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APPLICATION OF AN IMPROVED VERSION OF THE EROSION POTENTIAL METHOD IN ALPINE AREAS

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La valutazione dei processi erosivi e delle loro conseguenze riveste un ruolo fondamentale nella corretta gestione del territorio; gli ambiti d'interesse sono relativi alla fruibilità del suolo, inteso come risorsa ambientale ed economica, all'assetto idrogeologico e, non da ultimo, alle interazioni con numerose opere di ingegneria tra cui spiccano gli invasi ed i manufatti di derivazione. Per queste ragioni si rivelano di grande interesse applicativo le metodologie per la stima del contributo solido di un bacino idrografico ad opportune scale spaziali e temporali.

Nel presente contributo si considera un modello empirico, il Metodo dell'Erosione Potenziale (Gavrilovic, 1988), che fornisce indicazioni a scala annua sul volume di suolo eroso e trasportato alla sezione di chiusura di un bacino. Si propone una revisione organica di alcuni dei suoi criteri di parametrizzazione e delle modalità di implementazione. In particolare, al fine di garantire maggiore semplicità ed oggettività alla fase di stima dei valori dei parametri sul bacino, si è inteso riconsiderare le modalità di classificazione dell'uso del suolo e delle caratteristiche geomeccaniche dei terreni e delle rocce tramite schemi largamente diffusi nella comunità scientifica (e.g., Corine 2000 per la descrizione degli usi del suolo). Si propone inoltre di limitare il periodo d'applicazione, originariamente a scala annua, ai soli periodi in cui le temperature, le caratteristiche delle precipitazioni e le portate sono tali da garantire l'effettivo innesco dei processi di erosione ed il trasporto del materiale nei corsi d'acqua. Questo approccio permette quindi di superare alcune difficoltà legate alla soluzione delle equazioni che compongono il modello estendendone quindi l'applicabilità anche a zone con temperatura media annua negativa, che caratterizzano ad esempio i bacini alpini d'alta quota. Applicando il modello sia secondo la metodologia originaria che implementando le modifiche proposte, sì è potuto osservare che queste non alterano le stime di produzione di sedimento ma aumentano significativamente l'oggettività dei risultati e la semplicità di applicazione dello schema.

Si propone inoltre una analisi statistica sull'opportunità dell'applicazione del modello in forma distribuita piuttosto che a parametri concentrati. Sebbene l'applicazione a parametri concentrati risulti generalmente più semplice, l'implementazione distribuita del modello tramite opportuni codici di calcolo permette di cogliere maggiormente le specificità locali del bacino; le differenze conseguenti ai due diversi approcci metodologici possono raggiungere il 14%. Si è infine testata l'effettiva applicabilità del modello e delle modifiche proposte in ambiente alpino, per il quale esso non era stato originariamente derivato. Il modello è stato applicato in forma distribuita a 31 bacini in Alta Valtellina (Sondrio - Italia) le cui acque sono convogliate per lo sfruttamento idroelettrico negli invasi di San Giacomo di Fraele, Cancano e Val Grosina. Sulla base delle informazioni fornite dal gestore degli impianti, è stato possibile ricostruire il volume di sedimento, quasi esclusivamente composto da limo glaciale, attualmente raccolto negli invasi dopo circa 50 anni di esercizio. Al fine di rendere omogenee le stime del modello, che comprendono l'intero spettro granulometrico, e le informazioni di interrimento dei bacini, che invece riguardano la sola frazione fine, si è provveduto ad eseguire una serie di campionamenti dei terreni dei bacini studiati ed effettuare analisi granulometriche volte a definire la percentuale di materiale fine che costituisce i sedimenti. Tramite questa procedura è stato quindi possibile stimare il volume di materiale fine che annualmente viene eroso in ciascun bacino e convogliato in sospensione nei corsi d'acqua fino agli invasi e confrontare positivamente le informazioni di interrimento con i risultati del modello.

In conclusione, questo studio propone modifiche sostanziali nelle tabelle e nelle modalità di implementazione del modello senza influire tuttavia sulle relazioni, sulle ipotesi di base e sui risultati. La fase applicativa mostra che le stime fornite dal metodo, sebbene affette da significative soglie di incertezza peraltro insite in questo tipo di fenomeni, sono sostanzialmente in buon accordo con le osservazioni di lungo periodo sull'interrimento dei serbatoi.

ABSTRACT

The assessment of erosive processes is of great importance in environmental engineering, resource management and land planning. In this paper the empirical approach known as Erosion Potential Method (*EPM*) was improved to simplify the identification of the involved parameters. In addition, *EPM* suitability for alpine watersheds, where the average yearly temperature may be below 0°C, was discussed. The advantages of distributed approaches rather than lumped methodologies were tested. *EPM* was then implemented in a distributed form for a set of 31 catchments located in Alta Valtellina (Northern Italy) in order to capture the spatial variability of the parameters and the intensity of the erosion processes. The results obtained for these catchments were positively compared to long-term sedimentation data from three reservoirs and from a turbidimetric station.

Key words: *erosion potential method, soil erosion, Alpine reservoirs sedimentation*

INTRODUCTION

Sediment supply of rivers is a consequence of a wide set of distributed erosion phenomena acting in a watershed. The evolution of such processes might be slow (e.g., freeze-thaw action and growth of plant root system in rock joints, chemical weathering processes like hydrolysis and oxidation) or characterized by a greater velocity (e.g., soil creep, rill and gully erosion) and even by a very high velocity (e.g., some kind of landslides, debris flows). As a result, the volume of involved materials might be relevant and the effects are usually of primary importance both in the field of environmental engineering and of agriculture. It has been reckoned that almost 1.2 kg/m^2 of soil per years are lost in intensive agriculture areas in the USA as a consequence of water and wind erosive capacity (U.S. Department of Agriculture, 2009). In addition, sediments are an important source of pollution for water bodies both in terms of turbidity and of nutrients. Finally, the settling of sediments in reservoir may cause important related problems, such as the reduction of their storage capacity (Vanoni, 1975), damages to electromechanical machinery (pipes and turbines) and potential impairment of the properties of drinking water. For instance, about 30% of the original Italian storage volume is now occupied by sediments (ITCOLD, 2009) and this fraction is about 35% worldwide (Basson, 2010).

The importance of the consequences of soil erosion prompts continuous research for effective methodologies to quantify soil loss in catchments. To this purpose, different approaches might be identified in the literature. Hydraulic modelling focuses on the transport capacity of the river through the calibration of sediment transport formulae at the local level. These relations are generally obtained through laboratory experiments under the hypothesis of infinite sediment availability, steady, two-dimensional and uniform flow (e.g., Graf, 1971; Yalin, 1977; Raudkivi & Tan, 1984; Simons & Sentürk, 1992). The distribution of the suspended fraction is usually computed through additional considerations about turbulence and sediment concentration along the vertical direction. From this point of view, the estimate of the mean annual sediment transport volume may be performed by time integration using the flow duration curve of the studied stream. A possible criticism to this approach regards the intermittency of the actual sediment transport, which, also in steady flow conditions, is controlled by the sediment availability and is triggered by intense hydrologic events. This is particularly true in mountain areas, where most of the sediment production occurs during few strong events because of the strengthened carrying capacity of the flow and the increased availability of sediments into the streambed (e.g. Pitlick & Thorne, 1987). Accordingly, conceptualized approaches to assess the overall relevance of sediment production at the basin scale are justified.

