Evaluation of sediment yield from valley slopes: a case study

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Abstract

Hydro-geological hazards in alpine areas is a really common problem. Many calamitous phenomena (such as debris flows, landslides, and others) are related to the sediment yield from the slopes of the valleys. Sediment yields are far from being fully understood and predictable, due to a lack of knowledge of the physical mechanisms underlying these processes and to the variability of the peculiar geomorphologic characteristics of river basins. Key unknowns are the medium- and long-term average sediment production, the recharge time of the sediment sources (and consequently the frequency of the yields), the triggering factors and the thresholds for activation. The manuscript documents the results of the estimation of sediment production for the basin of the Tartano valley in northern Italy. The basin is characterized by a significant presence of weak rocks (cataclastic, mylonitic), that makes considerable amounts of loose sediments available. In this work, semi-quantitative models were applied to evaluate the basin-scale, yearly sediment yield. Estimates sediment volumes were compared to records of sediment volumes extracted from an artificial reservoir located at the downstream section of the catchments. In addition, the spatial distribution of the sediment instability level was obtained, highlighting a significant heterogeneity of the river basin. Therefore, the relevance of the basin-scale modelling of sediment yields for off-site and on-site processes was discussed. The dependency of the sediment yield regime on the spatial and temporal scale supporting the evaluations was analyzed and discussed.

Keywords: river basin, sediment yield, scale-based evaluation, soil erosion.

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1 Introduction

Sediment transport is a key aspect of the life of river basins. Sediments are eroded from the valley slopes by exogenous and endogenous agents. Then, as nicely pointed out by Phillips [1], the common sense is that any sediment particle may be deposited on the same slope from which it has been eroded, or it can be involved in landslides, debris flows, or also reach a river stream to be conveyed downstream by the flowing water. Proper evaluation of the sediment yield is important from a technical point of view, for example to evaluate the tendency of the basin system to some undesirable conditions such as riverbed aggradation, reservoir sedimentation, as well as debris flows and landslides.

The sediment yield in a river basin results from the composition of a number of effects. The conceptual picture proposed by De Vente and Poesen [2] involves several types of sediments source (splash erosion, sheet erosion, rill erosion, gully erosion, bank erosion and mass movements) and some sink terms (depression, parcel, footslope and floodplain storage) whose combination determines the total sediment yield at a certain downstream section. According to Wasson [3], the separate modelling of all the processes for a final composition of the effects is hardly possible. On the contrary, a sediment yield modelling at a large scale is more feasible and, therefore, most desirable in order to obtain practical results.

The models for the estimation of the sediment yield fall within few categories, namely: the physically based models, the conceptual models, the empirical models and the semi-quantitative models (see, for example, the review by De Vente and Poesen [2]). In principle, the physically based models enable quantitative evaluations to be made, even though they require extensive data for a proper application. The other models are progressively simpler to use and provide semi-quantitative results. In addition, other models can be used for a relative evaluation of the tendency of the basin to instability, without a numerical output for the sediment productivity.

A crucial aspect of the evaluation of the sediment yield is the scale with reference to which the model is made. The reviews of De Vente and Poesen [2] and Wasson [3] span several orders of scales, from the small basin to the global scale. A significant relationship emerges between the spatial scale of analysis and the type of model that is most suitable: physically based models can be used for small parts of the basins, in which only few source or sink terms are present, and then that a hard composition is not required; semi-quantitative models can be used for basin-scale evaluations; finally, if a regional or global scale is considered, a sort of self-similar behaviour emerges and the sediment yield can be obtained by some universal-like equations depending only on the basin area.

This manuscript presents an analysis of the sediment yield for the Tartano basin, which is located in the Italian Alps. Given the above considerations, the evaluation of the sediment yield will be mostly conducted at a basin scale. The suitability of the obtained results for analysis of off-site and on-site processes is discussed. An evaluation of the response of yield estimation to the spatial and temporal scale of modelling is presented at the end of the manuscript.

2 The case study: description of the Tartano basin

The present study refers to the Tartano Valley, located in Northern Italy. The Tartano basin (which is 49 km^2 wide) is part of the Adda catchments; furthermore, the Tartano flows into the Adda along the upper course of the latter (that is, upstream of the Adda flowing into the Como lake). Elevation in the Tartano catchments ranges from 950 to 2250 m above sea level. The climate is defined as Alpine continental. Meteorological records show that the local temperature is subjected to strong altitudinal gradients in temperature and precipitation. The strong rainfall, low temperature, snow precipitation and high annual and day-time thermal range favour the activity of the morphogenetic processes related to erosion. Therefore, soil erosion is pronounced in the Tartano basin, as in all the upland Adda catchments.

