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ANALYSIS OF THE TEMPORAL AND SPATIAL SCALES OF SOIL EROSION AND TRANSPORT IN A MOUNTAIN BASIN

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EXTENDED ABSTRACT

I processi di erosione superficiale in bacini montani possono avere significative implicazioni in numerosi ambiti: dalla gestione del suolo e delle strutture, alla pianificazione territoriale, ancora alla valutazione e mitigazione del rischio alluvionale. Per questo motivo una stima il più possibile affidabile dei volumi solidi coinvolti è di grande importanza. Numerosi sono i modelli di letteratura volti alla quantificazione del sedimento eroso; nell'ampio panorama di strumenti disponibili, la memoria considera il metodo dell'erosione potenziale, un modello empirico di semplice applicazione che è stato più volte usato in ambito alpino.

Il metodo dell'erosione potenziale è stato sviluppato intorno agli anni '70 dello scorso secolo con l'obiettivo di fornire stime di sedimento eroso su scala annuale. Più volte il modello è stato oggetto di avanzamenti, ad opera dello stesso ideatore nonché di altri autori. Gli sviluppi successivi hanno mantenuto una scala temporale di supporto relativamente ampia (un anno o comunque alcuni mesi). Il presente lavoro intende esplorare le possibilità di riduzione della scala di supporto temporale, con una motivazione prevalentemente legata a un intento degli autori di legare la produzione e l'apporto solido ai corsi d'acqua con la dinamica morfologica fluviale durante un evento alluvionale di breve durata. Infatti, la produzione di scenari di pericolo alluvionale per ambiti montani impedisce spesso di disaccoppiare il ruolo della frazione liquida da quello della frazione solida. La riduzione della scala temporale di riferimento, da qualche mese a qualche giorno, si accompagna con la riduzione della scala spaziale. Il modello non è applicato con riferimento a un intero bacino ma a un gruppo di sottobacini opportunamente definiti. Le caratteristiche dei vari sottobacini, così come richieste per l'opportuna parametrizzazione del modello, sono determinate grazie a sistemi informativi territoriali.

Il bacino montano considerato è quello della Valmalenco, sito nell'Italia settentrionale e percorso dal torrente Mallero. Un evento alluvionale pregresso (relativo alla ben nota alluvione della Valtellina del 1987) è usato per creare uno scenario centenario. La valutazione dell'apporto solido alla chiusura del bacino è condotta in diverse maniere: (i) considerando una scala temporale ampia e il bacino nel suo insieme, (ii) con riferimento a una scala temporale ampia ma introducendo la divisione in sottobacini e (iii) riducendo tanto la scala spaziale quanto quella temporale.

I risultati ottenuti sono suscettibili di diversa interpretazione. Da un lato, l'applicazione a scala di evento conduce a stimare circa il 20% della produzione annuale, indicando che in effetti alcuni eventi significativi possono mobilizzare tutto il materiale solido che raggiunge la chiusura del bacino in un anno. D'altro lato, però, evidenze storiche per il bacino in esame (si può per esempio citare ancora l'evento del 1987) hanno mostrato che un singolo evento può trasportare volumi solidi ben maggiori di quelli annuali, difficilmente ottenibili con il metodo dell'erosione potenziale anche ammettendo di forzare i parametri empirici corrispondenti all'uso e alla resistenza del suolo, nonché al grado di dissesto.

L'applicazione del modello a un gruppo di sottobacini mette anche in luce un ulteriore problema, questa volta legato alla composizione dei volumi solidi erosi in tutti i bacini. Si mostra che una semplice somma non può rappresentare la complessa dinamica di trasferimento del materiale solido da un bacino all'altro, e porta invece a stimare volumi di apporto solido molto elevati rispetto a quelli ottenibili dall'applicazione a scala di bacino.

Per cercare di dare una soluzione alle due incongruenze appena menzionate, si propone un'applicazione seriale del metodo dell'erosione potenziale. L'apporto solido di sottobacini posti in parallelo viene sommato, mentre l'apporto solido di bacini posti in serie viene progressivamente ridotto dalla composizione dei coefficienti di trasporto di sedimenti. È evidente che in tale maniera si corregge il problema della stima sovrastimata a causa della somma del contributo di tutti i sottobacini. Peraltro, quest'applicazione consente anche di spiegare l'altra incongruenza, relativa al fatto che eventi particolarmente intensi possano trasportare volumi di sedimento non spiegabili con i metodi di stima dell'apporto solido. Infatti, il volume solido eroso ma non trasportato a valle (in altri termini, il volume complementare a quello ottenuto dalla moltiplicazione in serie dei coefficienti di trasporto) contribuisce nel tempo a creare la disponibilità di materiale per gli eventi straordinari. Rispetto all'intento iniziale di determinare degli scenari di pericolo alluvionale tenendo in considerazione il ruolo della frazione solida, l'analisi dimostrerebbe che un'opportuna condizione al contorno per modelli di morfologia fluviale dovrebbe tener conto della produzione di solido tanto nel breve quanto nel medio-lungo periodo.

ABSTRACT

Analysis of erosive processes and sediment transport in mountain environments has numerous implications for proper river basin management, land use planning as well as flood risk evaluation. Temporal and spatial scales of these phenomena may vary greatly during intense precipitation events with respect to normal conditions, thus introducing significant differences between long- and short-term related sediment yield and transport. In this work, the Erosion Potential Method is applied to Alpine catchments located in Northern Italy. Method downscaling in space and time is proposed to estimate an event-related sediment yield rather than an annual one. Interpretation of the results suggests that the long-term sediment accumulation could control the volumes transported during a single storm. Thus, some considerations on the estimation of long-term related sediment yield are further introduced. Finally, a 'chain' routing pattern of sediment yield through consecutively positioned basins is suggested as an alternative to a simple sum of the eroded volumes of all contributing basins when a subdivision of the catchment is adopted. Emphasis is put on the validity of the result with respect to the classical application of the method as well as on its usefulness for an integrated assessment of hydro-geological flood risk.

