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Original Citation:

Case study: efficiency of slit-check dams in the mountain region of Versilia basin / M. Catella; E. Paris; L. Solari. - In: JOURNAL OF HYDRAULIC ENGINEERING. - ISSN 0733-9429. - STAMPA. - 131:(2005), pp. 145-152. [10.1061/(ASCE)0733-9429(2005)131:3(145)]

Published version:

DOI: 10.1061/(ASCE)0733-9429(2005)131:3(145)

Case Study: Efficiency of Slit-Check Dams in the Mountain Region of Versilia Basin

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Abstract: Slit-check dams are widely employed in mountain river control. However an analysis of their performance in the field is still lacking. In the present work a field verification to evaluate the interaction between solid discharge regime and four slit-check dams built in two subcatchments of the Versilia River in Tuscany, Italy is presented. The analysis is based on a relatively detailed field knowledge consisting of hydrological, topographical, and sedimentological data, together with a recent model proposed by Armanini and Larcher. Slit-check dam efficiency is analyzed in terms of deposit formation during major floods and its influence on long-term sediment transport regime. Results suggest that the design efficiency is affected by the high sediment trapping capacity associated with the relatively minor floods. A comparison between the deposit geometry predicted by the theory and the field measurements gathered during a systematic monitoring activity shows good agreement.

DOI: 10.1061/(ASCE)0733-9429(2005)131:3(145)

CE Database subject headings: Dams; Sediment control; Monitoring; Field investigations; Validation; Mountain streams; Italy.

Introduction

In recent years open-check dams are increasingly used to control sediment transport in mountain rivers, in order to control sediment transport associated with debris flow and heavy bed load during major floods (Üblagger 1972; Kettl 1973, 1984; Chanson 2002; Wu and Chang 2002).

The open-check dam restoration technique has been developed since the second half of the 20th century. A great variety of slightly different devices has been designed and tested on empirically based rules (Cola 1970; Mizuyama 1984; Zollinger 1984; Fiebiger 1997). According to Armanini and Benedetti (1996), two main categories can be recognized: beam and slit-check dams. In the former, sediment transport modulation is mainly due to a mechanical selection; in the latter it is due to hydraulic sorting.

The slit-check dams have shown to be more efficient than beam dams, characterized by less probability of clogging and a better sediment transport lamination (Cola 1970; Kettl 1984; Ferro and Ferreri 1988).

When major floods occur, slit-check dams should modulate sediment transport by reducing bed shear stress upstream through a backwater effect. Sediment load is then reduced in intensity, sorted by deposition of the coarsest fraction, while the finest one is transported through the slit.

When minor floods occur, slit-check dams should not interfere significantly with sediment transport in order to preserve the capturing volume upstream. In this condition the finer fraction of deposits can be eroded if the upstream flow has a nonsaturated transport capacity. This phenomenon leads to a self-cleaning and deposit armoring processes.

Hence, a well designed slit-check dam should on one hand maximize the trap selectivity with regards to the coarsest fraction of the sediment transport during the peak of the major floods, and on the other hand, minimize the effects on the long-term downstream morphological evolution.

Recent theoretical and laboratory observations (Armanini and Larcher 2001; Busnelli et al. 2001) clarify some aspects related to the deposit formation upstream of slit-check dams occurring during a flood event.

However, as pointed out by Okubo et al. (1997) and Armanini and Larcher (2001), many aspects of slit-check dam performance in the field still remain unclear because of the relatively short operation history compared to the return time of the design flood event.

Despite the great role played by these structures in preventing sediment related disasters, no field data are available to evaluate the behavior of slit-check dams in a real condition.

In this paper an analysis of the efficiency of four slit-check dams in the mountain region of Versilia (Tuscany, Italy) is presented using field data collected through a monitoring activity lasting 2 years and compared to results from a theoretical model.

Study Area

The mountain area of the Versilia basin (Fig. 1) was struck by an extraordinarily violent event on June 19, 1996, causing the loss of human lives and the destruction of wide urbanized areas. The event was characterized by the remarkable intensity of the flow discharge, having an estimated return period on the order of 200–300 years. A huge amount of about 2,300,000 m^3 of solid and floating material coming from a catchment area of about

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Note. Discussion open until August 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on April 15, 2003; approved on August 19, 2004. This paper is part of the ***Journal of Hydraulic Engineering***, Vol. 131, No. 3, March 1, 2005. ©ASCE, ISSN 0733-9429/2005/3-145–152/$25.00.

Fig. 1. Versilia river basin and streams analyzed: (a) Canale delle Mulina; (b) Fosso di Pomezzana; (c) Canale del Giardino; and (d) Canale del Bosco. Position of slit-check dams is identified by black dots (right map).

30 km^2 produced remarkable morphological alterations of the catchment basin.

