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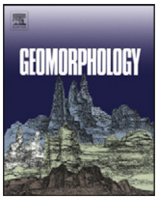

Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments

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ABSTRACT

Complex and rugged topography induces large variations in erosion and sediment delivery in the headwaters of alpine catchments. An effective connection of hillslopes with the channel network results in highly efficient sediment transfer processes, such as debris flows. In contrast, morphological conditions producing decoupling of hillslopes from channels (e.g. glacial cirques) may exclude large areas of the catchment from sediment delivery to its lower parts. Moreover, an efficient connection between hillslopes and channel network does not always ensure an effective downstream transfer of sediment. Low-slope channel reaches (e.g. in hanging valleys) cause sediment deposition, which often results in changes of the sediment transport processes, typically from debris flow to streamflow with low bedload and suspended load rates. The availability of high-resolution digital terrain models, such as those derived from aerial LiDAR, improves our capability to quantify the topographic controls on sediment connectivity. A geomorphometric index, based on the approach by Borselli et al. (2008), was developed and applied to assess spatial sediment connectivity in two small catchments of the Italian Alps featuring contrasting morphological characteristics. The results of the geomorphometric analysis were checked against field evidences, showing good performance and thus potential usefulness of the index.

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1. Introduction

Sediment connectivity, i.e. the degree of linkage which controls sediment fluxes throughout landscape, and, in particular, between sediment sources and downstream areas, is a key attribute in the study of sediment transfer processes in mountainous catchments. The spatial characterization of connectivity patterns in the catchment allows estimation of the contribution of a given part of the catchment as sediment source, and it defines sediment transfer paths. The assessment of sediment connectivity is of particular importance in alpine headwaters, in which both complex and rugged morphology, and heterogeneity in type, extent and location of sediment sources cause large variability in the effectiveness of sediment transport processes. The control of the morphological conditions on spatial sediment connectivity acts both through hillslope-channel coupling and decoupling, and through sediment transfer along the channel network.

Although several studies on sediment fluxes do not explicitly mention sediment connectivity, this concept underpins the establishment of sediment budgets (e.g. Dietrich and Dunne, 1978; Roberts and Church, 1986). Bracken and Croke (2007) have noted that sediment connectivity is implicit also in the approaches for sediment yield assessment based on sediment delivery ratio. Starting from early studies dating back to the 1980s (e.g. Caine and Swanson, 1989), the literature has shown an increasing attention to the linkage between various parts of a catchment, with particular regard to the connection between hillslopes and channels.

Brierley et al. (2006) developed a conceptual framework for sediment connectivity considering different types of landscape linkages at various spatial scales in a catchment, whereas Hooke (2003) focused on river-channel systems, proposing several types and degrees of connectivity. A recent paper by Fryirs (in press) progresses in the development of a conceptual model of sediment catchment (dis)connectivity, taking into account longitudinal, lateral and vertical blockages to sediment cascades. Although mainly oriented to hydrological connectivity, i.e. the linkage of water in catchments, the study by Bracken and Croke (2007) provides useful insights also for sediment connectivity, which is closely linked to hydrological connectivity in runoff-dominated systems. The fundamental issue of the linkage between hillslopes and channels was the object of a classical study by Harvey (2001) in northwest England. Harvey (2002) reviewed the influence of time and spatial scales on coupling mechanisms between the components of the fluvial systems, with examples from various geographical regions. Among the most recent contributions on this topic, those by Schwab et al. (2009) and

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Fuller and Marden (2011) are quite relevant to mention. Schwab et al. (2009) related differences in sediment flux from the opposite flanks of an alpine valley to differences in the predominant erosion processes (landsliding vs. sediment transport in channel systems), in turn due to varying bedrock structural settings. Fuller and Marden (2011) have developed a conceptual model of slope-channel coupling for an active gully system in New Zealand, with the connectivity between the gully and the receiving stream occurring through a large alluvial fan, which adds complexity to the pattern of sediment transfer.

In regions where a variety of agents (e.g. gravity, snow, ice, water) contribute to landscape evolution, sediment connectivity should take into account both the contributions of such agents to erosion and transport, and their influence on the morphological settings that control sediment conveyance. As an example, Brardinoni and Hassan (2006) underlined the control of relict glacial topography on geomorphic coupling between hillslope and channel processes currently active in basins of British Columbia (Canada). Schrott et al. (2003) investigated sediment storages resulting from different geomorphic processes in a basin of the Bavarian Alps and found that talus sheets, which are the dominant storage, are relict landforms decoupled from the present-day geomorphic processes. In the same geographical region, Wichmann et al. (2009) proposed an integrated modeling of rockfall, slope-type debris flows and channelized debris flows to assess the sediment cascade systems resulting from the interaction of various geomorphic processes.

