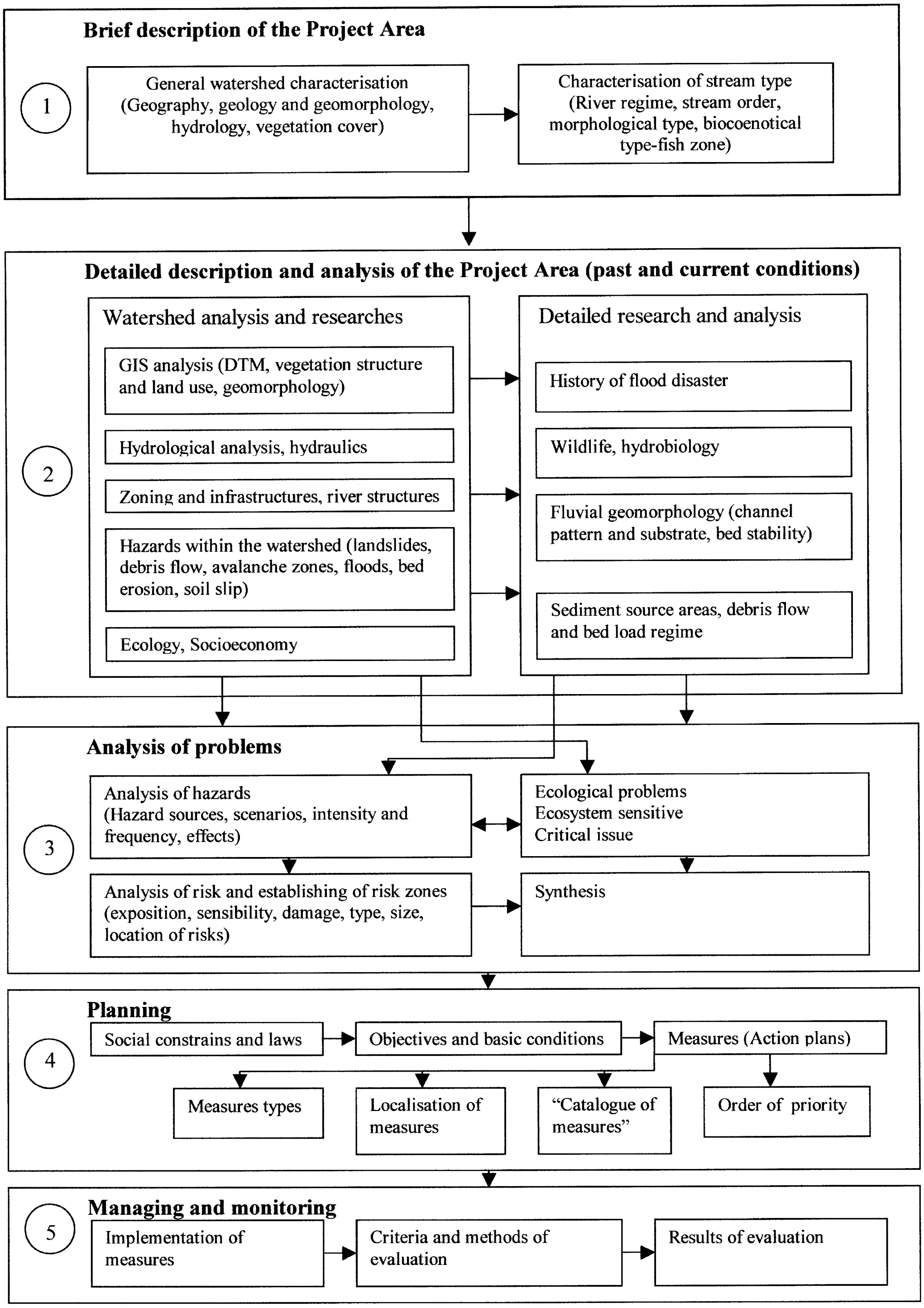

Fig. 5. Schematic illustration of the Maso di Spinelle Watershed Master Plan.

a viable option, so a partial restoration (rehabilitation) of the stream was proposed, attempting to improve the hydraulic, biological and aesthetic status of the torrent. The abundance of fine and poorly sorted material on the bed, combined with the disorderly arrangement of the large boulders present, suggested remedial options of minor impact which would also enhance the water course from an aesthetic and environmental aspect.