The Versilia basin was then subjected to wide restoration work. In particular, a series of slit-check dams have been built in the upper region of the basin in order to control sediment transport dynamics.

The four silt-check dams investigated here are shown in Fig. 2. Slit-check dams *a* and *b* are located in the basin of the Canale delle Mulina (10.7 km^2 wide), and slit-check dams *c* and *d* are located in the basin of the Canale del Giardino (16.3 km^2 wide). The main characteristics of subcatchment basins, channel reaches geometry, and design parameters of the slit-check dams are listed in Tables 1 and 2.

The slit-check dams have similar storage capacities ranging from 2000 to 5000 m^3 while the return period of design flood ranges from 20 to 100 years.

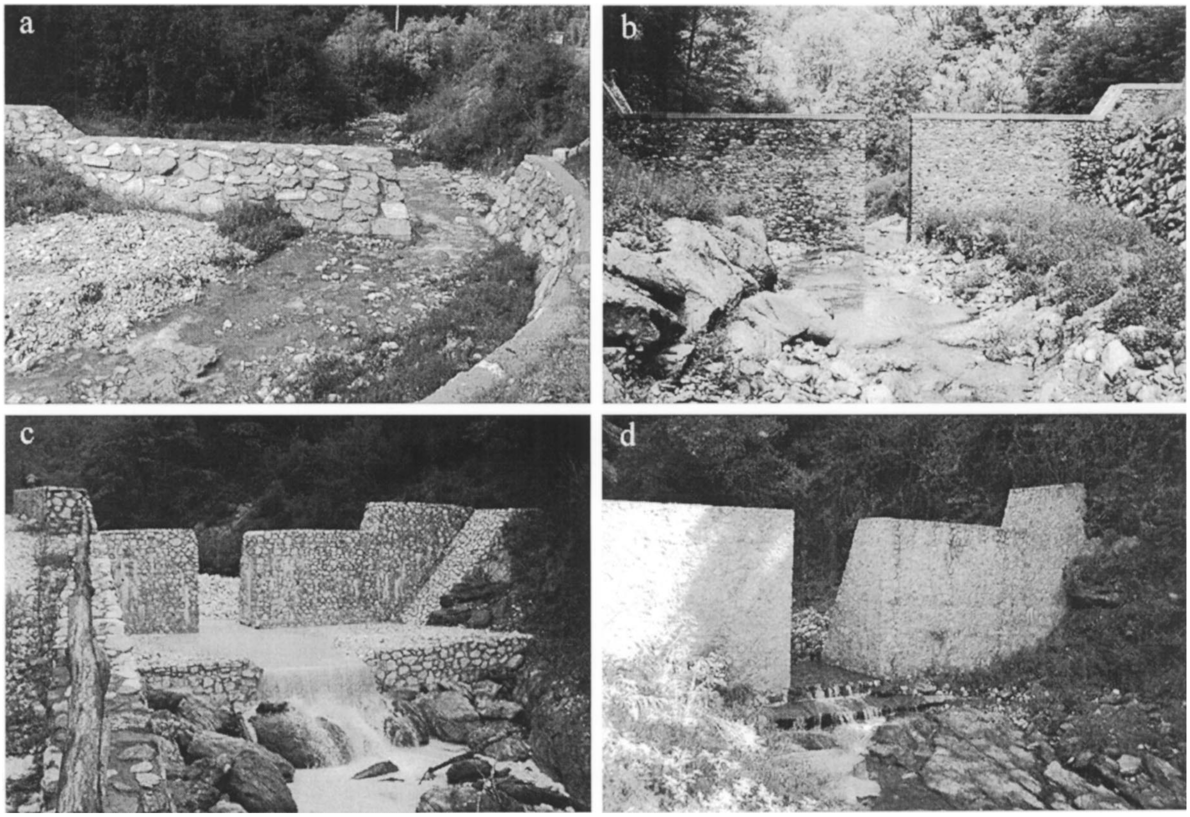

Fig. 2. Slit-check dams analyzed: (a) Canale delle Mulina; (b) Fosso di Pomezzana; (c) Canale del Giardino; and (d) Canale del Bosco (Stazzema LU-2001)

Table 1. Main Characteristics of: Subcatchment Basin (Surface A; Mean Elevation Level of Catchment Basin H_m; Main Reach Length L); Stream Reach Immediately Upstream Slit-Check Dam (Average Slope S; Average Width B; Median Diameter of Surface Bed Material D_{50})

Stream	A (km^2)	H_m (m swl)	L (m)	S (%)	B (m)	D_{50} (mm)
Canale delle Mulina	10.7	619.0	4,108	3.8	10.0	64.0
Fosso di Pomezzana	5.0	668.1	2,132	5.6	7.4	125.0
Canale del Giardino	16.3	682.6	2,715	4.0	9.0	67.0
Canale del Bosco	7.9	785.3	3,889	7.0	7.5	71.0