An aerial picture of the basin is shown in Figure 1, together with the catchments boundary and the main hydrographic network. The Tartano River originates from two main tributaries, namely the Val Lunga and the Val Corta. The downstream section of the basin in Figure 1 is not placed where the Tartano merges with the Adda but at the Campo dam (located a few km upstream of the confluence), because the annual data on the reservoir silting at this dam shall be used for comparison with the estimations of the sediment yields described in the following.

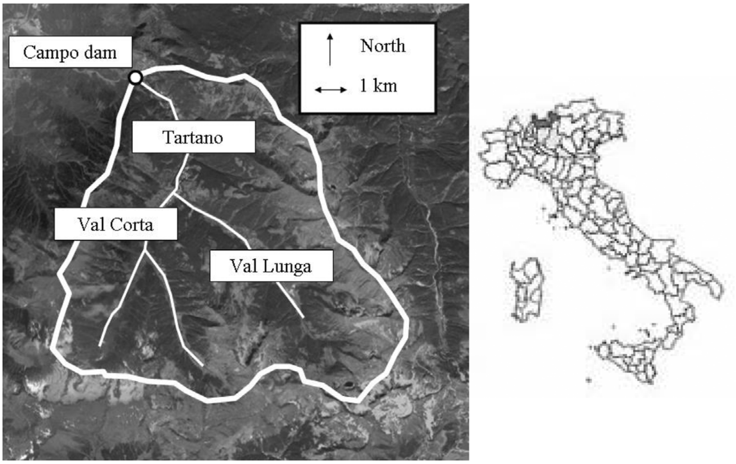

Figure 1: Aerial map of the river basin with indication of the main streams.

The vegetation of the basin is dominated by a forest of mountain pine (70 %). Different sediment sources occur in this valley: alluvial and colluvial storage, glacial deposit and colluvial breccia formed next to faults. Thus, this hydrographic basin is an effective prototypal case for sediment yield estimation. Structurally, the area under investigation belongs to the crystalline base of the Southern Alps, where the Gneiss of Morbegno emerges. The rocky substrate involves two systems of faults: NE-SW and NW-SE trending (Figure 2).

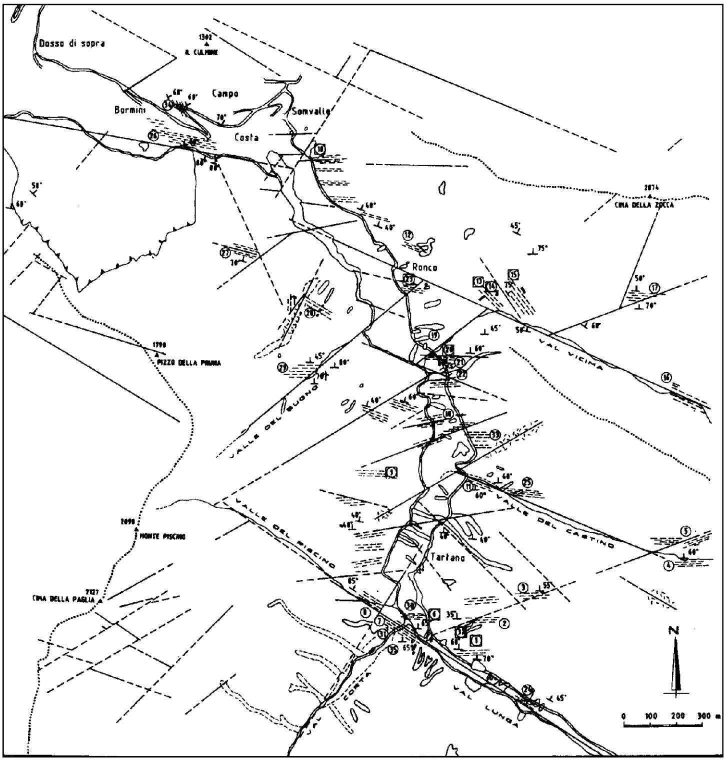

Figure 2: Fault lineaments in Tartano Valley.