The first such attempt was made following the 1993 flood in a reach affected by 10–15 m of bed lowering (Fig. 4). A block stone ramp was built from large boulders tied together by steel cords and laid on the sandy subsoil. The creation of this long, very rough ramp prevented the channel from taking on an artificial, engineered appearance, whilst its fixed bed armouring ensured almost complete immunity from erosion. The only drawback was perhaps the large workforce required to drill the boulders making up the artificially paved channel.

Since the channel required stabilising in two further reaches upstream that were affected by headward cutting, both to avert the risk of new bed incisions and to strengthen some bank slides overlooking the channel, it was decided to reproduce natural step–pool structures using boulder check dams. Conditions allowing this kind of intervention were: the gradients (10–14%) typical of step–pool reaches, the high availability of large boulders near the stream, the possibility of building these works on large boulders already present in the streambed and the presence of well-defined step–pool sequences on some tributaries of the Maso di Spinelle (Rivo di Caserine, Rio Val Sorda and Rio Montalon). The building solutions adopted envisaged the construction of uncemented boulder check dams for a 500-m reach of the channel downstream of the Maso's confluence with the Rivo di Caserine (Figs. 3 and 4) and the installation of boulder check dams strengthened with cement for the control of a reach further downstream, situated upstream of the block stone ramp (Sonda, 1998; Lenzi et al., 2000).

In accordance with the largest grain-sizes in the stream (D_{90}, D_{100}), a structure's height above ground (H) can be calculated, maintaining an average relation $H/D_{90}=2$ and keeping within the range $H/D_{90}=1-4$ (Lenzi and D'Agostino, 1998; Lenzi, 1999). After conducting four grain size surveys in the zones undergoing stabilisation works according to the "grid by number method" (Wolman, 1954, modified by Lenzi 1992), the most suitable heights were assigned to the steps (check dams). According to the largest grain sizes sampled in the channel ($D_{90}=0.7-2$ m), values between 1 and 3.5 m (with a more frequent value of 2.5 m) were assigned to the height above the ground (H) of the structures.

The distance between steps ($L_s=L$) can be estimated beforehand by applying the maximum flow resistance criteria as determined by Abrahams et al. (1995) in the laboratory. The authors, through four interconnected series of experiments, have observed that on a step–pool reach, there tends to be a condition of low mean flow velocity (and, therefore, of maximum global resistance to flow), when there is a combination of regular spacing between steps and the geometric condition:

$$1 < (H/L)/S < 2 \tag{1}$$

where H = the vertical height of the steps in the sequence and L = distance between steps, estimated in a parallel direction to the slope S of the stream (Fig. 2).

A comparable result to Eq. (1) has been obtained by D'Agostino and Lenzi (1998) from a sample of 49 natural step–pool sequences (Eastern Alps), for which the following equation has been obtained:

$$0.5 < (H/L)/S < 2.1. \tag{2}$$

D'Agostino and Lenzi (1998) have, however, obtained a mean value of 1.4 for the $(H/L)/S$ parameter which, therefore, corresponds with value proposed by Abrahams et al. (1995). In planning, one can attempt to create artificial steps which fall into the range suggested by Eq. (1) and which tend, where possible, towards $H/(LS)=1.5$. The criteria, however, should be applied in a flexible way, trying to follow the altimetric and planimetric course of the stream. One should also bear in mind local changes in gradient, widening, and sections which are most suitable for lateral keying (Lenzi and D'Agostino, 1998). Likewise, in assigning the wavelength, it is better to move within a certain range of variation for L_s, rather than attempting to keep a fixed distance between works. Lenzi and D'Agostino (1998) have noted average values of L_s between 0.5 and 1.6 times the breadth (B) of the stream in correspondence to the steps. An analogous study by Chin

(1999) (Santa Monica Mountains, CA) highlights how frequency peaks of the variable L_s/B are between 0.5 and 1.5 and how there was a notably low occurrence of values higher than 5.

After conducting a detailed longitudinal topographic survey of the restored main stream, the field of wavelength, $L=H/(1.1-1.3S)$ was chosen with distances of 10–25 m between the works.