Table 2. Main Characteristics of: Geometry of Slit (Elevation of Base of Slit H_b; Width b; Height h); Planning Parameters Relative to Dam (Design Discharge Q_{proj} and Relative Return Time Tr; Maximum Storage Capacity Volume $V_{\max}$, Estimated as for Water Tanks) and Catchment Area of Each Slit Check Dam A_s

Slit-check dam	H_b (m swl)	b (m)	h (m)	Q_{proj} (m^3/s)	Tr (years)	$V_{\max}$ (m^3)	A_s (km^2)
a	179.2	5.50	5.00	70	20	5,160	10.4
b	301.0	2.20	6.80	63	100	3,745	3.0
c	209.3	3.00	5.00	88	100	2,086	5.7
d	164.5	3.80	6.50	50	20	3,725	7.4

Framework of Analysis

The model by Armanini and Larcher (2001), hereafter cited as the AL model, has been proposed to estimate theoretically the sediment trapped volume associated with any flood event, through the characterization of the deposit geometry, i.e., the slope i_θ, the downstream step height ΔZ_v, and the length L_{dep} (Fig. 3). For a given liquid and solid discharge in uniform and steady flow, the slope i_θ of deposit upstream of the slit-check dam at the equilibrium condition is estimated by combining the Meyer-Peter and Müller and the Chèzy equations. The step height ΔZ_v can be estimated using two different criteria depending on the value assumed by the critical flow velocity in the slit section v_{fc} compared to the transport velocity on the deposit u_θ

$$u_\theta = \chi \cdot \left[\theta_{\text{cr}} \Delta D_{50} + \left(\frac{1}{8} \cdot \frac{Q_s \Delta}{B\sqrt{g}}\right)^{2/3}\right]^{1/2} \tag{1}$$

if $v_{fc} < u_\theta$ (wide slit)

$$\frac{\Delta Z_v}{h_\theta} = \frac{R}{\sqrt{\frac{\theta_{\text{cr}}}{\theta} \cdot (1 - R^{2/3}) + R^{2/3}}} - 1 + (1 - R^{2/3}) \cdot \frac{\mathsf{F}_\theta^2}{2} \cdot \left(\frac{\theta_{\text{cr}}}{\theta} - 1\right) \tag{2}$$

if $v_{fc} > u_\theta$ (narrow slit)

$$\frac{\Delta Z_v}{h_\theta} = \frac{3}{2} \cdot (\mathsf{F}_\theta R)^{2/3} - 1 - \frac{\mathsf{F}_\theta^2}{2} \tag{3}$$

where χ=Chézy friction coefficient; Δ=submerged material relative density; D_{50}=median diameter of surface bed material; Q_s=bed–load discharge; B=channel width; h_θ=water depth of the current in uniform condition above the deposit; R=ratio between the channel width upstream of slit-check dam and the slit width; θ_{cr}=threshold value of Shields parameter; θ=Shields mobility parameter on the deposit; and $\mathsf{F}_\theta = v_\theta / \sqrt{g h_\theta}$=Froude number on the deposit.

In the present analysis the deposit length L_{dep} is assumed to be confined in the region upstream of the slit-check dam affected by backwater. Finally, the following dimensionless parameter M is introduced to characterize the slit-check dam behavior:

$$M = \frac{\int_{t_0}^{t_p} Q_s(t)dt}{V_p} \tag{4}$$

where t_0 and t_p denote the instants of sediment transport beginning and the occurrence of solid peak discharge, respectively; and V_p=theoretical deposit volume at peak condition. According to the value of M, two opposite scenarios can be drawn: when $M \gg 1$, slit-check dams display a moderate lamination of the solid discharge and a great self-cleaning capacity; conversely, when $M \ll 1$, slit-check dams are characterized by a high interception capacity and a poor self-cleaning capacity.

The AL model has been extended to investigate slit-check dams operation under real conditions. To this purpose, a calculation method (Catella 2001) has been developed to evaluate deposit geometry in a natural channel by means of an iterative procedure based on a one-dimensional flow model coupled to a sediment transport equation. Computations are carried out under unsteady flow conditions simulated as a sequence of equilibrium steady states using a stepped hydrograph as shown in Fig. 4.