The catchment-wide soil erosion models available in the literature can be classified according to their conceptual features and different space and time scales of application (e.g., de Vente & Poesen, 2005). Moreover, some of these models were devised to estimate soil loss for specific purposes only (e.g., agricultural conservation) while others have a wider scope, with possible applications in land planning, river restoration and reservoir management. The choice of the most suitable model depends on the goal of the application, on the reliability of the model for the specific morpho-climatic environment (e.g., arid/semi arid landscapes, mountainous regions, agricultural lands) and finally on the available data. Physically based, conceptual and empirical methodologies can be found in the literature (e.g. Merritt *et alii*, 2003). Physically based models provide a mechanistic description of erosive processes through fundamental conservation principles and constitutive equations. These methods assess the interaction of each element and return the variation of sediment production in space and time, usually requiring a considerable amount of input data and of computational effort (Ranzi *et alii*, 2012). Among others, the widespread models CREAMS, KINEROS, EUROSEM, LISEM and WEPP might be cited (e.g., Nearing *et alii*, 1989; De Roo *et alii*, 1995; Smith *et alii*, 1995; Brazier *et alii*, 2000). Conceptual models may be regarded as a compromise between empirical and physically based models because they link conservation equations to empirical relationships. Finally, empirical formulae describe the phenomena in a simplified way through regressive relations of experimental data that link together the most statistically relevant parameters. Due to their simplicity, the use of empirical methodologies is widely documented in the literature. Indeed, despite a simple formal structure, they usually provide a valuable engineering approach to soil erosion estimate if used into the same geomorphological environment where they were calibrated. Among others the following models might be cited: USLE and further revisions for agricultural areas (Wischmeier & Smith, 1978); PSIAC for arid and semi arid regions; denudation index based on geomorphic parameters for badlands (e.g., Della Seta *et alii*, 2009).

Among empirical methodologies, the Erosion Potential Method (Gavrilovic, 1988), in the following also indicated as "*EPM*", is a semi-distributed model for the estimation of the mean annual soil erosion and sediment yield at the basin scale. Despite its original formulation, applications at a smaller time step can be found in the literature (e.g., Bemporad *et alii*, 1997) as well as space-distributed implementations that better account for the local variability of the involved parameters (De Cesare *et alii*, 1998; Emmanouloudis *et alii*, 2003; Globevnik *et alii*, 2003; Tangestani, 2006; Bozorgzadeh & Kamani, 2012; Bagherzadeh & Daneshvar, 2010). These improvements take advantage of the development of digital cartography and GIS technologies.

Although *EPM* was calibrated using laboratory and field data for the Dinaric Alps, several literature contributions test the applicability of *EPM* in different climatic areas. For instance, several researches assess the suitability of *EPM* to semiarid Mediterranean regions (e.g., Emmanouloudis *et alii*, 2003; Emmanouloudis & Kaikis, 2006; Tangestani, 2006; Solaimani *et alii*, 2009; Bozorgzadeh & Kamani, 2012) and to the Alpine and Appenninic area (e.g., Pozzi *et alii*, 1990; Mikoš *et alii*, 2006; Fanetti & Vezzoli, 2007; Tazioli, 2009; Zorn & Komac, 2009). Anyway, the original form of *EPM* cannot be applied in areas characterized by mean annual temperature below -1°C because of the definition of the temperature coefficient.

Another major stumbling block that hinders the widespread application of *EPM* arises from its parameterization tables, whose original definitions are sometimes of difficult interpretation and generalization. Hence, the reliability of the results might be significantly affected by the user's experience. To limit these effects, improving the reliability of the results and reducing the influence of users' know-how, many authors suggested modifications to the *EPM* tables (Stefanović *et alii*, 2010; Bozorgzadeh & Kamani, 2012; Tosic & Dragicevic, 2012). However these efforts have not delivered a complete and easy-to-use revision of the original classification.

This paper deals with these limitations of *EPM*: the model was applied to a cold alpine environment by suggesting a modification of the original temperature parameter and the classification tables were revised on the basis of widespread classification methodologies (e.g. Corine Land Cover for land use factor). This greatly simplifies the application of the model by increasing the objectivity of parameters definition. Moreover, a procedure for the distributed application of the methodology is presented and its actual advantages are briefly discussed. The model was applied to 31 alpine catchments in Alta Valtellina (Northern Italy) and the results were positively compared to measured sedimentation and turbidimetric data.

THE EROSION POTENTIAL METHOD

EPM is an empirical formula that supplies the mean annual volume of sediments eroded and the fraction yielded to the outlet of a river basin. Erosive phenomena arise from the interaction of lithological, topographic, climatic and land use quantities (e.g., Fournier, 1960; Morgan, 1979) that in this model are linked by the relation:

$$W_{sp} = T \cdot P \cdot \pi \cdot \sqrt{Z^3} \tag{1}$$

where W_{sp} (m^3/km^2) is the specific mean annual production of sediment and P (mm) represents the mean annual cumulative rainfall. With reference to the latter, Zorn & Komac (2009) highlighted some modifications introducing the maximum daily rainfall in order to make the model able to account also for extreme events which otherwise would not be considered (e.g., Mikoš *et alii*, 2006). The temperature coefficient T (-) is calculated as:

$$T = \sqrt{\frac{t}{10} + 0.1} \tag{2}$$

where T (°C) represents the mean annual temperature. The parameter Z (-) is defined as:

$$Z = X \cdot Y \cdot \left(\varphi + \sqrt{i}\right) \tag{3}$$

where X (-) describes the protection by vegetal or artificial coverage against erosive factors and is a function of land use; Y (-) represents soil resistance against water erosive capacity and is a function of the basin lithological and pedologic features; φ (-) indicates the intensity of the active erosion processes; i (m/m) is the mean slope of the investigated area, that can be calculated through an area-weighted average. The mean annual sediment yield G (m^3/y) at the outlet accounts for the actual transport capacity of the flow:

$$G = W \cdot R = W_{sp} \cdot F \cdot R \tag{4}$$

where the retention coefficient R (-) represents the percentage of sediments that reaches the outlet, W (m^3/y) is the volume of eroded sediment and F (km^2) the area of the river-basin. Accordingly, Eq. (4) reflects the possible reduction of transported sediments along the watercourse due to the local decrease of bed shear stress. Gavrilovic (1988) suggested to compute R as:

$$R = 4\frac{\sqrt{O \cdot \Delta\hat{H}}}{L + 10} \tag{5}$$

where O (km) is the perimeter of the catchment, $\Delta\hat{H}$ (km) the mean geodetic relief and L (km) the linear dimension of the catchment along the main channel. On the basis of further studies in alpine areas, Zemljic (1971) observed that Eq. (5) tends to overrate the effective ratio between eroded and yielded sediments. Sometimes it may even return unphysical values larger than 1. Hence, Zemljic (1971) suggested the following relation:

$$R = \frac{\sqrt{O \cdot \hat{H}}}{\left(L + 10\right)} \frac{\sum_i L_i}{F} \tag{6}$$

where $\hat{H}$ (km) indicates the mean altitude of the basin and L_i (km) represents the length of i^{th} order channels. Equation (6) was used in this paper.