Keywords: *Erosion Potential Method, soil erosion, sediment transport, hydro-geological hazard*

INTRODUCTION

Sediment transport in mountain streams has been progressively receiving more scientific as well as engineering attention in the past decades. This phenomenon has numerous environmental impacts in terms of land use planning (Pimentel *et alii*, 1995; Brown *et alii*, 1998; Montgomery *et alii*, 2000), agriculture (Haddadchi *et alii*, 2014), reservoir sedimentation (Gunatilake & Gopalakrishnan, 1999; Amitrano *et alii*, 2013; De Miranda & Mauad, 2014) as well as geomorphological evolution of river beds with possible implications in terms of flood risk (Dotterweich, 2008; Mandelli *et alii*, 2009; Ballio *et alii*, 2010; Radice *et alii*, 2013). The spatio-temporal variability of sediment transport between hillslopes and channels has been the focus of various studies. Its effect of linking distinct landforms or landscape units has been termed geomorphic coupling (Harvey, 2001). Moreover, sediment sources and sinks are often coupled through sediment cascades (Burt & Allison, 2010), where a sediment storage build up by one geomorphic process is depleted by another process. Further, the integrated effect of hillslope to channel (lateral) and coupling between reaches (longitudinal) is defined as sediment connectivity (Heckmann & Schwanghart, 2013). Connectivity or in fact disconnectivity impedes continuity of the processes within a catchment and thus to an inconsistency between erosion processes and sediment yield at the outlet of a basin, which varies with spatial scale as discussed by De Vente *et alii*, 2007, among others. Catchments with diverse geographic and geomorphic configurations respond differently to the same climatic forcing (Wainwright, 2006), where particular attention can be devoted to mountainous regions.

It can be argued that sediment material in such environments originates as a combination of different ongoing geological processes, defined as: splash, sheet, rill, and gully erosion, river bank erosion, and shallow mass movements (De Vente & Poesen, 2005). Sediment is then transported mainly through the hydrographic network, eventually reaching deposition spots or the basin outlet. Although the effects of these processes are typically perceivable as morphological changes in long terms (several decades), mountain environments provide conditions which can significantly accelerate erosion dynamics in comparison to lowland ones, thus making sediment movements significant even for events of short duration such as several tens of hours (Sear *et alii*, 1995; Stover & Montgomery, 2001; Lane *et alii*, 2007). Furthermore, short-term erosive activity is undoubtedly amplified by the intensity of the event. Erosion-stimulating conditions have been summarized by Klaassen *et alii* (1997) as: 1) a small basin leads to a swift time response of the system to intense and localized rainfall events; 2) steep slopes generate high flow velocities; 3) sediment transport phenomena can be very intense, as is the case during flash floods. The latter is of a particular interest since it results in sudden morphological change of the riverbed, with possible damage to structures or increase in water level due to channel aggradation (Radice *et alii*, 2012 and 2013). Therefore, a difference in time scales between the erosive processes and the morphological changes could become negligible or even non-existent. Historical events evidence the destructive nature of such phenomena. A past event that will be also referred to in the following is the flood that took place in Valtellina in July 1987.

A coupled approach between erosive activity and morphological changes due to sediment transport should be undertaken when dealing with flood risk analysis in mountain areas as pointed out by different authors (e.g. Jaeggi, 2008; Rickenmann & Koschni, 2010; Radice *et alii*, 2013). International guidelines, such as the European Floods Directive (2007) recognize the importance of such an argument by stating that flood risk maps should include information about "areas where floods with a high content of transported sediments and debris floods can occur." Hydro-morphologic river models are mostly based on shallow-water equations for one or two-dimensional frameworks, with the former (e.g. Papanicolaou *et alii*, 2004; Chiari *et alii*, 2010; Rosatti *et alii*, 2011) generally used for mountain environments where the possibility for lateral diversion of water is limited as opposed to lowland streams. In general, a given river reach is modelled in detail and a supply of water and sediment mass from the upstream area of the catchment is taken into account (e.g. Wright *et alii*, 2010; Mazzorana et alii, 2013) as an appropriate boundary condition. The present paper is indeed focused on the catchment erosion as the supplier of sediment material.

Estimation of sediment yield can be carried out by means of diverse models of varying nature, which were, for example, categorized by De Vente & Poesen (2005) in decreasing order of complexity as: physically based, conceptual, semi-empirical and empirical models. Different models are characterized by varying complexity, spatial resolution, type of erosion taken into account, applicability, etc. A good balance between different model characteristics and validity of its results is often found in the use of the Gavrilovic formula, with several application examples reported by De Vente & Poessen (2005) on a range of basins of different size and location. Further examples of application with a specific focus on alpine and pre-alpine catchments can be found, among others, in Ballio *et alii* (2010), Brambilla *et alii* (2011), Mazza *et alii* (2011), and Milanesi *et alii* (2015). However, a major drawback of the model may appear when the aim of the study is to perform an integrated flood risk assessment, as the method was developed to estimate a mean sediment yield over one year. A scale mismatch emerges due to a need to provide short-term sediment erosion volumes in mountain regions and the lack of appropriate models for such a purpose.

The target of this study is (i) an attempt to model an event-induced sediment yield by method downscaling in time and (ii) a discussion of the significance of short-term erosive activity due to intense rainfall events in mountain regions. The reference case-study of the Mallero River and its hydrologic catchment (in the Italian Alps) is used. Moreover, the river basin is divided into sub-basins with homogeneous features. Sub-basin division, which is the spatial counterpart of time downscaling, will also require some specific treatment of the sediment routing in consequent sub-basins. The manuscript is organized as follows: first, the case-study area is described. Further, the Gavrilovic method is introduced along with the proposed downscaling. Results of the model application to the relevant case-study are presented and discussed in terms of their validity and applicability as a boundary condition for a hydro-morphologic river model.