Knowledge of the fault network is relevant for erosion processes: the colluvial breccias is due to the presence of weak rocks (band of fault rocks) surrounding fault lineaments. A great accumulation of material can be observed along faults and, during strong meteorological events, this mass can move rapidly along the slopes, feeding the solid transport of Tartano River. Erosion process and consequently sediment yield are very common in these fault rock bands, due to low geotechnical parameters and high degree of fracturation.

The yearly records of the sediment volumes taken out of the Campo dam are presented in Table 1. A mean annual sediment volume of 38038 m^3 is estimated.

Table 1: Annual sediment yield (SY) into the reservoir at the Campo dam.

Year	1991	1992	1993	1994	1995	1996	1997	1998
SY (m^3)	34073	43504	53605	36737	26264	39749	35314	32800
Year	1999	2000	2001	2002	2003	2004	2005	2006
SY (m^3)	41876	57299	43187	42022	22957	50083	21287	27844
Mean SY value (m^3)		**38038**						

3 Basin-scale evaluation of the annual sediment yield

This section describes the estimation of the annual sediment yield using several models: Gavrilovic [4], USLE (Wischmeier and Smith [5]) and RUSLE (Renard *et al.* [6]). All models were applied to the entire catchments closed at the Campo dam. This choice was most suitable for comparison of the estimated yields with the field data mentioned above.

The Gavrilovic model involves a semi-quantitative analysis for erosion estimation in a defined closed loop of the hydro-geological basin. This method was originally developed for catchments in the south of Yugoslavia. The basic concept of the model is that the sediment volume transported by the stream (*G*, m^3/year) depends on the sediment yield by soil erosion (*W*, m^3/year) and the sediment deposition in the watershed (through a sediment retention coefficient *R*,), according to the following equation:

$$G = W \cdot R \tag{1}$$

The calculation of the sediment yield *W* involves empirical coefficients (erodibility coefficient, soil protection coefficient, and erosion coefficient) and some physical characteristics (annual precipitation, temperature, average slope, and surface area):

$$W = T \cdot H \cdot \pi \cdot Z^{\frac{2}{3}} \cdot F$$

$$R = \frac{(l + l_i) \cdot \sqrt{O \cdot D}}{(l + 10) \cdot F}$$

$$T = \sqrt{0.1 + \frac{t}{10}}$$

$$Z = \Xi \cdot \Pi \cdot (\Phi + \sqrt{I}) \qquad \text{(2a, 2b, 2c, 2d)}$$

where: *T* is a coefficient of temperature, *H* is the mean annual rainfall (mm), *F* is the area of the watershed (km^2), *Z* is the coefficient of relative erosion, *O* is the perimeter of watershed (km), *D* is the mean difference in elevation of watershed (km), *t* is the mean annual temperature of the whatershed (°C), *I* is the mean slope of the watershed, *l* is length of the principal waterway and l_i is total length of the secondary waterways (km). The coefficient of relative erosion *Z* depends on several factors related to the soil and to the basin: *Ξ* (coefficient of soil cover), *Π* (coefficient of soil resistance to erosion) and *Φ* (coefficient of the observed erosion process). The values for *Ξ*, *Π* and *Φ* are chosen based on qualitative descriptions of the basin, to which some numerical ranges correspond. The present choice was: *Ξ* = 0.2 (coniferous forest with little grove, scarce bushes, bushy prairie); *Π* = 1.6 (Sediments, moraines, clay and other rock with little resistance); *Φ* = 0.8 (50-80 % of the catchments area affected by surface erosion and landslides). All the parameter values chosen for the case study are described in Table 2, together with the yield computation results. For this simulation the worst meteorological condition was considered.

The coefficients *Ξ*, *Π*, *Φ* are crucial for model application because, as seen, only some range of values are suggested based on qualitative descriptions of the

Table 2: Annual sediment yield obtained from the Gavrilovic model.

T (° C)	H (mm/year)	I	l (km)	l_i (km)	F (km^2)	D (km)
3	1376	0.58	11.26	149.84	47.0	1.79
O (km)	Ξ	Π	Φ	W (m^3/year)	R	**G (m^3/year)**
29.22	0.2	1.6	0.8	45371	1.67	**52931**

basin. A sensitivity analysis was performed for these coefficients, even though the coefficient values were changed remaining within the range proposed for the qualitative features chosen. Table 3 shows the influence of these parameters on the final result. This sensitivity analysis provides G values ranging between 34380 and 63160 m^3/year. The mean value of sediment yield obtained by field surveys (Table 1) is near to the lower limit of the range while the upper limit can explain sediment yield in the worst years.