IMPROVEMENTS TO EPM

In this section some modifications to *EPM* are proposed in order to cope with the problems arising in the identification of its parameters and in the application in cold mountain areas. The application of Eq. (2) in alpine areas with mean annual temperature below -1 °C, is not possible because of the negative value of the radical. However, in these areas, erosion processes are mostly concentrated in the period from spring to fall, (e.g., De Cesare *et alii*, 1998), because in winter period both the soil and the streams are usually frozen and the snow precipitations have no erosive power. Indeed, although freeze-thawing cycles generate sediments and snow avalanches might convey significant amount of sediments only if the sliding plane coincide with the soil layer, in average terms the most effective sediment transport processes are related to rainfall and stream waters. Accordingly, it seems reasonable to apply *EPM* during the active erosion period only, computing the averaged temperature and the cumulative rainfall on such temporal window instead of using

EPM (Gavrilovic, 1988)	X_{EPM}	Zemljic (1971)	$X_{Zemljic}$	*Corine Land Cover* (EEA, 2000)	$X_{suggested}$
Denudated unarable lands (badlands)	1.00	Areas without vegetation cover	0.80-1.00	1.3.1. Mineral extraction sites 1.3.3. Construction sites 3.3.1. Beaches, dunes, sands 3.3.2. Bare rocks 3.3.3. Sparsely vegetated areas 3.3.4. Burnt areas 3.3.5. Glaciers and perpetual snow*	0.80-1.00
Fields ploughed up/down the hill	0.9				
Orchards or vineyards without low vegetation	0.70	Damaged pasture and cultivated land	0.60-0.80	1.3.2. Dump sites 2.1.1. Non-irrigated arable land 2.1.2. Permanently irrigated land 2.1.3. Rice fields 2.2.1. Vineyards 2.2.2. Fruit trees and berry plantations 2.2.3. Olive groves 2.4.1. Annual crops associated with permanent crops 2.4.2. Complex cultivation patterns 3.2.1. Natural grasslands	0.60-0.80
Field countour-farmed	0.63				
Degraded forestand shrub on eroded soil. Dry mountain pastures	0.60				
Meadows and similar perennial crops	0.4	Damaged forest and bushes, pasture	0.40-0.60	1.4.1. Green urban areas 1.4.2. Sport and leisure facilities 2.3.1. Pastures 2.4.3. Land principally occupied by agriculture with significant areas of natural vegetation 2.4.4. Agro-forestry areas 3.2.4. Transitional woodland-shrub	0.40-0.60
Grass-grown and drained pastures	0.3	Coniferous forest with little grove,scarce bushes, bushy meadows	0.20-0.40	1.1.2. Discontinuous urban fabric 3.2.2. Mors and heatland 3.2.3. Sclerophyllous vegetation	0.20-0.40
Good forest on steep slopes	0.20	Mixed forests and dense brushes, sparse forests with underwood	0.05-0.20	1.1.1. Continuous urban fabric 1.2.1. Industrial or commercial units 1.2.2. Road and rail networks and associated lands 1.2.3. Port areas 1.2.4. Airports 3.1.1. Broad-leveed forest 3.1.2. Coniferous forest 3.1.3. Mixed forest	0.05-0.20
Good forest on gentle slopes	0.05				

Tab. 1 - Values of the land cover parameter X

** Glaciers and perpetual snow, although protecting soil against rainfall erosivity, exert a relevant erosive action due to meltwaters. Accordingly, in order to cope with this ambiguity, these elements are associated to the maximum value of X, that would mean the lowest protection against erosion*

EPM (Gavrilovic, 1988)	Y_{EPM}	Zemljic (1971)	$Y_{Zemljic}$	Suggested	$Y_{suggested}$
Sand, gravel and loose soil	2.00	Fine sediments and soils poorly resistant to erosion	1.8-2.0	Fine and medium soils (sand, silt and clay)*	1.7-2.0
Loess, tuff, saline soil, steppe soil and the like	1.60	Sediments, moraines, clays and other weak rocks	1.3-1.8	Poorly sorted soils	1.4-1.7
Weathered limestone and marl	1.20	Soft rocks, stabilized (talus slope, schists, stiff clays)	1.0-1.3	Coarse soils (gravels, pebbles, boulders)	1.0-1.4
Serpentine, red sandstone, flysch deposits	1.10				
Podzol, parapodzol, disintegrated schist, micaschist, gneiss, argillaceous schist, etc.	1.00				
Compact and schistose limestone, tera rossa and fumose-silicate soils	0.90	Rocks partly resistant to erosion	0.6-1.0	Weak rock masses (shales, poorly cemented clastic rocks, evaporates, finely-foliated rocks, intensely jointed rock masses)	0.5-1.0
Brown forest soil and mountain soils	0.80				
Smonitsa, valley and back bog soils	0.60				
Chernozem and alluvial deposits of good texture	0.50	Hard rocks resistant to erosion	0.2-0.6	Hard rock masses	0.02-0.5
Bare compact igneous rocks	0.25				

Tab. 2 - Values of the erodibility parameter Y
** In order to avoid excessive refinement of the classification, fine soils are grouped in a single class although it is well known that clayey soils are less erodible than sandy ones. Accordingly higher values of Y are associated to sand and prevailing sandy soils*

the mean annual values. In this way it is possible to apply *EPM* also in regions characterized by periods with average temperature below zero.

In order to simplify the assessment of *EPM* coefficients in Eq. (3), reducing ambiguities in the parametric description of the catchment, we propose a systematic correspondence between the original classification tables and some widespread classification systems of land use, geology and active erosion processes. This task was already attempted to a more limited extent by other researchers (e.g., Emmanouloudis *et alii*, 2003; Globevnik *et alii*, 2003; Fanetti & Vezzoli, 2007), who related the original *EPM* classification table of the parameter *X* to the *Corine Land Cover* classes (EEA, 2000). The *Corine Land Cover* system represents a reference point at the European level and its maps are freely available in digital format on the web, fostering space-distributed *GIS* applications.

The analysis of the analogies between the elements of the original parameterization by Gavrilovic (1988) and Zemljic (1971) and the categories of the *Corine Land Cover* system suggests the correspondence proposed in Tab. 1.

The coefficient *Y* describes soil erodibility as a function of rock and soil properties (Tab. 2). The main goal of the re-classification of this parameter is to substitute the original classification, where geological and geomorphological characteristics of the deposits were mixed together, with a more systematic one where soils and rocks are divided in two distinct categories. Soils are classified on the basis of the particles size and rocks are subdivided according to their mean mechanical characteristics.