Time-step length Δt is chosen to take into account two opposite conditions: on the one hand it should be small enough to describe adequately the hydrograph and on the other hand it

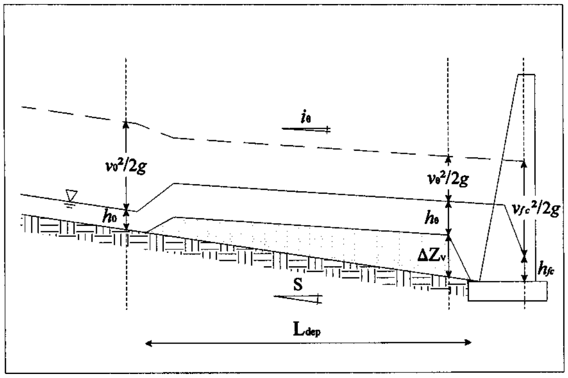

Fig. 3. Sketch of equilibrium deposit upstream slit-check dam

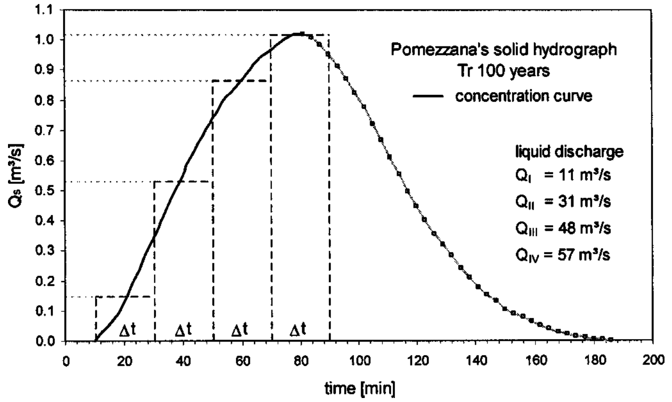

Fig. 4. Pomezzana solid hydrograph for return time of 100 years

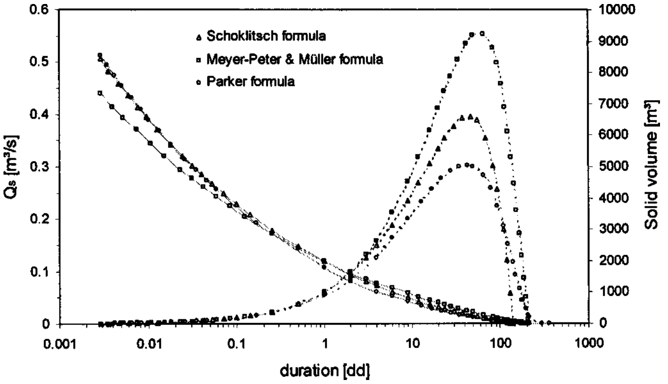

Fig. 5. Dimensionless parameter M for four slit-check dams analyzed as function of flood event return time

should be great enough compared to the morphological time scale t_{eq} (Table 3).

The extended AL model has been applied to predict deposit geometry and trap efficiency of the four slit-check dams under investigation.

First, major and minor floods concepts have been defined. The major floods regime is assumed to be characterized by events having a return period greater than 2 years, and the minor floods regime is assumed to be synthetically represented by the dominant discharge. In particular, by employing standard hydrologic methodologies, flood hydrographs for events with return periods of 2, 20, 50, and 100 years (major floods) and the dominant discharges (minor floods) have been determined.

The remaining input data are: bed material grain size distribution, stream bed, and slit-check dam geometry.

Solid discharge has been evaluated employing three different formulas: Meyer-Peter and Müller (1948), Schoklitsch (1962), and Parker (1990). As discrepancies among the three formulas are roughly negligible (Fig. 5), reference has been made to the Meyer-Peter and Müller formula.

Behavior of Slit-Check Dam

Interaction with Major Floods

The predicted characteristics of the equilibrium deposits under the major floods are reported in Table 3, while the values of parameter M are listed in Table 4.

Note that all the investigated slit-check dams are characterized by a narrow slit since critical flow conditions occur here. As expected, the average slope of deposit is smaller than the original bed slope (compare S in Table 1 with $i_{\theta \text{med}}$ in Table 3).

For each slit-check dam the dimensionless parameter M appears to be of the same order of magnitude for different return

Table 3. Main Characteristics of Theoretical Deposit Upstream of Slit-Check Dams after Occurrence of Flood Events Characterized by Various Return Time

Slit-check dam	Q (m³/s)	Tr (years)	d (min)	$i_{\theta\ \text{med}}$ (%)	ΔZ_v (m)	L_{dep} (m)	V_{dep} (m³)	t_{eq} (min)
a	48	2	78	0.9	0.94	30.2	123	2.20
	70	proj.	78	0.8	1.29	36.2	250	3.18
	103	50	81	0.7	1.82	52.1	523	5.10
	119	100	81	0.7	2.07	56.1	689	6.62
b	24	2	81	4.3	2.63	11.0	345	15.94
	49	50	81	2.6	4.49	30.8	1422	44.74
	57	100	81	2.8	4.96	34.7	1860	30.49
	63	proj.	81	3.0	5.30	38.6	2265	29.21
c	28	2	75	1.0	2.19	27.0	1073	46.68
	50	20	81	0.8	3.22	30.5	1732	40.97
d	37	2	81	1.2	1.51	19.6	175	2.58
	50	proj.	81	1.2	1.93	23.5	282	3.15
	81	50	90	1.5	3.50	31.3	831	5.90
	90	100	90	1.4	3.78	35.2	1012	6.61

Note: Q=liquid discharge; Tr=relative return time; d=time interval between the beginning and the peak of the sediment transport; $i_{\theta\ \text{med}}$=mean slope of the deposit; ΔZ_v=height of the downstream step of the deposit; L_{dep}=length of the deposit including the upstream step; V_{dep}=volume of the deposit; and $t_{\text{eq}}=V_{\text{dep}}/Q_s$, morphological time scale.