Table 3: Sensitivity analysis for the coefficient in the Gavrilovic model.

	Base case	Case 1	Case 2	Case 3
Ξ	0.2	0.15	0.2	0.2
Π	1.6	1.6	1.8	1.6
Φ	0.8	0.8	0.8	0.85
Z	0,50	0,37	0,56	0,52
W (m^3/year)	45371	29470	54139	47568
G (m^3/year)	52931	34380	63160	55494
G variation (%)		-35	+19	+5

USLE (Wischmeier and Smith [5]) is another empirical model used for sediment budget definition. This method was devised in the 1950s by the USA Department of Agriculture and evaluates the annual soil loss in farmland neglecting sediment deposition.

$$E = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{3}$$

where: E is the average annual erosion, R is the rainfall-runoff erosivity, K is soil erodibility, L is the slope length, S is slope gradient, C is crop cover and management factor and P is support/conservation practices factor.

R and K are two dimensional parameters that represent synthetically the aggressiveness of erosive agent (R) and soil characteristics (K), while L, S, C, P are dimensionless factors.

USLE model was revised and a new method (called RUSLE, Renard *et al.* [6]) was presented. The key difference with respect to USLE model is that in RUSLE the factors L and S are combined into a single factor LS. R is mathematically defined as the product between total kinetic energy in a single meteoric event and the maximum intensity in a period of 30 minutes during the same event. The sum of every erosive event during one year provides the annual value; the mean of annual values extended to a pluriannual period provides the value of *R* factor. The *K* factor explains the intrinsic aptitude to erosion of the soil. In USLE and RUSLE application the problem is related to the choice of *K* parameter because the equation used for quantification of *K* was defined through some experimental analysis conducted on different geological conditions.

Results obtained from the application of USLE and RUSLE models to the Tartano basin are listed in Table 4.

Table 4: Sediment yield estimated with USLE and RUSLE.

E_{USLE} (m^3/year)	24708
E_{RUSLE} (m^3/year)	12587

Some comments can be made with reference to the presented computations. The Gavrilovic model overestimates the mean annual sediment yield into the reservoir at the Campo dam, while USLE and RUSLE underestimate it. This contrasts with a reasonable expectation of USLE providing larger values (it shall be remembered here that this model neglects sediment deposition). It should be borne in mind, however, that the Gavrilovic model was calibrated with reference to basins presenting significant similarities with the Tartano catchments, while USLE and USLE-derived methods were devised for rural basins in the USA. Despite the variability of the results, all the models correctly estimate the order of magnitude of the yield.

4 Discussion: limitations of the basin-scale modelling

The evaluation of the sediment yield documented above is representative of the global, average behaviour of the river basin. On one hand, fluctuations of the annual sediment yield can be observed in the records previously shown (Table 1), indicating a long-period variability. On the other hand, as pointed out, for example, by De Vente and Poesen [2], the different parts of the river basin may contribute very differently to the average sediment yield and the largest volumes of sediments may come from small definable areas. Indeed, the conceptual picture by De Vente and Poesen [2] according to which the dominant sediment source and sink terms vary with the basin dimension holds also for the different homogeneous areas within river catchments.

The spatial variability of the tendency to the sediment yield can be visualized by means of thematic maps obtained from the application of specific models as SHALSTAB (Dietrich and Montgomery [7]) or USPED (Moore and Burch [8]). The former is a physically based model for shallow landslides, where the stability analysis of a slope is combined with the rainfall regime. For SHALSTAB a digital elevation model of the case study is necessary (in this work, a DEM with 1:10.000 scale was used). It is possible to insert the instable known areas in case a back analysis has to be conducted by the software. The model considers the ratio between effective rainfall and soil transmissivity (q/T): areas with lower values of this ratio are the more instable. So SHALSTAB evaluates for each DEM cell the stability ratio q/T and provides as output a grid of logarithmic values classified in seven intervals from “chronic instability” to “stable”. USPED is a simple model which predicts the spatial distribution of erosion and deposition rates for a steady state overland flow with uniform rainfall excess conditions for transport capacity limited case of erosion process. The rates of erosion and deposition depend on the variation of transport capacity in the considered domain. Where transport capacity increases erosion takes place while where it decreases water releases sediments causing deposition. The results obtained are depicted in Figures 3 and 4. The spatial variability of the basin is evident. In addition, a lot of instable areas are present. These instable parts are localized on the steep slopes for ShalStab. For USPED, it is possible to see that the instabilities roughly correspond to the hydrographic network.