Determination of discharge over the artificial steps can be carried out according to the estimation of peak discharge under critical flow conditions. It is necessary that the flow downstream of each step is not submerged by the water level caused by the next step downstream. An observation of the flow profile between the pool and the head of the next step during floods shows a strong ponding of the water and an almost horizontal hydraulic grade line with a very gradual lowering of the free surface towards the step. Cautiously one can then assume that the level of the hydraulic grade line does not go beyond the value:

$$y_m = 1.5(q^2/g)^{0.333} \tag{3}$$

where y_m = flow depth slightly upstream of the step, estimated according to the height of the jutting edge and q = design inflow per unt of transverse width of the step ($m^2\ s^{-1}$).

The design water discharge for a return interval of 100 years was estimated to be 85 $m^3\ s^{-1}$ by Sonda (1998). Considering the maximum width of the flow as equal to 23.5 m, is possible to obtain a value of y_m equal to 1.65 m; the flow depth slightly upstream of the step, estimated according to the height of the jutting edge and q the design inflow per unit of transverse width of the step ($m^2\ s^{-1}$). This value suggested that lateral bank stabilization should be built to a height of 2 m, using rootwads/boulders.

To estimate any possible structure failure, a reference design hypothesis, especially in the case of uncemented artificial steps, is represented by the calculation of stability for each boulder in the work. It should be pointed out that when analysing the extreme equilibrium condition for a cubic element (Benini, 1990), the limited sliding velocity is lower than that for rolling. For boulders in an artificial step, for which the longer axis is laid in the direction of flow, the limited sliding velocity on the bed or on the boulder below is, therefore, worse for stability than that of rolling. It is difficult to describe the general shape of a boulder with regular geometric terms. Usually they are pseudo-elliptic shapes which can be categorised according to their three main axes: in the direction of flow (D_x), perpendicular to the bottom (D_y) and in a transversal direction (D_z) to the flow (Fig. 6). If a generic boulder is placed on a slope $S = tg\beta$ and struck by a water flow with speed V_f (Fig. 6), the forces which destabilise the boulder are the drag force (F_D), the lift force and the weight of the element in the water in the direction of movement (P_x).

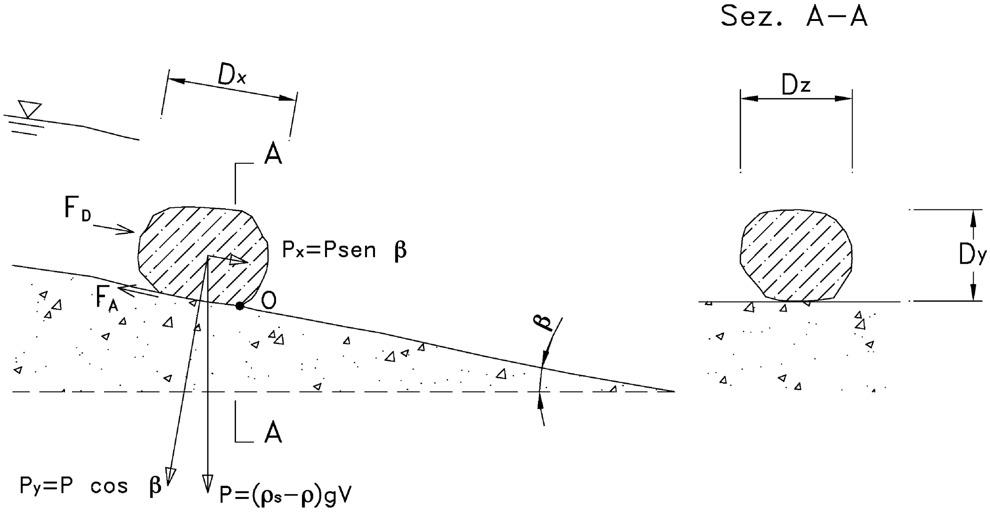

Fig. 6. Sketch of the forces acting.

Friction with the bed (F_A), which depends on the immersed weight of the boulder, and actions of lateral friction and anchoring between surrounding boulders, contribute to boulder stability.