The parameter φ, describing the intensity of the active erosion processes, can be calculated by two distinct procedures. The first approach is based on the general overview of the study area and returns a measurement of the intensity of erosion processes at the river basin scale. This study provides a simplified subdivision and includes some intensive erosion landforms not comprised in the original classification tables (Tab. 3).

Alternately, a more detailed approach for the assessment of φ goes through the *V*/*F* ratio, where *V* is defined as:

$$V = \sum_i F_{i\%} F_i P_i \tag{7}$$

where $F_{i\%}$ (-) represents the percent area covered by the i^{th} erosion landform and F_i (km^2) indicates the surface covered by the i^{th} erosion landform. The weight of each erosive type, P_i (-), is given in Tab. 4. The parameter φ is finally provided by Tab. 5 as a function of the ratio *V*/*F*.

VALIDATION OF THE MODIFIED VERSION OF EPM

In order to compare the improved and the original *EPM* formulations, they were both tested in two small alpine catchments in Alta Valtellina (Northern Italy) using a lumped approach. Although the most effective comparison would have been with respect to the same environment of calibration of *EPM*, the model was partly calibrated using laboratory tests and experimental plots, so that the original data are not relevant for implementation at the basin scale. Moreover, tests in the Dinaric alps would not allow to verify the effect of the modifications provided to cope with negative temperatures.

EPM (Gavrilovic, 1988)	φ_{EPM}	Zemljic (1971)	$\varphi_{Zemljic}$	Suggested	$\varphi_{suggested}$
Basin or area fully attacked by gulling and deep processes of erosion	1.00	Fully eroded basin with gullies and landslides.	0.90-1.00	More than 50% of the catchment area with gullies. Debris flows	0.80-1.00
About 80% of area under rills and gullies.	0.90				
About 50% of area under rills and gullies.	0.80	50-80% of the catchment with rill erosion and landslides.	0.80-0.90	More than 50% of the catchment area with rill erosion. Less than 50% of the catchment area with gullies, landslides, rockfalls, avalanches.	0.60-0.80
Entire area attacked by surface erosion: detritus and debris, few rills and gullies (deep erosion) and heavy karst erosion.	0.70				
Entire area attacked by erosion but without visible deep effects (rills, gullies, rockfalls, etc.).	0.60	Sheet erosion, talus debris, slope with rills and gullies, karst erosion	0.60-0.70	More than 50% of the catchment area with sheet erosion. Less than 50% of the catchment area with rill erosion.	0.40-0.60
50% of area attacked by surface erosion, while the rest of the basin is unattacked.	0.50				
20% of area attacked by surface erosion and 80% unattacked.	0.30	Sheet erosion on 20-50% of the catchment	0.30-0.50	20%-50% of the catchment area with sheet erosion	0.20-0.40
Land surface without visibile erosion effect; minor rockfalls or slips in stream channels.	0.20				
Land surface without visibile erosion effect; mostly crop fields.	0.15	Low erosion signs in the basins	0.10-0.20	Less than 20% of the catchment area with sheet erosion	0.05-0.20
Land surface without visibile erosion effect; mostly under woods or perennial crops (meadows, pasture. etc.).	0.10				

Tab. 3 - Values of the parameter φ describing the active erosion processes in the basin

Erosion landform		Suggested meaning	P_i
A_1		Landslides in rock	5
A_2		Landslides in soil	6
A_3		Gully erosion	7
A_4		Debris flow	7.5
A_5	$A_{5\text{-}A}$	Sheet erosion	2.5
	$A_{5\text{-}B}$	Rill erosion	4
A_6		Areas with avalanches	2

Tab. 4 - Values of the parameter P_i describing the active erosive processes in the catchment

V/F	φ
0	0
0.05	0.02
0.10	0.04
0.15	0.06
0.20	0.08
0.25	0.1
0.50	0.2
1	0.3
2	0.4
4	0.6
6	0.8
7	0.9
7.5	0.95

Tab. 5 - Values of the parameter φ describing the active erosion processes in the basin

The first test case regards Val Cancano, a small catchment (3.8 km^2) on the left side of the Cancano reservoir (Fig. 1). The input data and the results provided by the original methodology, based on Zemljic (1971) tables, were obtained by Quintavalle (2004). It is important to remark that the study by Quintavalle (2004) used a parameterization based on yearly averaged quantities, while the current study is based on the modified formulation, that makes use of the cumulative precipitation and of the average temperature for the period (from May to October) when the average temperature is positive. As shown in Tab. 6, the results obtained from the two different formulations of *EPM* are in good agreement. Accordingly, it is possible to state that the new parameterization and the introduced variations on thermal and rainfall coefficients have no relevant effects on the results but simplify the applicability of the model, widening its scope to cold regions. The relevant difference on the active erosion coefficient might be partly explained by considering that we applied the procedure based on Eq. (7), while Quintavalle (2004) used Tab. 3.

The second test case regards the Cedec creek basin (Fig. 1) and focuses only on the effect of the introduced variations to the parameterization tables. This watershed has an area of 17.3 km^2 and a mean slope of 42.5%. The results obtained with the modi-

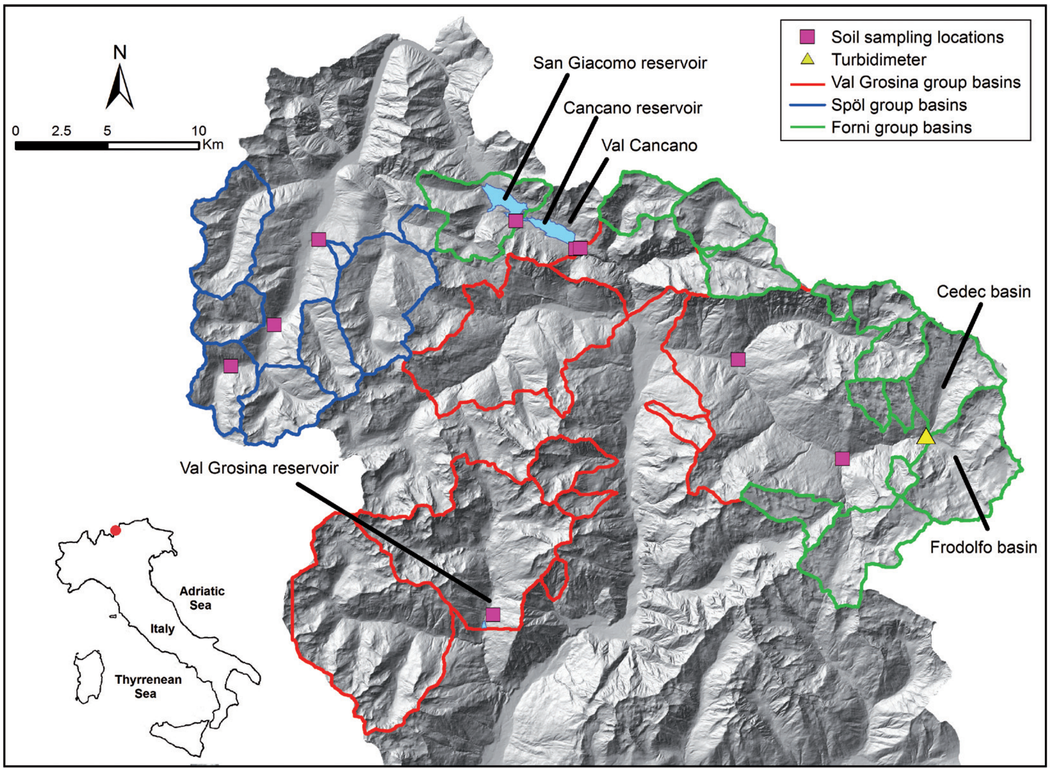

Fig. 1 - The alpine catchments considered in this paper

	i (%)	φ (-)	X (-)	Y (-)	Z (-)	P (mm)	T (-)	W (m^3/y)	G (m^3/y)
Quintavalle (2004)	70	0.54	0.84	1.2	1.39	808	0.65	9170	6328
Modified *EPM*	78	0.15	0.82	1.51	1.29	555	1.00	9609	6645