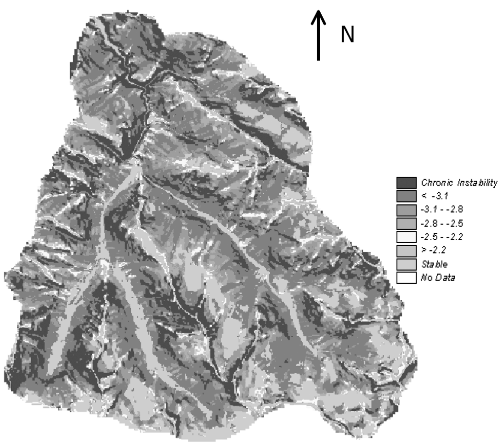

Figure 3: Application of SHALSTAB model.

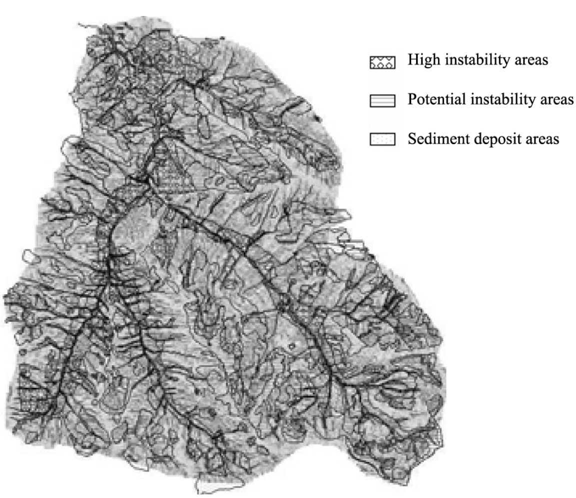

Figure 4: Application of USPED model.

The presented maps indeed support the concept that the expected sediment yield present significant spatial variability. As argued by De Vente and Poesen [2], an evaluation of the sediment yield at a basin scale is suitable for the analysis of off-site process (for example, the silting regime of a reservoir situated downstream of the last section of the basin, as that providing the field data used here). By contrast, there are several on-site processes that are conditioned by local sediment yields: among others, reference is made here to sediment transport within the water courses and debris flows along the valley slopes. A proper modelling of such processes requires adequate boundary condition in terms of the sediment yield. For the case of river sediment transport, Mandelli *et al.* [9] have identified three major flaws of the models based on lumped variables, namely: (i) the spatial scale, already discussed; (ii) the temporal scale, since the majority of the sediment volume conveyed by rivers is transported in the few days with largest discharge within the year whilst the yield modelling provides only an integral value for the whole year; (iii) the granulometry of the yielded sediments, which is a key piece of information for all the sediment transport models (e.g., Chanson [10]) but is not furnished by the models for sediment yield. Similar considerations may hold for debris flow phenomena (e.g., Iverson [11]). All the above considerations stimulate local-scale modelling for the sediment yield within short periods, for example those where significant events take place. An attempt of such modelling for a parcel within the Tartano basin is presented in the next section.

5 Scale issues in the evaluation of the sediment yield

This section presents some preliminary attempts to evaluate the response of the sediment yield evaluation to the spatial and temporal support scale of the modelling. For the evaluation of the spatial scale effect, the USLE and RUSLE models were applied to some sub-basins of the catchments. The chosen sub-basins are depicted in Figure 5 and correspond to: the entire Val Corta basin (see section 2); the entire Val Lunga basin; a pasture-covered parcel within the Val Lunga (henceforth indicated as subL); a wood-covered parcel within the Val Corta (sub C). For the temporal scale effect, the event-induced sediment yield was estimated using the MUSLE model. The latter was proposed by Williams and Berndt [12] for the evaluation of the sediment loss during a single rainfall event (Y_S). The proposed equation is:

$$Y_s = R_d \cdot K \cdot LS \cdot C \cdot P \tag{4}$$

where Y_s is the sediment yield (tons per storm) and R_d is a runoff factor, while the other symbols have the same meaning as in previous USLE and RUSLE models. For the application of the MUSLE model two events were considered, with return period of 10 and 100 years, respectively. Results of the evaluation are displayed in Table 5.