In developing the condition of stability, it has been decided to ignore the lateral anchoring and the effect lift force has in making the boulder lighter. The stability condition, therefore, is:

$$F_D + P_x = F_A. \tag{4}$$

The drag force is a function of; the coefficient of hydrodynamic resistance of the element (C_D) struck by flow, the density of the liquid (ρ), the surface covered in the normal direction of flow (A_x) and of the flow velocity (V_f). Therefore:

$$F_D = C_D \rho A_X V_f 2/2. \tag{5}$$

P_x can be expressed by the relation:

$$P_x = (\rho s - \rho) g \ V \ sin \ \beta \tag{6}$$

where V is the boulder volume and ρ_s its density.

Friction force F_A is given by the product of the orthogonal immersed weight force to the bottom for the friction coefficient (f) between boulder and boulder (v between boulder and bed):

$$F_A = f \ (\rho s - \rho) g \ V \ cos \ \beta. \tag{7}$$

The boulder volume can be expressed as:

$$V = \alpha A_x D_x \tag{8}$$

where α is a shape parameter with 1 for a prismatic solid, 2/3 for an ellipsoid and 0.6–0.8 for natural or broken boulders.

If Eq. (8) is now replaced in Eqs. (6) and (7) and these are then inserted with Eq. (5) in Eq. (4) one obtains:

$$C_D \rho A_x V_f^2/2 + (\rho s - \rho) g \ \alpha \ A_x D_x \ sin \ \beta = f(\rho s - \rho) g \ \alpha \ A_x D_x \ cos \ \beta \tag{9}$$

from which the near bed velocity under incipient movement conditions can be obtained:

$$V_f = \surd\,(2(\rho s - \rho) g \ \alpha)(f \ cos \ \beta - sin \ \beta) D_x / C_D \rho. \tag{10}$$

The drag coefficient C_D essentially depends on four factors: Reynolds number, Froude number, shape of the boulder and relative submersion. Depending on the value obtained for the Reynolds number, the boundary layer on the boulder varies from laminar to turbulent with a corresponding shift of the separating zone of flow and, therefore, of the form resistance induced by the boulder. Bathurst (1993) has observed that this can be considered a secondary factor for a natural boulder, since irregularities in form and possible angularity of the boulder have considerably more influence than the boundary layer on the position of the separating zone. In the case of moderate flows, the effects of Froude number (Fr) and relative submersion (that is the relation between the flow (y_m) upstream of the boulder and its size (D_y)) have a greater influence. The influence of Froude number is connected to the energy loss that the boulder's protrusion causes at the free surface. Even though there is not an exact estimation for the relation that links the coefficient C_D to Fr and to y_m/D_y, a significant indication is given in a study by Flammer et al. (1970). The authors carried out experiments on a hemisphere with height D_y on a smooth surface, and showed that, as with relative submergence, the coefficient C_D decreases with the increase of Fr. Flammer et al. (1970) highlight three distinct behaviour fields: the first is characterised by y_m/D_y values higher than 4 where the dissipating surface effects are negligible and, therefore, where C_D, not influenced by the Fr value, remains nearly constant ($C_D = 0.3-0.5$); a second field, included in the interval $y_m/D_y = 1.5-4$, where the surface effects begin to be noticeable and the coefficient C_D just manages to overtake the unit for $Fr = 0.5$ and $y_m/D_y \approx 1.7$; the third field has a low relative submergence ($y_m/D_y < 1.5$) where surface disturbance is very evident and the influence of Froude number on C_D predominates (Lenzi et al., 2000).

To propose a simplification of Eq. (10), which conservatively accounts for the C_D value, one could hypothesise that the boulders on the upstream face of the crest of an artificial step are not completely silted up (or even that there has been a partial removal of material artificially placed between the boulders). Following this hypothesis, each boulder would be struck by a flow whose regime is slightly lower than the critical state ($Fr = 0.9$) and characterised by a relative submergence value close to unity. With these values, Flammer et al.'s graph suggests $C_D = 2$. If, in addition, one enters into Eq. (10) a submerged boulder density of 1.65, a friction coefficient $f = 0.7$, an intermediate value of the form parameter ($\alpha = 0.7$) and one ignores the bed gradient ($\beta = 0$), the equation is reduced to:

$$V_f \approx 3\sqrt{D_x}. \tag{11}$$

A similar relation was already indicated by Sternberg (1875) with a coefficient of 4 and a reference diameter corresponding to the b axis rather than to the long axis D_x as in Eq. (11).