PRESENTATION OF THE CASE STUDY

The river basin is located in Northern Italy (Fig. 1), with an area of about 320 km^2 and an altitude ranging from 280 to 4,050 m a.s.l. Average precipitation is between 1,000 and 1,500 mm/year, with higher values generally corresponding to higher elevations. Significant lithological heterogeneity is documented, including various metamorphic and sedimentary rocks. At the highest elevations, outcropping metamorphic and magmatic formations with local debris cover are present (Montrasio *et alii*, 2005) Glacial deposits cover a wide surface of steep slopes at altitudes between 2,100 and 2,400 m a.s.l., whereas at higher altitude only localized glacial deposits can be found. The lower part of the valley is covered by glacial, fluvio-glacial, and colluvial deposits of variable thickness (Crosta *et alii*, 2003). The soil cover is mostly associated with bare rock (34% of the total area), coniferous (20%), broad-leaved (4.5%) and mixed forests (3.2%), sparse vegetation (13.5%), and glaciers and permanent snowfields (8.4%). Several landslides occurred throughout the basin, with the largest rock landslide located near the town of Spriana, also indicated in Fig. 1 (Longoni *et alii*, 2014). Inhabited areas account for 1% of the total surface of the watershed. The most populated town of the valley (Sondrio, with around 22,000 inhabitants) is located close to the downstream section of the basin. The 25-km long Mallero River is the major water stream of the basin. The springs of the river are located at an altitude of 1,650 m a.s.l., while the downstream section of the watershed coincides with the inflow of the Mallero into the Adda River, which is the main watercourse of Valtellina.

Several flash floods occurred in the past: events have been reported for 1817, 1834, 1885, 1911, 1927 and 1987 (Molinari *et alii*, 2013). The existing documentation highlights that flood hazard for Sondrio is mostly related to reduction of channel conveyance due to sediment deposition. The flood of 1987 was relatively well documented by some post-event studies (e.g. Ismes & Cae, 1988a, 1988b; Italtekna *et alii*, 1989, 1990) which estimated for that flood a peak discharge of 500 m^3/s, compared to 640 m^3/s corresponding to a return period of 100 years. The total sediment volume mobilized throughout the catchments was 3×10^6 m^3. The sediment yield into the river 5 km upstream of the confluence was estimated as equal to 7×10^5 m^3 (with no further significant yield from the valley slopes downstream of that location). Around 2.2×10^5 m^3 were deposited in the in-town reach, with aggradation depths up to 5 m that represents a significant fraction of the total bank height (ranging from 5 to 8 m in the in-town reach). Figure 2 depicts the severity of the flood during the event.

THE EROSION POTENTIAL METHOD

The estimation of soil erosion at different scales is often carried out by models of diverse nature, based on their characteristic features. Such models can be divided into three main categories: physically based, conceptual, semi-empirical and empirical models (Aksoy & Kavvas, 2005). Physically based models (e.g. CREAMS, KINEROS, EUROSEM, LISEM, WEPP) rely on considerable amounts of input data and may involve significant computational effort in order to account for

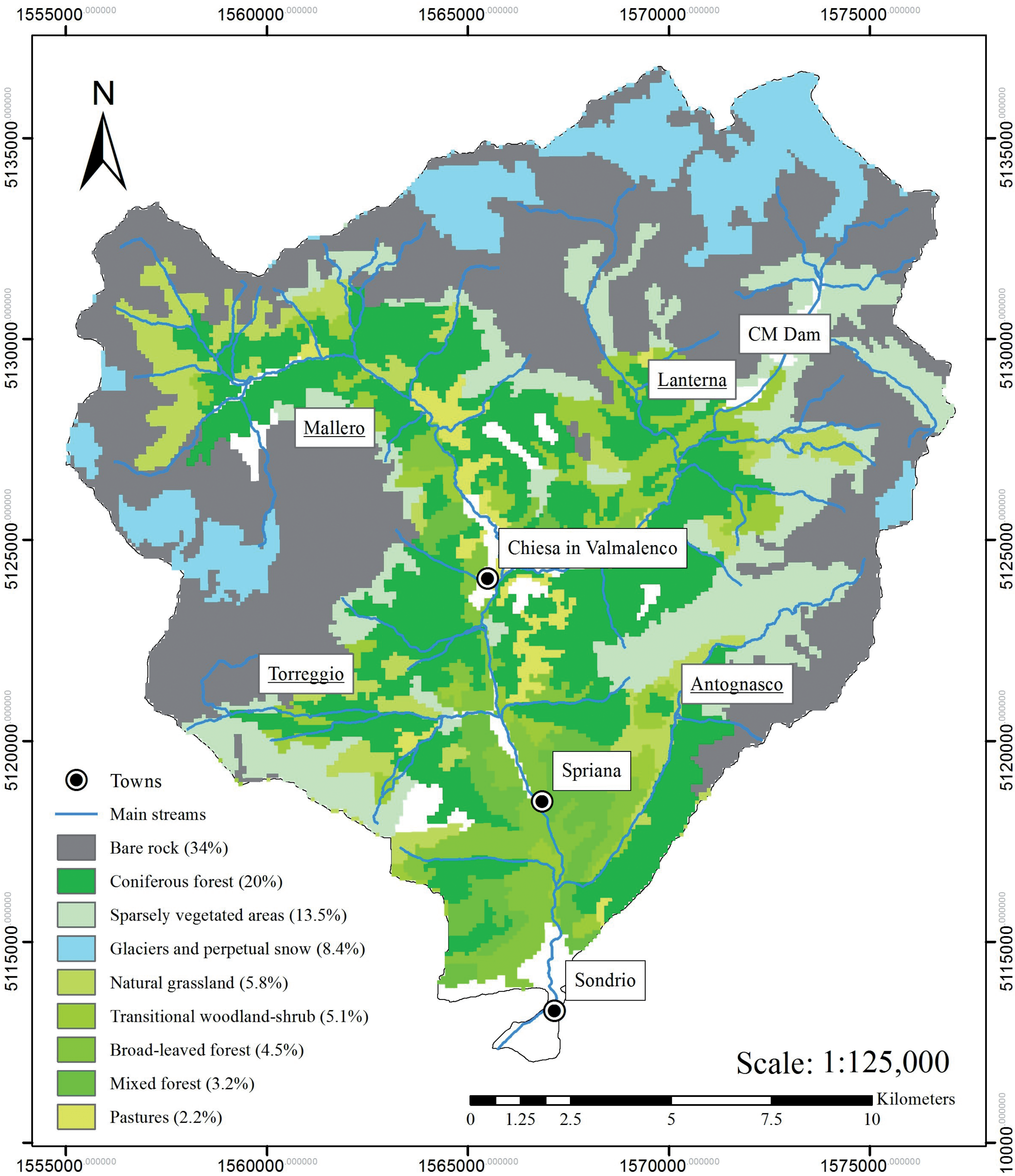

Fig. 1 - The Mallero basin located in Northern Italy. Some towns are located along the course of the Mallero river, as indicated in the map. Major streams are indicated in underlined text. Land cover classes are associated to the basin according to the Corine Land Cover classification system. Spatial Reference System: Monte Mario (Rome 1940)/Italy zone