The relative variability of the results using the Gavrilovic, USLE and RUSLE models for the Tartano catchments was already discussed above (section 3). Now, the results for the different sub-basins and USLE models can be taken, for

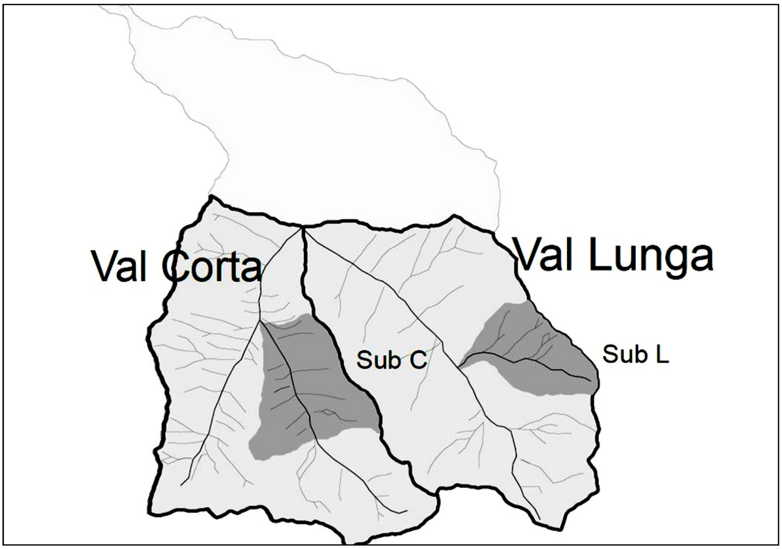

Figure 5: Sub-basins considered in the Tartano catchments.

example, to discuss the spatial scale effect. It appears that the spatial scale has no significant effect as long as the considered sub-basins are large enough to ensure the presence of several types of surface (Val Corta and Val Lunga sub-basins). By contrast, as parcels with only one type of soil cover are considered (sub L and sub C) a dramatic effect of the spatial scale appears, which is due to the presence of few types of surface (in other words, moving to little scales terrain features become predominant). The effect of the temporal scale is even more pronounced: considering events with significant intensity, huge sediment yields are obtained compared to the yearly ones (it should indeed borne in mind that the low number in Table 5 for the event-induced yields refer to very small durations compared to a whole year). In addition, the previously mentioned effects of the sub-basin surface are detected also for events with a short duration.

Table 5: Estimated scale response of sediment yield.

Basin	**Tartano**	**Val Corta**	**Val Lunga**	**Sub L**	**Sub C**
Area (km^2)	49	18	18	2.3	3.1
Annual specific sediment yield (tons/ha/year)					
Gavrilovic	22.5				
USLE	10.5	10.8	12.0	44.7	12.1
RUSLE	5.4	7.5	8.7	28.5	8.3
MUSLE evaluation of event-induced sediment yield (tons/ha)					
10-year event	0.7	0.9	1.1	6.3	0.8
100-year event	1.0	1.2	1.3	8.3	1.0

6 Conclusions

This manuscript considered the evaluation of the sediment yield in a mountain basin by means of semi-empirical models, with particular reference to the test case of the Tartano Valley in northern Italy. The estimation of the sediment yield was performed at the basin scale using the Gavrilovic, USLE and RUSLE models. The results obtained with these models presented a significant variability, yet in all cases the order of magnitude of the annual sediment yield was consistent with that obtained from periodic observation of sediment volumes extracted from a reservoir located at the downstream section of the basin.

The application of stability models like SHALSTAB and USPED provides significant pieces of information about the spatial heterogeneity of the basin in terms of the surface features and of the consequent tendency to soil erosion. The internal dynamics of the basin is visualized showing erosion and deposition areas. The scaling issues in sediment yield processes were discussed in light of this variability, which is expected to influence also the spatial distribution of the specific sediment yield. It was indeed found that the spatial scale of modelling influences the expected values of the specific sediment yield when small parcels having homogeneous soil cover are considered. In addition, the temporal scale of modelling was considered, showing that short-duration events with significant return period lead to concentrated (in time) sediment yields which may be dangerous even if the total amount of yielded sediments is low compared to the yearly one.

In the authors' opinion, applying models with reference to a variety of spatial and temporal scales might enable synoptic analyses of the basin dynamics to be made. Much further work is however needed to achieve a comprehensive perspective on these issues.

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