In testing the stability of artificial steps, the velocity which is obtained from Eq. (11) has to be estimated for the D_x values of smaller particles in the construction. Moreover, in low submergence conditions, the flow speed affecting boulders in the central zone of surface A_x cannot be estimated by hypothesising a logarithmic profile of velocity (Nowell and Church, 1979; Bathurst, 1993). It is, therefore, advisable to directly compare the velocity V_f with the mean flow velocity (V) (Benini, 1990). A conservative deduction can be made by applying the hypothesis that the design inflow is already found in transition conditions slightly upstream of the boulder. This velocity, therefore, is:

$$V = \sqrt{(g\,y_m)}/1.5 \tag{12}$$

where y_m is expressed by Eq. (3). The safety coefficient for checking the stability of boulders in a step, then, will be represented by the relation between V_f and V. It would have to be higher than the unit for cemented boulder works and at least equal to 1.2–1.3 for uncemented boulder steps.

Boulders forming the upper part of the steps are characterised by an axis parallel to the flow direction (D_x) of at least 1.6–1.7 m. If Eq. (11) is applied, a value of $V_f = 3.8$ m s^{-1} is obtained; this value is the mean greater than the mean flow velocity calculated from Eq. (12) ($V = 3.3$ m s^{-1}), and so a degree of safety relating to the stability of boulders is greater than unity.

5. Geomorphological implications of boulder check dams

Traditional streambed stabilization through the use of concrete check dams requires the designer to determine the ultimate slope of the channel upstream of the dam (Fig. 1). In artificial boulder step sequences with a reverse slope longitudinal profile (Fig. 2) and characterized by a condition of maximum flow resistance (steepness parameter $c = (H/L_s)/S$, between 1.2 and 1.4 in this study), it is not necessary to predict the equilibrium slope. In step–pool systems, water flows over groups of large elements that act like weirs and plunges into pools below these elements. The flow in step–pool systems is described as tumbling flow, in which a great part of the flow energy is dissipated by rollers in the pools. Wohl and Thompson (2000) measured velocity profiles and velocity fluctuations over steps and pools throughout the snowmelt hydrograph. They found that flow became more turbulent as stage increased, particularly at lower-gradient reaches with less variable bed roughness. Flow also became more turbulent as gradient increased, and as bed roughness increased. The wake-generated turbulence leads to higher energy dissipation in step–pool reaches relative to more uniform-gradient reaches (Wohl, 2000).

Morphological implications and effects of boulder check dams can be synthesized as follow: if we assume both that the breath (B) of the restored stream and the distances between step, L_s, can not change even during less-frequent higher-discharges, the only possibility for changing the configuration is the variation of the H parameter. Then, during a series of "ordinary" (Lenzi et al., 1999) flood events, we will expected bed armouring to dominate the sediment transport response and a stable bed. However, following an extraordinary flood ($T_r > 50$ Years) and unlimited supply conditions, the steepness factor, c, should suddenly decrease as a result of sediment trapped in the pools, and a general levelling of reaches should also be expected. The higher gradient of the artificial step–pools along with the high overall channel roughness should be replaced by a morphological configuration with a flatter profile and reduced channel roughness. Lenzi (2001) suggested that this transition from a step–pool profile to a plane bed profile is more attributable to the downstream transportation of solid materials than erosion processes in pools, and causes the burial of transversal structures. After an extraordinary flood, subsequent ordinary floods can reestablished the morphological features of the step–pools scouring out loose sediment from pools. In this way, pools become deeper inducing the formation of a negative bed slope between steps, and due to fact that bed erosion processes and pool scouring will prevail over deposition, the relationship $c=(H/L_s)/S$ will assumes a value equal or greater than 1.