physical mechanisms of erosive processes through conservation principles and constitutive equations (Milanesi *et alii*, 2015). Conceptual models link conservation equations and empirically derived relationships to provide erosion estimates. They are regarded as a compromise between the complexity of physically based and the less demanding empirical models. The latter offer the opportunity for a quick and easy calculation using a set of parameters that are considered the most relevant for erosion in the light of experimental data. Such models have found a widespread application (De Vente & Poesen, 2005) and, despite their simplicity, they usually provide a valid soil loss estimation, as long as they are applied on regions characterized by similar geomorphic features as those where they were calibrated (Milanesi *et alii*, 2015). Among the most widely applied empirical methodologies, the Universal Soil Loss Equation (USLE, Wischmeier & Smith, 1978) and its derivatives (RUSLE, MUSLE) are used for the estimation of erosion. However, their conception and calibration has been carried out on agricultural areas and therefore their application for different environments would most likely provide inaccurate erosion estimates. On the other hand, the application of the Erosion Potential Method (EPM henceforth) for mountain areas (Gavrilovic, 1962, 1970, and 1972) benefits from the advantage the advantage of being calibrated on the basis of laboratory and field data from the Dinaric Alps. Therefore, it is suitable for the estimation of soil erosion in various areas regardless of their specific mode of land use, such as e.g. agriculture (Gavrilovic, 1994; Zorn & Komac, 2009). The EPM has been considered applicable to regions of similar geographical characteristics: semiarid Mediterranean regions (e.g. Globevnik *et alii*, 2003; Emmanouloudis *et alii*, 2003; Tangestani, 2006; Solaimani *et alii*, 2009; Bozorgzadeh & Kamani, 2012), Alpine (e.g. Pozzi *et alii*, 1990; Mikos *et alii*, 2006; Fanetti & Vezzoli, 2007; Zorn & Komac, 2009; Ballio *et alii*, 2010; Brambilla *et alii*, 2011b; Mazza *et alii*, 2011, Milanesi *et alii*, 2015) and Apennine areas (Tazioli, 2009), where the former has been successfully studied also by means of other empirical methods (e.g. Della Seta *et alii*, 2009). The method has taken advantage of the development of digital cartography and GIS software, which facilitate its application.

The EPM is based on the empirical equation (1), which provides a mean annual sediment yield that is the result of sediment erosion given by (2) and sediment routing towards the outlet of the basin, obtained through (3). The EPM accounts for lithological, topographic, climatic, and land-cover quantities according to the following set of formulae:

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

$$W = \pi \times T \times H \times F \times Z^{3/2} \tag{2}$$

$$R = 4\frac{\sqrt{O \times \Delta D}}{\left(l_p + 10\right)} \tag{3}$$

Fig. 2 - a) The Mallero River and b) the town of Sondrio during the flood of July 1987 (Images courtesy of geologist Maurizio Azzola)

$$T = \sqrt{0.1 + \frac{t}{10}} \tag{4}$$

$$Z = \Xi \times \Pi \times (\Phi + s^{0.5}) \tag{5}$$

where the following correspondences apply:

- G annual sediment yield [m^3]
- W gross annual erosion [m^3]
- R routing coefficient [-]
- T temperature coefficient [-]
- H mean annual rainfall depth [mm]
- F area of the catchment [km^2]
- Z erosion coefficient [-]
- O perimeter of the catchment [km]
- ΔD difference between mean elevation and elevation at the outlet of the basin [km]
- l_p length of the main water course [km]
- t annual average temperature [°C]
- Ξ coefficient of soil cover [-]
- Π coefficient of soil resistance [-]
- Φ coefficient of type and extent of erosion [-]
- s average valley slope [-]

Several modifications of the method have been suggested in the literature, stimulated by its application to various case studies. The changes proposed aimed at facilitating the EPM application to a broader range of catchments, removing some of its operational difficulties as well as accounting for extreme precipitation conditions.

It has been argued that mean annual values of rainfall depth would damp the effect of extreme rainfall events, which could indeed be strong enough to erode and mobilize large sediment quantities. Therefore, Zorn & Komac (2009) proposed the use of the maximum daily rainfall for the estimation of the mean annual sediment yield.

The mean temperature in mountain regions often has negative values. However, the originally proposed temperature coefficient, *T*, cannot be computed in areas characterized by a mean annual temperature below -1°C because of its definition. With reference to this issue, Milanesi *et alii* (2015), proposed the use of a mean temperature related to the active erosion period during the year only (May-October), which would exclude winter months characterized by negative mean temperatures. As a support for the mathematical trick, they argued that both soil and watercourses would be frozen, thus significantly decreasing the susceptibility of the terrain to erosion.

The routing coefficient R has been revised by Zemljic (1971) in order to incorporate more physically relevant features into the originally proposed formulation. The proposed equation (6) replaces a constant (most likely resulting from a calibration procedure) with the ratio of the cumulated length of all water courses to the area of the basin (hydrographic density). This modification remarkably limits the possibility that *R* assumes unphysical values larger than 1.

$$R = \frac{(l_p + l_a)}{F} \times \frac{\sqrt{O \times D}}{\left(l_p + 10\right)} \tag{6}$$

where l_a [km] is the cumulative length of the secondary water courses throughout the basin and *D* [km] is the mean elevation of the basin.

Further, Milanesi *et alii* (2015) elaborated a correspondence between the original classification tables (Zemljic, 1971; Gavrilovic, 1988) and the freely available maps of the Corine Land Cover classes. The proposed table has been validated on a case study in the Italian Alps by comparison between the results of the EPM and sediment yield data. This improvement facilitates the application of the method as it reduces ambiguity in the choice of appropriate parameter values. An example of the proposed correspondences is represented in Tab. 1, containing an extract of the aforementioned elaboration.