Tab. 6 - Parameters and results for the Val Cancano test case, according to the original and the modified EPM versions

	φ (-)	X (-)	Y (-)	Z (-)	W (m^3/y)	G (m^3/y)
Bassi (2000)	0.38	0.55	0.88	0.50	6906	5387
Modified *EPM*	0.05	0.68	1.18	0.56	8308	6477

Tab. 7 - Comparison of input data and results for the Cedec catchment

fied *EPM* were compared with those by Bassi (2000), obtained on the basis of Zemljic (1971) tables, in order to test the influence of the modified tables only. In order to obtain fully comparable results independent from the extent of the simulation period, we used the same average yearly temperature and cumulative precipitation (1145 mm) introduced by Bassi. In order to cope with the negative value of the radical in Eq. (2) in a situation where the actual average yearly temperature of the basin would be -1.3°C, Bassi set this value to 0°C. Moreover, he considered X equal to 0 for the glacier area, a low value that would reflect the protection exerted by ice to soil and rocks. Although the erosive effect usually exerted by glacial meltwaters could lead to much higher values of X (see also Tab. 1), in this test case we assumed a fictitiously low value of X for glaciers as done by Bassi, in order to keep constant this term of the problem and obtain directly comparable results. Finally, one could observe that this assumption lead to an underestimation of the sediment volume since the role of glaciers is completely neglected. Tab. 7 shows that the results provided by the modified version of *EPM* approximate properly the ones based on the original classification tables. Indeed, in this kind of complex problem covering a large basin, a 20% error in the evaluation of sediment volume might be regarded as a good result, although the lack of literature data (e.g., Boardman, 2006) does not allow statistical analyses and confirmations. Hence, the modified parameterization tables do not affect significantly the results of the original procedure and simplify the application of the model, fostering its automated implementation.

COMPARISON BETWEEN LUMPED AND DISTRIBUTED MODELLING OF EPM

The spatial scale of application of erosion models is a relevant aspect that controls the physical meaning of the input data and, accordingly, the quality of the results. In particular, there is often the need to preserve the original spatial distribution of the parameters at the slope (*parcel*) scale (in the order of 10^3 m^2), while providing results at the basin scale (in the order of 10^6 m^2). In a strongly non-linear process like sediment erosion, there is no guarantee that the use of space-averaged parameters leads to an outcome similar to that provided by the space averaging of the results obtained at the local scale. In addition, the averaged parameters at the basin scale may lose their original physical meaning.

The *EPM* parameters were defined through parcel observations (Gavrilovic, 1988), but its practical application is often for large catchments (e.g., Gavrilovic, 1988; Emmanouloudis *et alii*, 2003; Tazioli, 2009). In order to find a compromise between these two scales, *EPM* is usually applied in a semi-distributed fashion, according to which the catchment is subdivided into geomorphologically and climatologically homogeneous units. In this direction, the use of automated computational procedures, along with geomorphological surveys, is mandatory and in the following we shall make use of the geomorphological information contained within the space filling drainage network of a basin to deal with *EPM* computation.

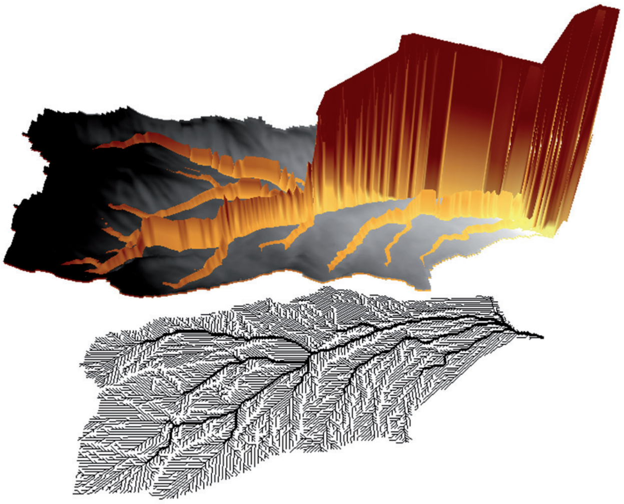

Fig. 2 - The cumulative EPM sedimentogram, computed in a distributed fashion along the drainage network, is represented on the DTM and then superimposed to the Space Filling Drainage Network (SFDN; thin solid lines) and Channel Network (CN; thick solid lines)

Considering the control exerted by the topography on the movement of water within a catchment, it is not surprising that over the last decades a great effort has been done to couple quantitative geomorphology and hydrology. In this perspective the use of Digital Terrain Models (*DTM*) has become a well established practice for the extraction of topologic and geomorphological information. Typically, *DTM* have been used for the computerized extraction of the connected space filling drainage network (*SFDN*) and of the channel network (*CN*). The first one is the set of all local flow directions for the physically based simulation of runoff processes and the second one is the subset of *SFDN* where free surface flow takes place, to be used for flood routing within a river basin. Considering that both bedload and washload depend on water erosive and transport capacity, which are a function of local properties (e.g., the local slope) but also of integrative properties of the locally drained catchment, as already proposed by Ciccacci *et alii* (1986), Pilotti & Bacchi (1997) computed the sediment yield from a catchment exploiting the informative content of *SFDN* and *CN*.

The scale gap between parcel and basin information can be filled by taking advantage of the powerful reorganization of the *DTM* informative content accomplished by the *SFDN* and the *CN* as described by Pilotti *et alii* (1996). To this purpose, an extensive automatic *DTM* pre-processing can be used, in order to filter depressions and flat areas that would prevent the identification of the drainage network. Then, using this enhanced information, the steepest directions can be identified and the *SFDN* derived. By filtering the *SFDN* on the basis either of a fixed threshold contributing area principle (O'Callaghan & Mark, 1984; Band, 1986, 1993) or of a slope dependent critical support area (Montgomery & Dietrich, 1992; Montgomery & Foufula-Georgiou, 1993), the *CN* can be extracted (Fig. 2). Finally, the hillslope drainage network is obtained by logical subtraction of the *CN* from the *SFDN*.