Bedload studies in natural step–pool channels demonstrate complex relations between discharge and sediment transport: transport rates are dependent on seasonal and stochastic sediment inputs, flow magnitude and duration, and antecedent events (Ashida et al., 1981; Sawada et al., 1983; Whittaker, 1987; Schmidt and Ergenzinger, 1992; Warburton, 1992; Montgomery and Buffington, 1997; Blizard and Wohl, 1998; Wohl, 2000; Lenzi, 2001). Warburton (1992) suggested three phases of sediment transport in natural step–pool channels: a low-flow flushing of fines; frequent high-flow mobilization of pool-filling gravels; and less-frequent higher-discharge mobilization of step-forming grains (Montgomery and Buffington, 1997). Ashida et al. (1981) observed a 10-h lag between hydrograph peak and onset of bedload transport for step–pool channels scoured of all pool-filling sediment during a previous storm. Hydrograph peak and sediment transport were, however, directly correlated during a subsequent storm due to the availability of sediment deposited in pools. Attempts to predict sediment transport along step–pool channels using some of the standard sediment relations developed for coarse sediments and steep gradient indicated that these relations tended to over-predict actual measured bedload transport by more than three orders of magnitude (Wohl, 2000). Working on a step–pool channel in the Rio Cordon (Northeastern Italy), Lenzi (2001) found that "the evolution over time of the *c* parameter mimics the trend of the measured bedload rate for different floods events. Before the September 1994 large flash flood the $c=(H/L_s)/S$ 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 (Lenzi et al., 1999; 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 and bedload rates close to those predicted by the Schoklitsch (1962) formula. Successive ordinary events took the bedload rate back towards the values recorded before 1994. Nevertheless, most recent values (1997–1998) are slightly increased owing to the excessive supply of fine sediment present in the bed".

The intervention described was, from a hydraulic point of view, put to a rigorous test during the final stages of construction. Between 14 and 18 October 1996, there was considerable heavy rainfall (in particular from 15–17 October when the Cruccolo rainfall measuring station recorded around 170 mm of rain). The maximum discharge caused by the event was around 43 $m^3\ s^{-1}$. This was estimated by the clear traces left by the flow upstream of the check dams at the end of the torrent. The exact contribution of the flood ($\approx 0.9\ m^3\ s^{-1}\ km^2$) indicated a return interval of between 7 and 10 years. On October 7, 1998 another flood, with a peak discharge of 52 $m^3\ s^{-1}$ and a return interval of 20–25 years occurred. On both these occasions, the behaviour of both check dams strengthened with concrete and uncemented boulder steps was satisfactory. Neither subsidence or damage to the check dams nor bank erosion or fragmentation were evident. From a hydraulic point of view, the investigations carried out during the flood have also highlighted the energy dissipating behaviour typical of step–pool sequences, with a tendency to almost completely submerge the vortex created by the step's sault into the next pool downstream during slow flow (Fig. 7).

To evaluate both the stability and the hydraulic behaviour of these artificial step–pool sequences a set of experiments was performed at HR Wallingford (UK). The experimental activity was performed using the "Tilting Sediment Duct" facility, a flume which can be tilted up to 40°. A model of the artificial steps in the Maso di Spinelle torrent was built using Froude similarity; with a length scale of 1/40 (time scale about 1/6 and discharge scale about 1/10,000). Calibration, performed by simulating the flood hydrograph occurred in 1998, showed both the effectiveness of the model and the importance of a good positioning of the boulders while building the steps. Another hydrograph with a peak discharge of 85 $m^3\ s^{-1}$ ($T_r=100$ years) has been used to verified the stability of the artificial steps (Giacometti, 2000). Moreover, the distance between two subsequent steps has been changed trying to validate the antidune and the maximum flow resistance theory. Finally, the analysis of the failure of a step at high discharge values pointed out the importance of toe protection to ensure reliability and more durability to the artificial structure. The results showed that toe

Fig. 7. Uncemented boulder step–pool sequence during the October 7, 1998 flood (photograph courtesy of D. Sonda).

failure is the main cause of collapse for a well-shaped step (Giacometti, 2000). This hypothesis is also supported by the results of field research on the evolution of natural step–pool sequences following a large flood, carried out by Lenzi (2001) on the Rio Cordon, Italy.