MODEL APPLICATION

The EPM has been applied to the case study in three modes. Modes 1 and 2 are concerned with the classical application of the formula along with the implementation of some improvements proposed in the literature as previously described (e.g. Zorn & Komac, 2009; Milanesi *et alii*, 2015). The formula has been applied both to the entire area as a single basin (mode 1) and to each sub-basin separately (mode 2). In the latter, the total sediment yield has been computed as the sum of each individual contribution. Finally, mode 3 features an attempt to downscale the model in time by reconsidering the relevance of some of its variables and to be consistent with a short-term intense rainfall event. Mode 3 involves the spatial downscaling described above as well.

SPATIAL DOWNSCALING

The entire Mallero catchment has been divided into twelve hydrographic sub-basins (Fig. 3) with areas ranging from 11 km^2 to 53 km^2. This introduced a spatial downscaling into the application of the model, where an average value of the relevant parameters has been estimated for each sub-basin. Since Campo Moro Dam would capture the sediment eroded from upstream, only the fraction of the area of sub-basin 12 downstream of the dam has been considered relevant for the estimation of the total volume. In addition, no contribution to the total sediment yield has been considered from sub-basin 1 since its area is occupied by the town of Sondrio and its surroundings.

Mean annual rainfall depth data interpolated over the area of the Mallero basin have been obtained from the regional environmental authority (ARPA Lombardia) and a mean value

EPM (Gavrilovic, 1988)	Ξ	Zemljic (1971)	Ξ	Milanesi *et alii* (2015) on the basis of Corine Land Cover classes (EEA, 2000)	Ξ
Denudated unarable lands (badlands)	1.00	Areas without vegetation cover	0.80-1.00	1.3.1. Mineral extaction sites 1.3.3. Construction sites 3.3.1. Beaches, dunes, sands 3.3.2. Bare rock 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				

Tab. 1 - Correspondence between the Corine Land Cover classes (EEA, 2000) and the originally proposed classification tables

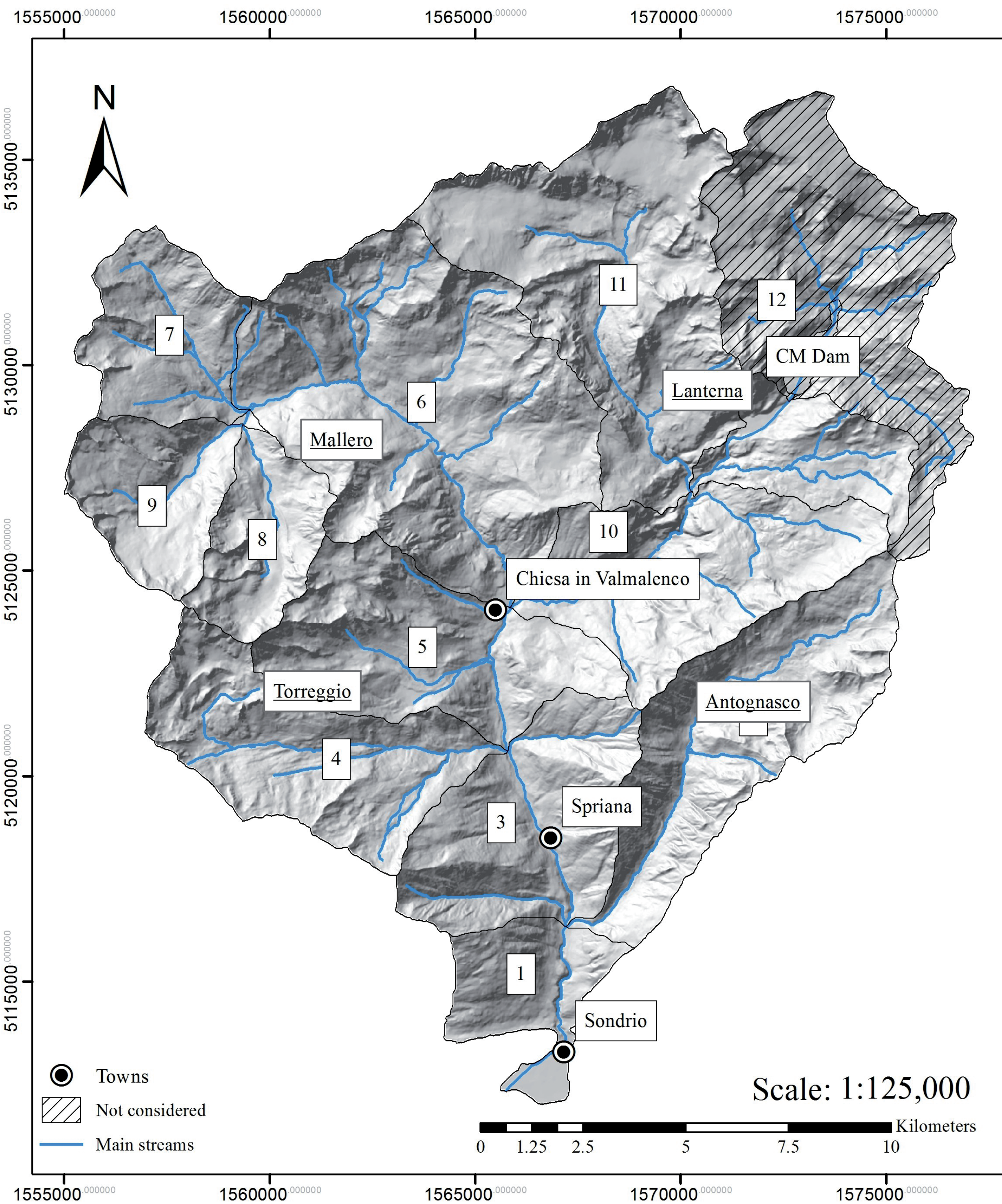

Fig. 3 - Basin subdivision. Spatial Reference System: Monte Mario (Rome 1940)/Italy zone 1

for each sub-basin has been estimated.