Table 4. Main Quantities Defining Operation and Efficiency of Each Check Dam

Slit-check dam	Tr (years)	V_s (m³)	V_{peak} (m³)	V_{dep} (m³)	M
a	2	4,956	2,746	123	22.2
	projected	5,416	2,883	250	11.5
	50	10,800	5,755	528	10.9
	100	11,986	6,097	689	8.8
b	2	1,469	767	345	2.2
	50	2,394	1,158	1,422	0.8
	100	3,543	2,628	1,860	1.4
	projected	4,488	2,232	250	1.0
c	2	1,250	597	1,073	0.6
	20	2,388	1,130	1,732	0.7
	Tr>20 years have not taken into account due to physical constraint				
d	2	3,287	1,707	175	9.7
	projected	4,579	2,303	282	8.2
	50	8,309	3,982	831	4.8
	100	7,557	4,291	1,012	4.2

Note: Tr=return time of liquid discharge; V_s=solid volume transported during the whole flow hydrograph; V_{peak}=solid volume transported during the rising part of the hydrograph; V_{dep}=volume of deposit; and M=dimensionless parameter defined in Eq. (4).

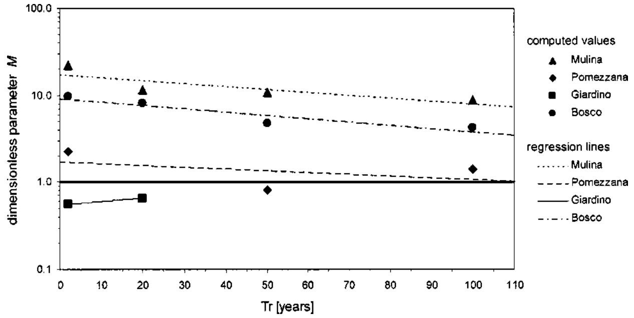

Fig. 6. Solid discharge Q_s (continuous lines) and contribution to mean annual solid volume (dashed lines) as function of duration of flood event for reach upstream Canale delle Mulina slit-check dam, as from three bed-load transport formulas adopted

periods (Fig. 6). However, a great difference among values of M for the four slit-check dams appears, suggesting a broad range of behaviors as discussed below.

Slit-check dam *a* is characterized by $M \gg 1$: moderate lamination of the bed load and high self-cleaning capacity. The slit-check dam *d* exhibits an analogous behavior (being $M > 1$), even if the trapping capacity is a little higher than the previous one. The slit-check dam *c* is characterized by $M < 1$: high interception capacity and limited attitude to release the stored sediments. The latter behavior may trigger an erosion process in the downstream reaches. Finally, the slit-check dam *b*, characterized by $M \cong 1$, displays intermediate behavior.

Interaction with Minor Floods

The storage capacity as well as the efficiency decreases during a slit-check dam's lifetime. A maintenance plan is then needed in order to preserve an adequate capturing volume when floods occur. In order to formulate any maintenance plan the influence of the slit-check dams on the solid discharge regime must be evaluated, even in relation to the minor but more frequent flood events.

In order to investigate this matter, the interaction of the slit-check dams with the dominant discharge has been evaluated. Such discharge is assumed to be significant in determining river morphodynamic evolution (Wolman and Miller 1960). Among the several criteria proposed to estimate dominant discharge, the method by Biedenharn and Thorne (1994) has been used. According to this method the dominant discharge provides the maximum contribution to the mean annual solid discharge, being associated with the mode of the curve duration–contribution to the mean annual bed load (see Fig. 5).

The values of the dominant discharge and their relative duration for the reaches upstream of the slit-check dams are reported in Table 5. It appears that, due to different characteristics among the reaches investigated here, the dominant discharge displays a relative broad variation in terms of duration, ranging from 45 to 103 days per year. Such features indicate dominant discharge as a "frequent" event.