The methods most commonly used for the analysis of sediment connectivity include geomorphological and sedimentological field observations, and monitoring of sediment fluxes by means of field instrumentation (Harvey, 2001; Becht et al., 2005; Brown et al., 2009; Mao et al., 2009; Schlunegger et al., 2009; Beel et al., 2011; Berger et al., 2011). Geophysical surveys of sediment thickness have been performed to evaluate the long-term effect of geomorphic coupling and decoupling on sediment storages (Schrott et al., 2003). The calculation of geomorphometric indices enabling the identification of areas with potential for erosion and deposition and the linkage between landscape units may usefully contribute to the assessment of sediment connectivity. Mitasova et al. (1996) proposed GIS-based methods for modeling the topographic potential for erosion and deposition both with the USLE (Wischmeier and Smith, 1978) and with stream-power based approaches. Dalla Fontana and Marchi (2003) developed a topographic index related to the stream power for evaluating the impedance to sediment conveyance in alpine streams. The assessment of sediment connectivity by means of GIS analysis is part of a comprehensive procedure for mapping sediment-related processes in small alpine watersheds proposed by Theler et al. (2010) which includes also aerial photograph interpretation, historical topographic maps and field observations. Reid et al. (2007) proposed a modeling approach which combines the assessment of landslide-generated sediment, computed using a modified version of SHALSTAB (Montgomery and Dietrich, 1994) with an index of hydrological connectivity based on a network index version of TOPMODEL (Beven and Kirkby, 1979). A sediment connectivity index developed by Borselli et al. (2008), initially tested in a catchment in Tuscany (Italy), was then successfully applied in other catchments in the Mediterranean region (Sougnez et al., 2011; López-Vicente et al., in press) and showed positive properties also for defining hillslope sediment delivery ratio, i.e. the fraction of hillslope gross erosion that is delivered to stream, in a semiarid catchment of south-east Australia (Vigiak et al., 2012).

These models are strictly related to the approaches applied to the modeling of physical landscape evolution, where sediment fluxes are commonly modeled with a linear or nonlinear relation with the hillslope gradient (Roering et al., 2001; Bishop et al., 2012). The detailed characterization of the topographic surface plays a fundamental role in this context, both with a view to improving geomorphological interpretation (e.g. individuation of sediment source areas) as well as for the quantitative modeling of sediment fluxes and connectivity (Brown et al., 2009; Bishop et al., 2012). Accordingly, the availability of high resolution digital terrain models (hereafter referred to as HR-DTMs), often derived via airborne LiDAR surveys, coupled with a wide set of geomorphometric approaches, extends the applicability and potentialities of topography-based modeling approaches. The geomorphological interpretation of the earth's surface can be profoundly improved via the geomorphometric analysis of HR-DTMs (Hengl and Reuter, 2009; Tarolli et al., 2009; Trevisani et al., 2009; Bishop et al., 2012; Jaboyedoff et al., 2012). Moreover, geomorphometric analysis permits a detailed characterization of drainage area and drainage pattern together with the possibility of characterizing surface roughness (Cavalli et al., 2008; Trevisani et al., 2010; Grohmann et al., 2011), which represents a proxy of sediment transport impedance.

In this paper, a sediment connectivity index has been developed to model sediment pathways dealing with debris flows and channelized sediment transport, based on the one proposed by Borselli et al. (2008) with ad hoc modifications aimed at better exploitation of HR-DTMs (Section 2). The proposed geomorphometric model, implemented via a GIS procedure, has been applied in two small adjacent catchments of the Eastern Alps, characterized by contrasting morphology and affected by sediment transfer processes of different type and intensity (Section 3). Section 4 presents the results of the application of the connectivity index and compares them with field observations of morphological features representative of the long-term delivery of sediment from source areas to the lower parts of slopes and channels. Moreover, model results are interpreted in light of an extensive field survey subsequent to an intense recent flood — debris flow event. Finally, the results obtained are discussed in Section 5 and the major findings of this study are summarized in Section 6.

2. Methods

The assessment of sediment connectivity was carried out by means of a topography-based index. This index is intended to represent the potential connectivity between different parts of the catchment and aims, in particular, at evaluating the potential connection between hillslopes and features which act as targets or storage areas (sinks) for transported sediment. In estimating sediment connectivity, we considered two aspects: (i) sediment delivery across the whole drainage system (i.e. the potential connection of sediment between hillslopes and catchment outlets), and (ii) sediment coupling-decoupling between hillslopes and main channels and two small lakes. The choice of modeling these two aspects stems from the need to address two main sediment management issues: (i) what is the probability that sediment from a certain sediment source will reach the catchment outlet? (ii) what is the probability that sediment eroded from the hillslopes will attain the drainage network?

The connectivity model has been implemented through the Model Builder application running in ArcGIS 9.3 (ESRI, 2006) using functionalities and algorithms available in the Spatial Analyst extension and TauDEM 4.0 tool (http://www.engineering.usu.edu/dtarb/taudem).

2.1. Index of sediment connectivity

The connectivity index (IC) was derived following the approach of Borselli et al. (2008), who defined IC as:

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) \tag{1}$$

where D_{up} and D_{dn} are the upslope and downslope components of connectivity (Fig. 1), respectively. IC was defined in the range of $[-\infty, +\infty]$, with connectivity increasing for larger IC values.

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