Due to the lack of availability of distributed temperature data, the values recorded at the weather stations in Sondrio and Chiesa in Valmalenco (Fig. 1) have been extrapolated for each sub-basin, through the application of the mean lapse rate (7) that relates changes in elevation to changes in temperature (ICAO, 1993). As a result, a mean temperature value for each sub-basin has been estimated.

$$\gamma = -(\Delta t/\Delta z) \approx -6.4°C/km \quad (7)$$

The geometrical features of the catchments have been estimated by means of a GIS software and are summarized in Tab. 2. The calculation of the routing coefficient R is based on the reported characteristics, which determine what fraction of the eroded sediment, would reach the outlet of each sub-basin. For the estimation of the land cover coefficient Ξ the European land use classification system (Corine Land Cover system) has been used due to its widespread availability. Exploiting the proposed correspondence with the original classification tables, each land cover class has been assigned a coefficient, which was averaged in space accounting for the relative presence of each soil cover in each sub-basin. The main classes accounting for 96.4% of the total basin area and their respective coefficients are reported in Tab. 3.

The choice of the erodibility coefficient Π and the coefficient of type and extent of erosion Φ requires a rather detailed knowledge of the geomorphological features of a basin, particularly in large scale basins, such as the one examined in the current work. Despite the improvements related to their choice suggested by Milanesi *et alii* (2015), the evaluation of soils' particle size, rock mechanical characteristics and the relative presence of erosive landforms such as localized bank erosion would involve extensive field work (e.g. Longoni *et alii*, 2016) as well as laboratory experiments. Therefore, the choice of values related to those coefficients has been made on the basis of case studies with similar geographical characteristics, for example: the Tartano Valley (Ballio *et alii,* 2010; Mazza *et alii*, 2011), the Rossiga Valley (Brambilla *et alii*, 2011), and the Cancano Valley (Milanesi *et alii*, 2015). Moreover, in order to address the uncertainty associated with the choice of those coefficients, constant minimum and maximum values have been assigned to each sub-basin in order to define a range of sediment yield volumes. Π adopts values of 0.5 and 1.3, while Φ ranges from 0.2 to 0.4.

TEMPORAL DOWNSCALING

A downscaling in time of the EPM is proposed as an attempt to estimate an event-related sediment yield. The downscaling procedure involves the use of event-related precipitation values as well as mean temperature characteristic for the summer season (June, July, August) since this period of the year is characterized by heavy rainfalls of high intensity and short durations. The intensity of such events is comparable to the aforementioned flood of 1987, which involved significant sediment yields and transport rates and therefore represents a prototype situation for an integrated hydro-geological risk assessment.

The relevant rainfall depth for a 100-year return period was estimated on the basis of Depth-Duration-Frequency (DDF) curves, to be used as H in (2). DDF curves were expressed as:

Basin ID	F [km^2]	O [km]	D [km]	l_p [km]	l_a [km]	s [-]	R
1	11.00	18.98	0.80	5.14	6.21	0.50	0.27
2	29.64	29.06	2.17	13.89	53.98	0.73	0.76
3	23.29	20.66	1.41	4.82	39.02	0.73	0.69
4	25.08	25.69	2.21	8.67	28.44	0.57	0.60
5	25.60	25.05	1.82	3.82	30.34	0.60	0.65
6	53.10	32.62	2.08	11.03	93.67	0.62	0.77
7	14.19	17.09	2.46	12.44	35.47	0.65	0.98
8	11.22	14.96	2.54	4.35	5.31	0.73	0.37
9	13.12	15.10	2.53	4.67	16.46	0.70	0.68
10	26.61	25.85	1.86	6.54	55.88	0.63	0.98
11	42.73	34.69	2.66	9.25	33.65	0.60	0.50
12	46.33	43.78	2.68	7.47	65.55	0.51	0.98
Downstream of CM Dam	11.42	19.09	2.28	7.28	14.90	0.52	0.74
Entire basin	320	92	2	92.5	464	0.61	0.22

Tab. 2 - Geometrical features of the sub-basins and corresponding values of the routing coefficient R

Fraction [%]	Corine Land Cover class (EEA, 2006)	Ξ
33.9	Bare rock	0.9
19.9	Coniferous forest	0.1
13.5	Sparsely vegetated areas	0.8
8.4	Glaciers and perpetual snow	0.9
5.8	Natural grassland	0.6
5.1	Transitional woodland-shrub	0.4
4.5	Broad leaved forest	0.1
3.2	Mixed forest	0.1
2.2	Pastures	0.5

Tab. 3 - Land cover coefficient, Ξ. Values of the coefficient chosen according to the tables proposed by MILANESI et alii (2015)

$H = a \times w \times t_c^n$, where a is the scale invariance coefficient, w is the rainfall quantile depending on the return period, t_c is the time of concentration of the basin and n is the duration exponent. Parameter values were provided for the Lombardia region by DE MICHELE *et alii* (2005): a = 18 mm/hour^n; w = 2.1; n = 0.44. The time of concentration t_c has been estimated on the basis of the 100-year return period flow hydrograph estimated for the Mallero River (ITALTEKNA *et alii*. 1990). Since the hydrograph reaches its peak in 30 hours, this duration was used as a time of concentration, obtaining H = 170 mm. In the absence of more specific data, this value was assumed constant over the area of the case study.

RESULTS AND DISCUSSION

Table 5 includes the results obtained from all the approaches. Ranges of values correspond to the variability of the parameters across the sub-basins. Moreover, minimum and maximum values associated with the coefficients of erodibility and type and extent of erosion are presented in order to address the uncertainty of the method and the sensitivity to its most arbitrary parameters.

The introduced spatial downscaling shows a significant difference in results when compared to a single basin computation (for example, maximum G values in Tab. 5 change from 125,000 to 357,600 m^3 when moving from mode 1 to mode 2). This can be explained with the use of average values for the parameters involved in the computation. Indeed, averaging geomorphic and meteorological characteristics over such a vast area is likely to overlook local effects of the individual parameters (e.g. slope, perimeter, elevation). Another reason for the difference is summing the G values for the sub-basins, which discards complex sediment migration dynamics at the larger scale. Namely tributary junction and reach-to-reach coupling (HARVEY, 2002) are disregarded in such a framework. The degree of such coupling (connectivity) considered within mode 2 is however influenced by the level of subdivision chosen prior to the computation. The detailed quantitative description of this effect is however yet to be explored.