Table 5. Value and Duration of Dominant Discharge in Reaches Immediately Upstream Slit-Check Dams Employing Three Different Bed-Load Transport Formulas

	Schoklitsch		Meyer-Peter Müller		Parker	
Slit-check dam	Q_{dom} (m^3/s)	Duration (dd)	Q_{dom} (m^3/s)	Duration (dd)	Q_{dom} (m^3/s)	Duration (dd)
a	9.5	45	7.7	65	9.8	42
b	5.3	35	3.2	85	4.2	55
c	5.7	50	5.4	55	7.4	30
d	4.3	120	4.6	110	5.7	80

Results obtained by the extended AL model (Table 6) lead to the following considerations. The volume stored at equilibrium conditions in the slit-check dam *a* is much lower than the volume V_{peak}, suggesting that the major part of the volume mobilized by the dominant discharge can be transported through the slit, thus still contributing to the downstream bed morphodynamics.

The opposite behavior is displayed by the slit-check dam *c*. In this case the equilibrium storage volume is much greater than V_{peak}. The strong interaction with dominant discharge implies a frequent deposition phenomena, thus leading to a more difficult planning and management of the maintenance operations.

An intermediate behavior is shown by slit-check dams *b* and *d*.

Comparison of Model Results with Field Evidence

In order to investigate the performance of the slit-check dams and their influence on the evolution of the river dynamics, a systematic monitoring activity was carried out since September 2000 in the Versilia river basin.

Cross sections, sediment characteristics, and deposit geometries have been surveyed in the reaches of interest before and after the flood event of November 6, 2000. The return period of this event for different subcatchments has been derived by a statistical analysis of historical data available from the raingage stations of Pomezzana and Retignano, Italy (Fig. 1).

Results show that the return time ranges between 2 and 4 years for the Canale delle Mulina subcatchment and between 10 and 20 years for the Canale del Giardino subcatchment.

Field data concerning deposit geometry associated with this event is reported in Table 7.

A comparison between theoretical results and field data has been made in terms of deposit step height ΔZ_v as shown in Figs. 7 and 8. Agreement between predicted and observed data appears

Table 6. Main Theoretical Characteristics of Deposit Upstream of Slit-Check Dams after Occurrence of Dominant Discharge (Duration: Duration of Dominant Discharge)

Slit-check dam	Q (m^3/s)	Duration (dd)	d (min)	$i_{\theta\ \mathrm{med}}$ (%)	ΔZ_v (m)	L_{dep} (m)	V_{dep} (m^3)	t_{eq} (min)	V_s (m^3)	V_{peak} (m^3)	M
a	9	51	75	1.5	0.21	6.0	6	1.12	324	102	17
b	4	58	78	9.9	0.74	5.5	51	40.16	91	31	0.6
c	6	45	70	6.0	0.74	11.2	235	12.41	83	31	0.1
d	5	103	75	2.6	0.38	5.9	13	2.09	43	17	1.3

Table 7. Deposit Upstream of Slit-Check Dams as from Measurements on November 8, 2000, and Return Period of Flood Event of November 6 2000. Note that Field Observations Do Not Reveal Any Step Upstream Deposits

Slit-check dam	ΔZ_v (m)	L_{dep} (m)	V_{dep} (m^3)	Tr (years)
a	0.65	40	123	3
b	2.10	23	241	4
c	2.90	23	840	16
d	1.60	16	165	16

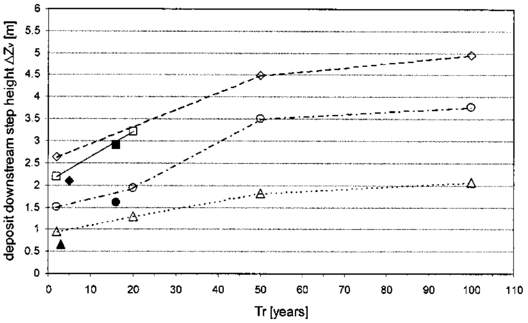

Fig. 7. Downstream step height ΔZ_v of deposit as function of flood event return time

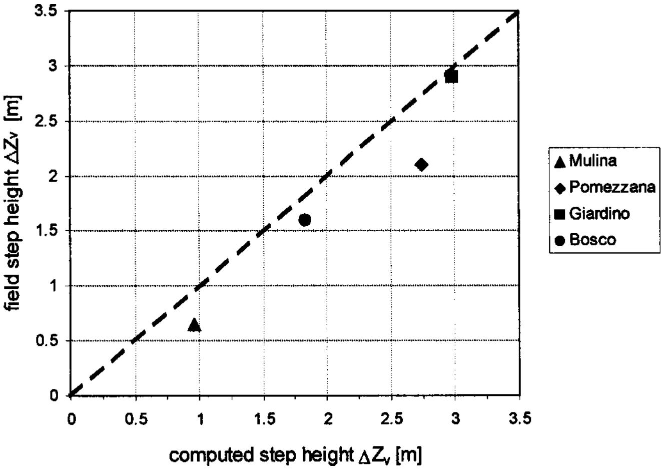

Fig. 8. Comparison between estimated and measured deposit step height ΔZ_v

very good both in respect of the return period (Fig. 7) and in terms of absolute values (Fig. 8).