Evaluation of the ecological effects of the artificial boulder step structures was carried out with the RCE-2 model. To understand the differences in the ecological assessment of the varieties of the protective structures implemented on the Maso torrent, a comparison of results was made between concrete check dams, artificial boulder steps, block stone ramp and a natural step–pool sequences of the Maso di Calamento stream (AKL-SASSM, 1999). The RCE-2 model is based on the “Riparian Channel and Environmental Inventory” (RCE-1), a qualitative method of assessment of the ecological and flood prevention function of water courses. It was developed by Petersen (1990) and re-

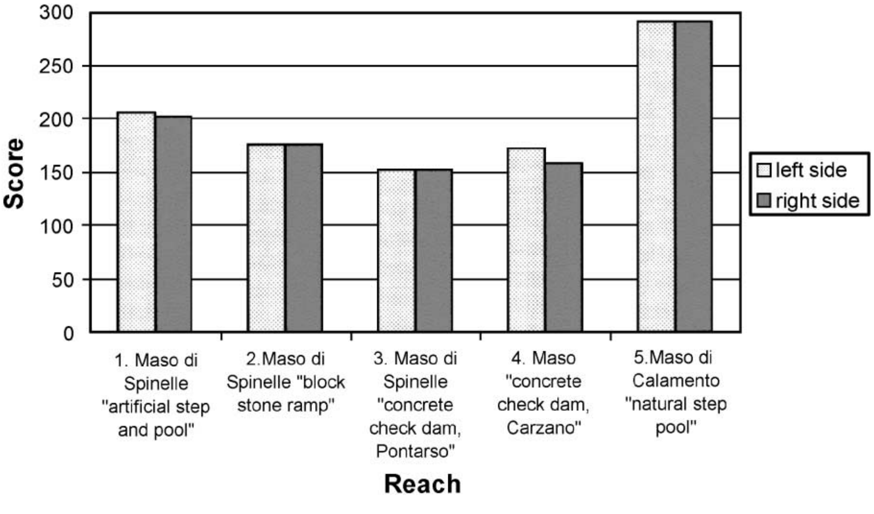

Fig. 8. Total result of the ecological evaluation of the various structures.

vised and adapted to the North Italian mountain environment by Siligardi (1997). The survey shows clear differences in the ecological assessment of the varieties of protective structures building on the torrent Maso (Fig. 8). Section 1 (Maso di Spinelle with artificial boulder step and pool) reached a total of 203 or 207 points and, therefore, is just within class 2 quality; Section 2 (Maso di Spinelle block stone ramp) reach 176 points and class 3 quality although there is the possibility that it will improve when the vegetation of the bank has grown again along the ramp; both the sections with the concrete check dams (Section 3 of the Maso di Spinelle and Section 4 of the Maso) also reach class 3 quality; a more natural sequence of the Maso di Calamento (Section 5) was investigated for comparison. This natural step–pool sequence reach a score of 290 points and, therefore, reached class 1 quality. Altogether, the ‘‘boulder step and pool structure’’ (Section 1) prove to be the best ecological and environmental variation. Where channel stabilization structures are required, a stepped series of low boulder step–pools structures is preferable to a single large check dam. Multiple low structure designing according to morphologic principles provide, as reported by Haltiner et al. (1996), improved habitat for macroinvertebrates, fish passage and also passage by other wildlife which often use the channel as transportation corridors between regional habitat areas.

6. Conclusions

Progress of construction technology in hydraulic stream control sites has given a considerable impetus to the creation of boulder check dams. These have been built according to several design and construction procedures. This category of works is suitable for channel management in accordance with the usual criteria of step–pool protection, offering greater naturalness together with structural intervention. The different designs for boulder check dams also allow the planner to choose the kind of work appropriate to the degree of protection needed. Nevertheless, geomorphologic criteria should also be considered, so that use of boulder check dams, as an alternative to the use of more traditional protection works and ones with a greater impact on the course of water, does not merely become of aesthetic and landscape benefit. Only by identifying the physiographical units making up the stream, analysing channel roughness, bed grain size distribution and longitudinal profile, taking into consideration geological conditioning, and linking channel and catchment sediment system can one deduce the informative elements on which to apply principles of engineering geomorphology for managing channel erosion and bedload. Further efforts have to be made to understand fully the morphological individuality of streams, even in situations that are not easily classified, and to better predict channel dynamism. This will lead to increasingly functional interventions that are more in keeping with channel stability.

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