The proposed application of the method for an event-related sediment yield stimulates a twofold interpretation. On one hand, the outcome of the downscaled approach represents more than 20% of the annual sediment yield. Considering such a significant percentage, the result is in accordance with the statement that high intensity events of short duration control the sediment production in a basin (KIRCHER *et alii*, 2001; LENZI *et alii*, 2006; DELLA SETA *et alii*, 2009). Moreover, such events show the tendency to increasingly dominate the sediment transport in rivers in future, according to global climate models (VERHAAR *et alii*, 2011). Furthermore, the erosion and transport of sediment material would be extremely different under conditions of intense precipitation due to the direct impact of rainfall, its soil destabilizing effect as well as the increased energy of the streams. An analogy could be found between the proposed downscaling and the adaptation of the Universal Soil Loss Equation to an event-related sediment yield estimation, where the erodibility factor of the formula has been modified so as to include parameters characteristic for a single rainfall event (MUSLE) without introducing any changes in the general formulation of the method. Moreover, comparisons of post event sediment yield data to mean yearly values often indicate that a calamitous rainfall event has the capacity to greatly increase rates of erosion production as well as the transport of sediment volumes that could be similar to the mean yearly ones (e.g. ZORN & KOMAC, 2009) or, in fact, even several times larger (e.g. KIRCHER *et alii*, 2001). Indeed, post-event estimations related to the 1987 flood event recorded deposited volumes of around 7×10^5 m^3 in the last 5 km to the outlet of the Mallero basin, to be compared to 8×10^4 m^3 computed in mode 3 of the current application. Therefore, the result of the downscaling approach could be interpreted as a short-term related sediment yield only, without taking into account the possibility that eroded sediment could have concentrated within

	t [°C]	H [mm]	T [-]	Z [-] Π_{min}, Φ_{min}	Z [-] Π_{max}, Φ_{max}	W [m^3] min	W [m^3] max	G [m^3] min	G [m^3] max
Mode 1	8.03	1,190	0.94	0.3	0.6	222,000	554,000	50,000	125,000
Mode 2	4.6 - 11.8	925 – 1,500	0.75 - 1.13	0.1 - 0.69	0.24 - 1.02	2,600 – 55,000	9,300 – 130,000	134,300	357,600
Mode 3	7.2 - 14.8	170	0.91 - 1.26	0.12 - 0.82	0.3 - 1.27	650 – 11,900	2,100 – 26,800	28,800	83,100

Tab. 5 - Result of the application of the EPM. Ranges of values correspond to the variability across different sub-basins, while the 'min' and 'max' columns indicate the variability of the results with respect to the minimum and maximum values chosen for the parameters Π and Φ the basin in the longer time scale. It can be argued that there is a considerable accumulation of sediments, which is readily available throughout the basin and can be mobilized during an event of particular (threshold exceeding) intensity. Such accumulations are probably built-up during regular conditions, when erosive processes do not occur with the same intensity and thus, sediment material remains deposited on the hillslopes throughout the basin. Hence, the long-term sediment production would be controlled by accumulations, which build up during the time gap between calamitous events (recovery time). More precisely, during a flood of particular magnitude the entrained sediment material would be the combination of the direct erosive activity of the storm (short-term related) and the material, which is already present as a consequence of previous, milder events which took place during the timespan between two major calamitous events (long-term related). Several authors have explored such catchment behaviour through monitoring of experimental catchments. Harvey (2002) describes the coupling between hillslopes and streams where eroded sediment is stored at gully bases, later eroded by floods each 2-6 years. In their work, Gallart *et alii* (2013) discuss the prevailing effect of infrequent runoff events to mobilize sediment loads in the long-term evolution of humid bandlands in terms of sediment transport and form connectivity.

When dealing with hydrogeological risk evaluation, emphasis should be put on the long-term sediment yield estimation in order to define the proper boundary conditions for a hydro-morphological model. An application of the EPM for the purpose of long-term sediment yield estimation could be realized by changing the perspective in the analysis of the routing coefficient R. More precisely, if this coefficient indicates the portion of the total sediment yield that is effectively transported to a basin outlet in a year, the remaining volume, $G_{deposited} = W\,(1\text{-}R)$, then accumulates as a readily available material and could potentially be mobilized during an extreme rainfall event of a following year. For instance, the sediment volume which did not reach the outlet of sub-basin 4 (Fig. 4a) during one year would be: $G_{4,\,deposited} = W_4\,(1\text{-}R_4)$. It should be however noted that each year is characterized by different meteorological features and therefore sediment accumulated during one year may be mobilized immediately in the next one or could continue to build up until the subsequent severe storm. The basin subdivision (or, in other words, the spatial downscaling) introduces another arguable element in the application of the EPM that could be analysed in conjunction with a hydraulic model. The coefficient *R* indicated what fraction of the gross annual volume reaches the outlet of each sub-basin, it has to be considered that each consecutive sub-basin would receive the sediment yield from upstream. Therefore, being transported downstream, the received material would be subject to the same conditions as the gross erosion volume produced in the sub-basin and thus, should be factored by the corresponding routing coefficient. A scheme depicting the suggested routing behaviour is presented in Fig. 4b. In the case of the Mallero basin, in order to reach the outlet of sub-basin 6, the sediment yield arriving from the outlets of sub-basins 7, 8, and 9 needs to be factored by the routing coefficient of sub-basin 6 and so forth. An application of the proposed routing scheme shows that the sediment yield at the inlet of sub-basin 1 would be around 200,000 m^3 or slightly more than 50% of the maximum yearly sediment yield computed with mode 2 in Tab. 5. This opens another perspective to the long-term accumulation of sediment, where a considerable portion of the eroded material is in fact not transported to the outlet of the basin. This consideration is usually not applied and the total amount of sediment yield at the outlet of the basin is computed as the sum of the volumes estimated for each sub-basin (De Vente & Poesen, 2005), such as in mode 2 here. This leaves a void in the application of the EPM, since it was conceived and calibrated on a single catchment with homogeneous geomorphic features. The behaviour of sediment erosion and transport in a succession of sub-basins would doubtlessly be different and therefore, the routing and deposition of sediment would follow a different model, such as the ‘chain’ pattern hypothesized earlier. However, *R* has been designed and calibrated to encompass the fraction of erosion due to hillslope as well as fluvial processes. Thus, its application to an eroded volume that is essentially transported solely by the main river stream could under or overestimate the actual transport rate. Hence, such a hypothesis requires an extensive analysis and possible differentiation between hillslope and fluvial processes. An insight on the sediment transport capacity of a stream could be further obtained by means of a hydro-morphological model. The use of more complex models would also be an advance in this field. A distributed model for the simulation of water and sediment budget has been developed, for example, by Bemporad *et alii* (1997). In that case, the erosion driving phenomena were modelled at the raster cell scale. A similar model is the CAESAR-Lisflood model (Coulthard *et alii*, 2013), which incorporates a landscape evolution model and a simplified 2D flow model to simulate long-term (hundreds – thousands of years) erosion and deposition over catchments of relatively large scale (hundreds of km^2). Although the numerical simulations prove to furnish adequate results, the high data demand and the required computational effort remain as main drawbacks of a similar approach.