Note that the theory tends to slightly overestimate the deposit height, probably due to the fact that present analysis does not take into account the erosion process of the deposit occurring during the falling part of the hydrograph.

The photographs of Fig. 9 have been taken upstream of the slit-check dams *a* and *c* before and after the flood event. It appears that observed deposit dynamics confirm the predicted behavior expressed in terms of the parameter *M*.

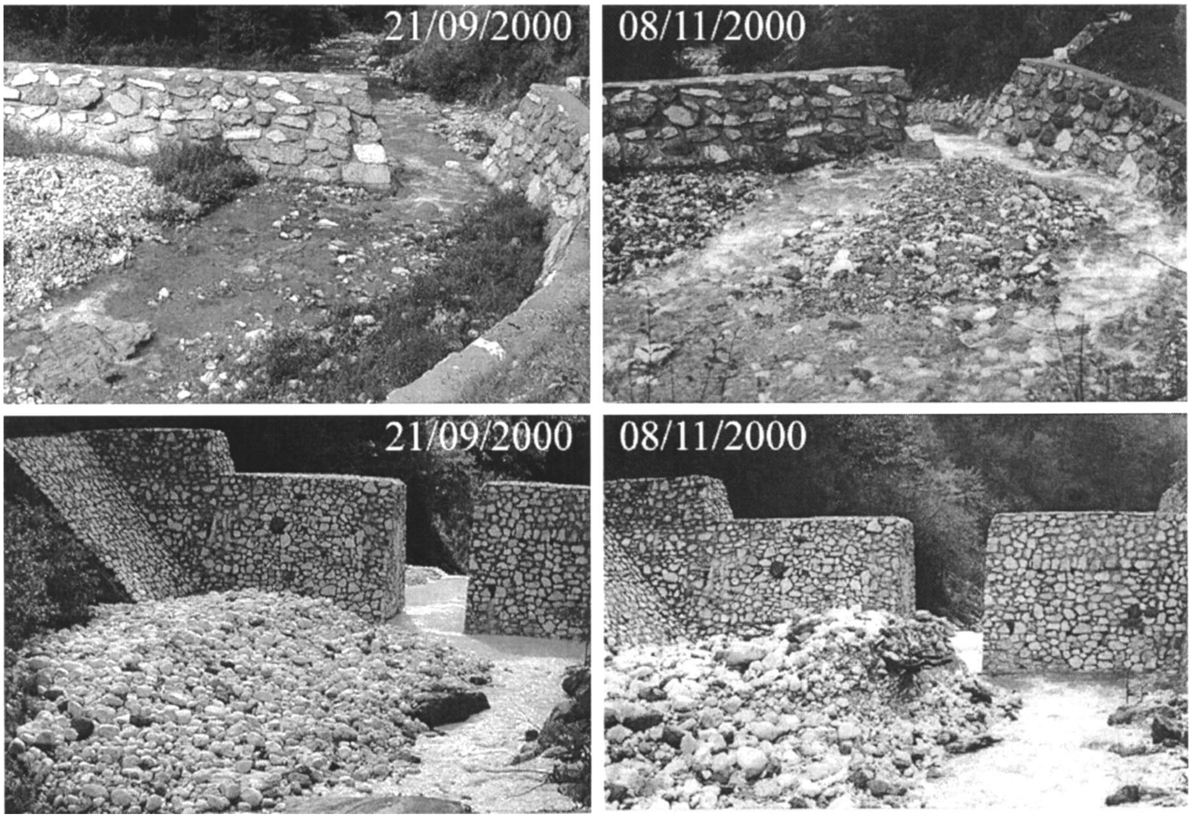

Fig. 9. Comparison between volumes stored upstream of check dams realized in Canale delle Mulina and in Canale del Giardino before and after November 6th 2000 flood event