The networks allow a complete reorganization of the information contained within the *DTM*, using non-binary logical tree structures that can be effectively explored by so-called "visiting" recursive algorithms. The use of such procedures allows to compute locally Eq. (1), moving from link to link within the *SFDN* and following the same order that would be followed by runoff on the terrain. At each cell, these algorithms operate on data computed locally from the *DTM* (e.g., local slope and temperature) and on raster data made available by the user (e.g., soil properties and land use). At the same time, they take memory of the integrative properties that are a function of the upstream explored cells (e.g., the local discharge or the overall drained area).

In order to test the advantages of distributed versus lumped approaches in this problem, a set of seven basins, with area F ranging from 1 to 110 km^2 and described by a *DTM* of constant

Tab. 8 - Average variation Δ of sediment production between distributed and lumped applications of EPM

$\mu(X)$	0.5				
$\sigma(X)$	0	0.05	0.1	0.15	0.2
$CV(X)$	0	0.1	0.2	0.3	0.4
$\Delta(\%)$	0.00	0.38	1.52	3.44	6.06

$\mu(\varphi)$	0.5				
$\sigma(\varphi)$	0	0.05	0.1	0.15	0.2
$CV(\varphi)$	0	0.1	0.2	0.3	0.4
$\Delta(\%)$	0.00	0.04	0.20	0.47	0.84

$\mu(Y)$	1				
$\sigma(Y)$	0	0.1	0.2	0.3	0.4
$CV(Y)$	0	0.1	0.2	0.3	0.4
$\Delta(\%)$	0.00	0.34	1.43	3.30	5.85

$\mu(i)$	0.6				
$\sigma(i)$	0	0.05	0.15	0.2	0.25
$CV(i)$	0.00	0.08	0.25	0.33	0.42
$\Delta(\%)$	0.00	- 0.04	-0.48	-0.94	-1.60

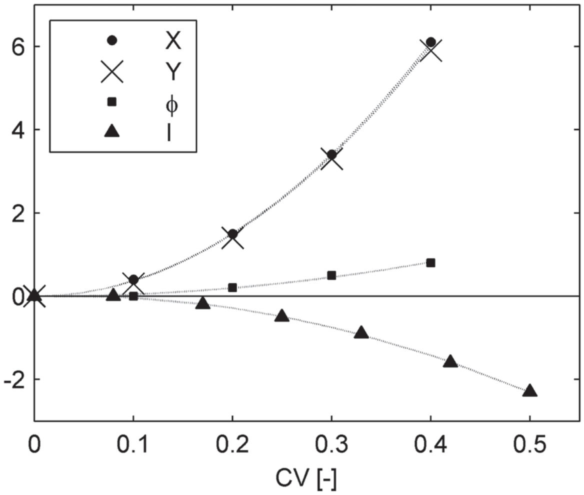

Fig. 3 - Average variation Δ of sediment production between distributed and lumped approaches as a function of the variation coefficient CV

cell size of 20 m, were studied. The parameters *X*, *Y*, *φ* and *i* were assumed to be randomly distributed in space according to a normal distribution law. After computing the average parameter values, *EPM* was applied in both lumped and distributed forms. The percentage variations *Δ* between the results obtained from the two approaches were computed, progressively increasing the variation coefficients *CV* of the parameter distributions. The analysis were repeated for each parameter keeping the others constant to their mean value *μ*. Since the variation of these parameters (except the local slope *i*) is set by *EPM* tables in limited ranges (e.g. 0-1 or 0-2), the mean value and the maximum standard deviation of the distributions were limited to keep at least 96% of the values within these ranges. In case of parameters generated outside of their definition range, their value was reset to the closest acceptable value.

Tab. 8 and Fig. 3 show the tested *CV* ranges and the average computed variation *Δ* for the seven cases. The results highlighted a substantial independency of *Δ* with respect to the area of the catchment. In real applications all the parameters change simultaneously so that, in this case, the value of *Δ* might increase up to 14%.

Although in the following we applied *EPM* will be applied in a distributed fashion, the small difference between the results obtained operating in a distributed and lumped way shows that the *EPM* is sufficiently robust to provide fairly reliable results also in lumped applications. The advantages of a distributed application mostly lie in the possibility to preserve the physical meaning of the parameters and in the possibility to identify the most productive areas within the catchment, as shown in Fig. 2 where the cumulative sediment production along the drainage network is shown.

APPLICATION TO ALPINE CATCHMENTS AND RESULTS

In order to test the reliability of *EPM* estimates, the results of a distributed application on 31 catchments in Alta Valtellina, Northern Italy (Tab. 9 and Fig. 1), were compared to the measured data of long term reservoir sedimentation and turbidity.

The study area, located in the Retic Alps, is drained by the Adda river and is a part of the Austro-Alpine geological domain which is constituted by a complex series of allochthonous units (overthrusts and nappes) which overlapped each other's during the alpine orogenesis. Within such units, both crystalline (phyllite and gneiss) and sedimentary (Triassic and Jurassic limestones) formations are present. From a geomorphological perspective, periglacial and glacial landforms are combined with gravitative and water erosional elements. The mean cumulative precipitation of this area is about 880 mm/y, mainly concentrated during the period from May to October (590 mm). Most of the catchments surface is covered by natural vegetation with different levels of protection (e.g., forests, pastures, etc.) whilst 35% of the surface is characterized by bare rocks and sediments. Only 4% of the whole area in the east side of the investigated region is occupied by glaciers.

In order to perform a distributed application of *EPM*, the algorithm proposed by Pilotti & Bacchi (1997) was modified to compute locally Eq. (1), through a recursive visiting algorithm that explores the *SFDN* (Fig. 2). The cumulative sediment yield *G* was finally obtained by multiplying the sediment production at the outlet *W* by the retention coefficient *R* from Eq. (6). The local slope maps were automatically calculated during the identification of the steepest descent directions from the *DTM* with cell size 20 m. The raster input data files of erodibility, land use and precipitation were automatically associated by the software to the corresponding cells of the *SFDN*. The input data were derived both from the literature (e.g., Pozzi *et alii*, 1990) and from digital information made available by Regione Lombardia: on the basis of these data, the values of the *EPM* parameters were selected using the modified tables proposed in Section 3. The hydro-meteorological quantities referred to the period from May to October were calculated using a 15 years dataset of daily recorded temperature and precipitation in 14 stations located within the study area. The local temperature in each cell was calculated as a linear function of the cell elevation, considering an altitude gradient of -0.004 °C/m. On the contrary, precipitation was assumed constant on the basin (see also De Cesare *et alii*, 1998). According to the approach based on Eq. (7), the active erosion processes parameter was assumed constant at the basin scale (see also De Cesare *et alii*, 1998). Indeed, although erosive processes are diffused on the basin and their influence should be compute in a distribute form, no procedures that allow to consider the distributed influence of active erosion processes is available in *EPM*.