CONCLUSIONS

This work presented an attempt to downscale the Erosion Potential Method in time and space for the estimation of soil erosion in an intense event. This would be needed as a suitable boundary condition for a subsequent hydro-morphological model and thus, for the conceptualization of the development of a complete flood risk scenario chain. More generally, the significance of an event-induced sediment yield was discussed as a part of the total sediment volume eroded and transported

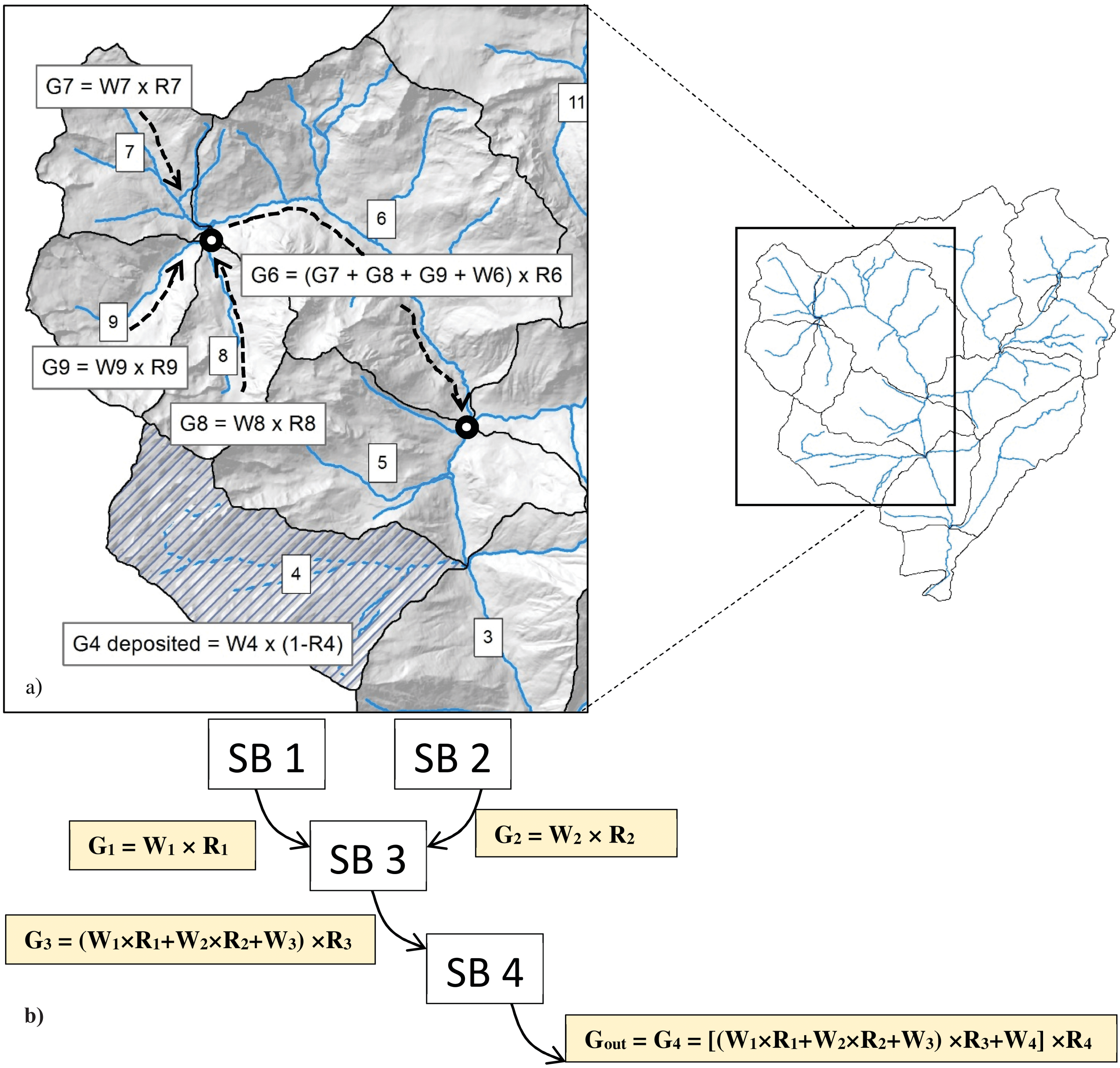

Fig. 4 - a) 'chain' routing applied to sub-basins 6, 7, 8, and 9. Estimation of deposited sediment material in sub-basin 4. b) a schematized 'chain' application of the routing coefficient

during an intense rainfall event, where the second volume can incorporate also sediment volumes deposited over previous years and reactivated by the intensity of the event.

The method has been applied to an Alpine catchment, characterized by high erosion rates. The attempted downscaling of the model showed a result which can be interpreted as the sediment yield generated by the intensity of the event. However, since studies and observations showed much larger sedimentation rates during calamitous events, the discrepancy that appears has been attributed to the long-term accumulation of sediment throughout the basin. Therefore, it can be concluded that the short-term sediment yield may be of a scarce importance for the development of flood events. Thus, the analysis of a long-term sediment production could be beneficial for the estimation of a proper sediment transport boundary condition. Some tentative considerations were introduced for the possible application of the EPM towards a long-term sediment yield estimation by means of a new treatment of the routing of sediment loads along subsequent sub-basins. However, extensive future work would be necessary in order to relate the long-term sediment yield to erosion accumulations during a time gap between consecutive calamitous rainfall events.

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