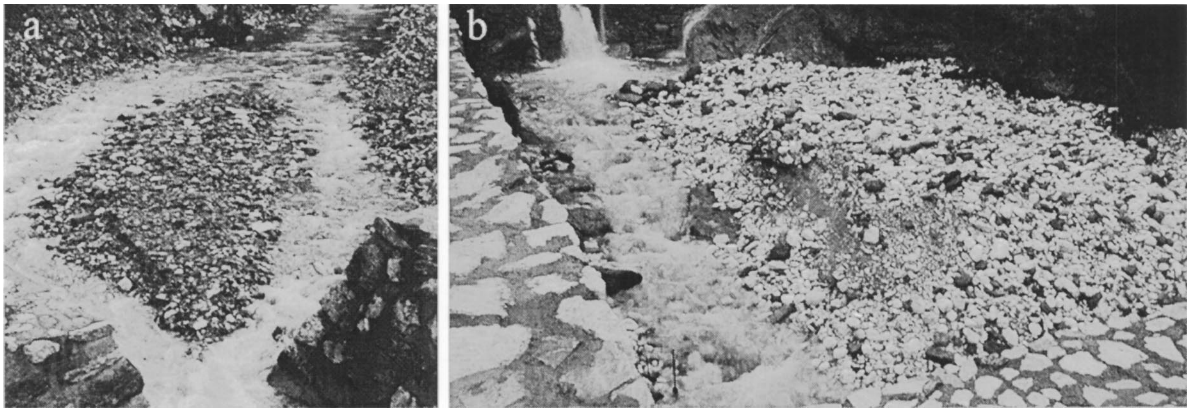

Fig. 10. During minor flood events water flows in minor lateral channels carved inside main deposit: (a) Canale delle Mulina and (b) Canale del Giardino

Finally, field inspections revealed that during minor floods, water flows in smaller channels carved inside the existing deposit (Fig. 10). In such channels the flow is generally supercritical and the transport capacity is sufficiently high to prevent the deposition of the material coming from upstream.

Conclusions

In recent years, sediment transport control in mountain regions is increasingly achieved by slit-check dams. Nevertheless, in spite of the availability of several theoretical and laboratory investigations, many aspects of slit-check dam performance in the field still remain to be verified.

In the present paper the interaction between four slit-check dams in the Versilia river basin (center of Italy) and sediment transport dynamics has been analyzed by means of numerical and field investigations with the aim of predicting the slit-check dams efficiency under different floods and of planning the maintenance strategies in order to preserve a given trap efficiency.

The model by Armanini and Larcher (2001) has been extended to represent the deposit dynamics under unsteady flow conditions in a natural channel and then tested in field conditions. Input data, including cross sections, sediment characteristics, and slit-check dam geometries, have been collected by surveying and field measurements. Deposit geometrical characteristics have been collected during significant flood events that occurred in the period from September 2000 to December 2002.

Results show that slit-check dams display a broad range of behaviors. Two slit-check dams present a moderate lamination of bed load peak and a high self-cleaning capacity that minimizes maintenance operations and the erosion processes triggered in the downstream river reaches; one slit-check dam exhibits an opposite behavior, thus inducing possible relevant maintenance problems, and finally the remaining slit-check dam shows an intermediate behavior performing an efficient peak sediment transport reduction.

Comparison of model results with field measurements related to the November 2000 flood event seems to confirm the validity of the proposed model, showing in particular the significance of the dimensionless parameter M as a reliable indicator of the slit-check dam behavior in terms of trap efficiency and self-cleaning capacity.

Acknowledgment

This research was funded by the Istituto Nazionale per la Ricerca Scientifica e Tecnologica sulla Montagna (INRM) in the framework of the research program "Dinamica e regimazione del trasporto solido in relazione della difesa del territorio montano" 2001.

Notation

The following symbols are used in this paper:

A = basin area;
A_s = catchment area of each slit check dam;
B = average width of stream bed;
b = width of the slit of check dam;
D_{50} = median diameter of surface bed material;
d = time interval between beginning of sediment transport and instant in which solid discharge reaches peak value;
F_θ = Froude number relative to current in uniform condition above deposit;
H_b = elevation of base of check dam slit;
H_m = mean elevation level of catchment basin;
h = height of check dam slit;
h_θ = water depth relative to current in uniform condition above deposit;
i_θ = slope of deposit upstream dam;
$i_{\theta\mathrm{med}}$ = mean slope of deposit;
L = main reach length;
L_{dep} = length of deposit;
M = dimensionless parameter defined in Eq. (4);
Q = liquid discharge;
Q_{dom} = dominant discharge;
Q_{proj} = design discharge of slit-check dam;
Q_s = bed-load discharge;
R = contraction ratio;
S = average bed slope of primary stream bed;
Tr = return time;
t_{eq} = V_{dep}/Q_s, morphological time scale;
t_p = instant when peak solid discharge occurs;
t_0 = instant when sediment transport begins;
u_θ = transport velocity on deposit defined in Eq. (1);

V_{dep} = volume of deposit;
$V_{\max}$ = maximum storage capacity volume of slit-check dam estimated as for water tanks;
V_p = theoretical volume stored by check dam evaluated for peak condition;
V_{peak} = solid volume transported during rising part of hydrograph;
V_s = solid volume transported during whole flow hydrograph;
v_{fc} = critical velocity in narrowing of check dam;
v_θ = uniform flow velocity on deposit;
Δ = $(\rho_s-\rho)/\rho$relative density of submerged material;
Δt = duration of time step;
ΔZ_v = height of downstream step of deposit;
θ = Shields mobility parameter;
θ_{cr} = threshold value of Shields parameter; and
χ = Chézy friction coefficient.

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