The 31 catchments are linked for hydropower purposes to the San Giacomo, Cancano and Val Grosina reservoirs (Fig. 1) and can be subdivided into 3 main groups: "Forni", "Spöl" and "Val Grosina" (Fig. 4). The "Forni" and "Spöl" groups are connected through a diversion canal to the San Giacomo reservoir; the "Val Grosina" group delivers its water to the dam of Val Grosina by a different diversion canal. The reservoir of San Giacomo is just upstream of the Cancano reservoir, so that water and suspended sediments flow from the San Giacomo to the Cancano reservoir. Finally, the Cancano reservoir is connected for daily regulation purposes to the Val Grosina reservoir.

The computed mean sediment yield of each group of catchments (Tabs. 9 and 10) was compared to the sedimentation measurements of their reference reservoirs. In particular, the results of the "Forni" and "Spöl" groups were related to the amount of sediment estimated by bathymetric surveys in the San Giacomo and Cancano reservoirs. As a matter of fact, these two reservoirs are set in series and, according to the reservoirs manager, most of the sediment that settles down in Cancano comes from suspended load from the San Giacomo reservoir, because the watershed directly drained by Cancano is negligible. The Val Grosina reservoir is periodically emptied and the mean annual sediment yield is estimated by the observed variations of the bathymetry.

The amount of sediment settled down within these reservoirs is mostly representative of the fine sediment fraction: actually, the tyrolean intakes used at most of the barrages prevent the coarse fraction of sediments from entering into the diversion canals, where this fraction is further intercepted within settling basins. However, *EPM* estimates include the full spectrum of particle sizes and, accordingly, they are not directly comparable with the measured data. In order to evaluate the relative importance of the volume of fine sediments with respect to the overall sediment production estimated by *EPM*, a soil sampling campaign, aimed at measuring the granulometric curves, was accomplished in nine watersheds within the investigated area (see filled squares in Fig. 1). The sites are mostly located on accessible slopes rather than in streams and they were selected in order to obtain a sufficiently complete coverage of the study area. Since the studied basins are in most cases small and characterized by high energy geological processes, the granulometric distribution of sediments might be considered scarcely affected from the sampling location and, accordingly, it was assumed representative of the entire basin. Fig. 5 shows the averaged granulometric curves for each group of catchments.

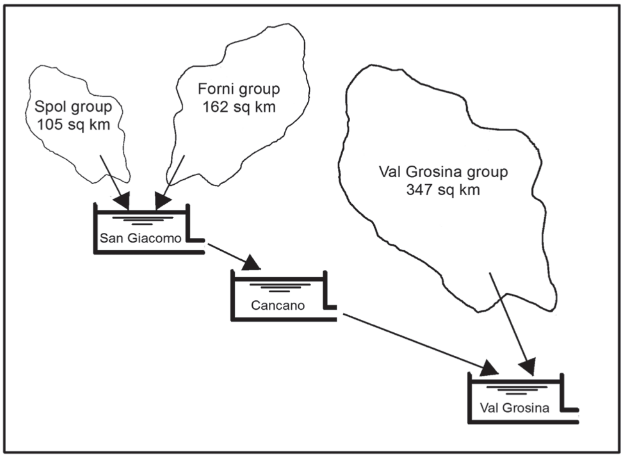

Fig. 4 - The connections between the studied groups of basins and the related reservoirs

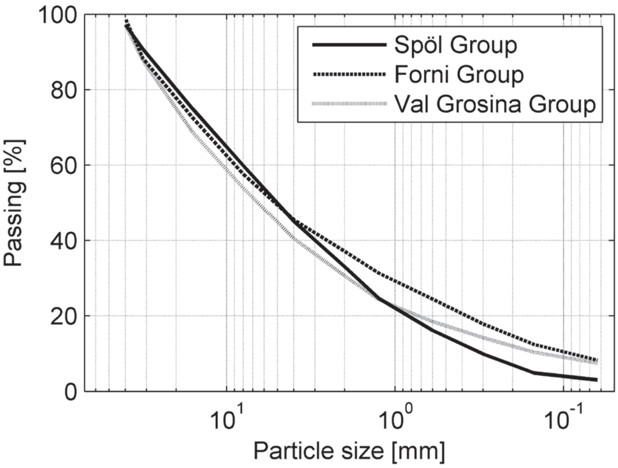

Fig. 5 - Averaged granulometric curves of the sampled soils

The percent of fine particles (Φ<0.15 mm) of each soil sample was computed using the granulometric curves. Although this percentage showed a remarkable variability, within each group of basins the samples were consistent. The "Spöl" group basins have a mean percentage of fine materials below 5%. For the catchments of the "Val Grosina" group and of the "Forni" group, this percentage is respectively 10% and 12%. Furthermore, other ag-

	“Forni” Group													
Basin code	1	2	3	4	5	6	7	8	9	10	11	12	13	14
F (km^2)	8.4	21.7	2.3	29.1	17.8	3.2	4.2	9.7	7.3	2.7	11.6	12.8	9.8	21.8
$h_{\max}$ (m a.s.l.)	3295	3667	3594	3755	3851	3240	3308	3850	3732	3552	3472	3089	3122	3040
$\hat{H}$ (m a.s.l.)	2728	2833	2892	3014	2909	2801	2883	2860	3021	2994	2819	2599	2577	2283
$h_{\min}$ (m a.s.l.)	2180	2168	2150	2171	2182	2291	2352	2192	2179	2222	2029	2023	2006	1870
i (m/m)	0.43	0.47	0.82	0.50	0.48	0.47	0.45	0.62	0.67	0.77	0.51	0.48	0.59	0.53
$t_1(\hat{H})$ (°C)	-0.6	-1.0	-1.2	-1.7	-1.3	-0.8	-1.2	-1.1	-1.7	-1.6	-0.2	0.7	0.8	2.0
$t_2(\hat{H})$ (°C)	5.2	4.8	4.6	4.1	4.5	5.0	4.6	4.7	4.1	4.2	5.5	6.4	6.5	7.7
$\Phi<0{,}15$ mm (%)	8	8	8	45	45	8	8	23	23	23	18	18	18	17.4

	“Spöl” Group								“Val Grosina” Group								
Basin code	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	9
F (km^2)	12.5	15.5	10.0	12.3	1.1	20.4	28.9	4.6	112.7	26.2	60.2	3.9	9.7	3.1	2.1	61.0	67.8
$h_{\max}$ (m a.s.l.)	3055	3294	3093	3130	2778	3089	3132	2907	3557	3042	3078	3146	3420	2992	2909	3372	3257
$\hat{H}$ (m a.s.l.)	2472	2655	2618	2577	2425	2545	2475	2434	2254	2151	1983	2352	2478	2337	2082	2279	2279
$h_{\min}$ (m a.s.l.)	1996	1998	2007	1978	1966	2001	1977	2019	1202	1227	1219	1233	1240	1440	1316	1168	1253
i (m/m)	0.54	0.57	0.53	0.60	0.39	0.51	0.47	0.47	0.58	0.73	0.52	0.57	0.70	0.64	0.83	0.64	0.60
$t_1(\hat{H})$ (°C)	-0.4	-1.2	-1.0	-0.8	-0.2	-0.7	-0.4	-0.3	1.4	2.5	3.9	2.9	2.4	3.0	3.5	2.7	2.7
$t_2(\hat{H})$ (°C)	6.1	5.3	5.5	5.6	6.3	5.8	6.1	6.2	7.6	8.2	9.3	8.3	7.8	8.4	8.9	8.1	8.1
$\Phi<0{,}15$ mm (%)	3	3	3	1.4	1.4	3	1.4	1.4	23	20	1.4	15	1.7	1.7	1.7	1.7	1.7

Tab. 9 - Main morphological and meteorological features of the considered basins, divided in three groups. The parameters t_1 and t_2 represent the average yearly temperature and the mean temperature of the period from May to October, both calculated at the mean altitude of the basin. h_{min} and h_{max} represent respectively the minimum and the maximum altitude of each basin

gregate granulometric data (Bassi, 2000) were measured for the Cedec and Frodolfo catchments (Fig. 1), where a fine sediment percentage of about 45% was measured.

In order to extrapolate the volume of fine sediments from the overall *EPM* estimates, the percentage of fine materials was assigned to each basin on the basis of the most representative granulometric curve, considering geographical proximity and geological criteria based on lithological and morphological characteristics of the basins. Finally, the amount of fine sediment yield from each group was computed by multiplying the total volume of sediment yield of each basin for the related percentage. The basins that are directly drained by the reservoirs contribute to the sediment yield with their whole sediment production.

A mean sediment yield of about 165000 m^3/y was calculated by *EPM* for the “Forni” and “Spöl” group of catchments. After 50 years of activity, a volume of about 800000 m^3 of sediment was measured within San Giacomo and Cancano reservoirs. This volume, that would correspond to an average input of 16000 m^3/y, is related to the fine sediment fraction from the “Forni” and “Spöl” groups and to the overall sediment yield from the basin that is directly drained by the San Giacomo reservoir. The fine sediment yield from the “Forni” and “Spöl” groups can be derived by the overall *EPM* computation by applying the percentages of Tab. 9 and amounts to 31000 m^3/y. The contribution from the basin directly drained by the San Giacomo reservoir increases this value up to 43500 m^3/y. Accordingly, for these two groups of basin *EPM* provides an estimate that is three times the measured values.

The application of *EPM* to the “Val Grosina” group of basins provided an overall sediment yield of about 168000 m^3/y, of which 17400 m^3/y are related to the fine sediment fraction. This value, increased to 35200 m^3/y by the sediment contribu-

Reservoirs	F (km^2)	W_{sp} (m^3/km^2/y)	G_{sp} (m^3/km^2/y)	R (-)	W (m^3/y)	G (m^3/y)	G_{fine} (m^3/y)
San Giacomo-Cancano	267.5	1078	617	0.57	288342	164980	30768
Val Grosina	346.9	740	486	0.66	256782	168590	17407
Frodolfo and Cedec basin	46.9	1058	741	0.72	49631	34786.13	15654

Tab. 10 - Averaged results of the application of EPM to the studied basins. The Frodolfo and Cedec basin is a subset of the "Forni" group

tion from the directly drained basin, can be compared to about 17500 m^3/y of sediments measured in the reservoir by bathymetric comparison.

In conclusion, as shown in Tab. 10, in both cases *EPM* overestimates the measured values of sediment yield, with a multiplicative factor that ranges from 1.5 to 3. Considering the range of uncertainty that affects this type of problems (e.g., Brazier *et alii*, 2006), the results obtained by the application of *EPM* are encouraging since they are of the same order of magnitude of the sedimentation data. A possible reason to explain the observed difference, in addition to the potential errors deriving from the application of the model into an environment different from the calibration one, is provided by the fact that during flood events, when relevant sediment transport occurs, the plants manager does not divert water to the reservoirs. This conclusion is supported also by the measurements accomplished at the confluence of the Frodolfo and Cedec streams (Fig. 1), where a turbidimeter was installed since 2009, so that information on the overall suspended load from these basins is available. This dataset provides a mean annual volume of suspended sediments of about 18000 m^3/y, to be compared with 16000 m^3/y of fine sediment yield provided by *EPM* for these two basins (Tab. 10). Since the turbidimeter registrations are not affected by the diversion regime, the measured mean annual volume of suspended sediments is directly comparable to the computed value. The match between the measured and the computed values of suspended sediment is very good and supports the reliability of the overall procedure.

CONCLUSIONS

In this paper we considered some simple improvements to stumbling blocks of the original *EPM* methodology, whose application entails ambiguities and operational difficulties that are mainly a consequence of the unclear parameters classification tables. Moreover, when applied in areas where the annual average temperature drops below -1 °C, a second difficulty arises, that is tied to the mathematical definition of the temperature coefficient (Eq. 2).

In this contribution we introduced some "physically based" changes to the classification system to increase the objectivity and the applicability of the model, making use, among others, of the widespread *Corine Land Cover* methodology. Moreover, since the most relevant erosion processes in cold areas are mainly concentrated in the thawing period and often related to intense rainfall events, we proposed to calculate the averaged hydro-meteorological parameters for this temporal window only. This modification to the original methodology allows to remove the operational difficulties for the assessment of the temperature coefficient in basins with negative mean annual temperature. Both these changes widen the application scope of the model and substitute the original classification with easy-to-use and more clear tables, without changing the global methodology. Some tests on two small alpine basins showed good agreement between the results obtained by the application of the modified version of *EPM* and of the original methodology.

A simple statistical analysis was performed to compare distributed and lumped applications of *EPM*. The results obtained with a set of synthetic watersheds showed maximum variations in sediment production up to 14% between the two approaches. Accordingly, the greatest advantage of distributed approaches is the possibility to preserve the physical meaning of the parameters and to represent the prevailing mechanics of soil erosion processes. Moreover, it allows to locate easily the sediment production areas within the catchment and to quantify their specific contribution to the overall sediment yield.

Finally, *EPM* was applied to a set of 31 alpine catchments in northern Italy. In order to test the reliability of the results, they were compared to the sedimentation data of three reservoirs and to turbidimetric measurements. The model was applied for the period from May to October and it was implemented using a software specifically designed for a spatially distributed application along the drainage network. A mean overall sediment production of 165000 m^3/y and 168000 m^3/y was calculated for the catchments drained by the San Giacomo-Cancano and Val Grosina reservoirs respectively. In order to make comparable the calculated values with the measured siltation data (respectively, 16000 m^3/y and 17500 m^3/y) soil sampling and granulometric analysis were performed, reducing the above values to 43500 m^3/y and 35200 m^3/y. Considering the complexity of the involved processes and the high level of uncertainties (e.g., Brazier *et alii,* 2000), these results are in fair agreement with the measurements and the discrepancies can be partly explained by several considerations on reservoir management. This conclusion is supported by the results obtained for the Cedec and Frodolfo catchments, where the computed values of fine sediment yield (16000 m^3/y) are in good agreement with the integral of the turbidimetric measurements (18000 m^3/y). These two volumes are directly comparable since both account for fine sediment only and include sediment load carried during flood events. Accordingly, the link with widespread classification systems and the extension to alpine glacial and periglacial regions makes *EPM* a valuable and easy-to-use instrument for soil erosion mapping also in alpine areas.

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