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Structural sediment connectivity assessment through a geomorphometric approach: review of recent applications

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Abstract— **Sediment connectivity, defined as the degree to which a system facilitates the transfer of water and sediment through itself by means of coupling relationships between its components, has become a key issue in sediment transfer processes analysis and one of the building blocks of modern geomorphology. The growing availability of high-resolution Digital Elevation Models (DEMs) offers new opportunities for the characterization of sediment connectivity spatial patterns. An index of sediment connectivity, based on DEM derivatives as drainage area, slope, flow length and surface roughness, has been recently developed along with related freeware software tool (SedInConnect). The index aims at depicting spatial connectivity patterns at the catchment scale to support the assessment of the contribution of a given part of the catchment as sediment source and define sediment transfer paths. The increasing interest in the quantitative characterization of the linkages between landscape units and the straightforward applicability of this index led to numerous applications in different contexts. Such works demonstrate that, when carefully applied considering the intrinsic limitations of the geomorphometric approach, the index can rapidly provide a spatial characterization of sediment dynamics, thus improving the understanding geomorphic system behavior and, consequently, hazard and risk assessment. This work presents and discusses the main applications of this sediment connectivity index.**

I. Introduction

In recent years, connectivity has emerged as a paramount property of geomorphic systems [1-3]. The growing interest of the earth sciences community on water and sediment connectivity led these concepts to become key issues in research on hydrological and sediment delivery processes and on the characterization of source to sinks pathways [e.g. 4-8].

The assessment of the degree of linkages exerted by coupling/decoupling relationship between different parts of a system is pivotal to comprehend the behavior of hydro-geomorphic systems and thus to predict their responses. Geomorphic coupling and connectivity play a relevant role in the assessment of the sediment budget in watersheds since they reflect the contribution of different processes that can have a large spatio-temporal variability.

Among the numerous definitions of connectivity available in literature, the one by Heckmann et al. [9] *("…the degree to which a system facilitates the transfer of water and sediment through itself, by means of coupling relationships between its components. In this view, connectivity becomes an emergent property of the system state, reflecting the continuity and strength of runoff and sediment pathways at a given point in time*") is one of the most comprehensive. Accordingly, the interaction governed by geomorphic processes among natural landforms and man-made structures is fundamental to understand connectivity [10] (Fig. 1). The spatial configuration of system components and their potential linkage is known as *structural connectivity* whereas the term *functional connectivity* refers to the dynamics of geomorphic and hydrologic processes within the system [11].

The increasing availability of high-resolution Digital Elevation Models (DEMs) from different sources as LiDAR and Structure from Motion (SfM) paved the way to a more quantitative approach for assessing sediment connectivity. Recently, a geomorphometric index of sediment connectivity has been developed [12] along with related freeware software tool [13]. The index, based on the original work by Borselli et al. [14], aims at characterizing connectivity patterns at the catchment scale allowing to estimate the contribution of a given part of the catchment as sediment source and define sediment transfer paths.

In this work, this index of connectivity is presented along with its most recent applications in different contexts.

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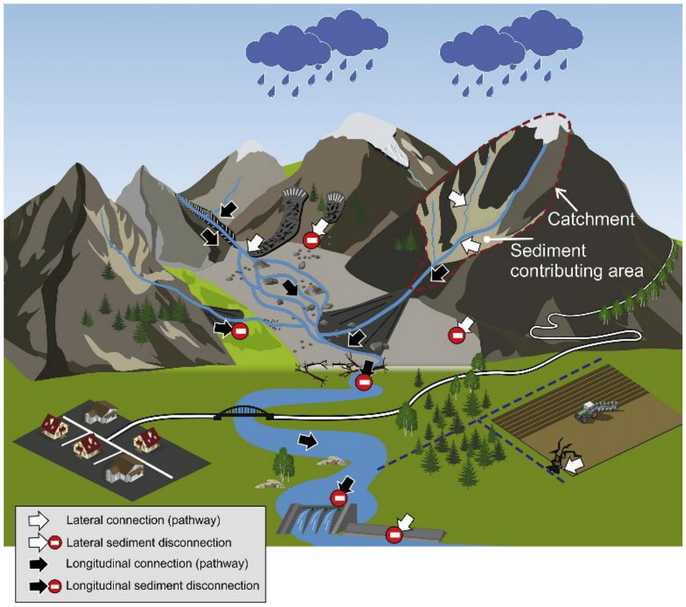

Figure 1. Schematic illustration of sediment connectivity distinguishing between lateral (i.e. hillslope-channel) and longitudinal (along channel network) and of the most relevant factors controlling it (modified from [9]).

II. The Index of Connectivity *IC*

Following the approach by Borselli et al. [14], the index of connectivity (*IC*) is computed as:

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

where D_{up} and D_{dn} are the upslope and downslope components of connectivity, respectively (Fig. 2). *IC* is defined in the range of [−∞,+∞], with connectivity increasing for larger *IC* values.

The upslope component D_{up} represents the potential for downward routing of the sediment produced upslope and is estimated as follows:

$$D_{up} = \bar{W}\bar{S}\sqrt{A} \quad (2)$$

where $\bar{W}$ is the average weighting factor of the upslope contributing area, $\bar{S}$ is the average slope gradient of the upslope contributing area (m/m), and *A* is the upslope contributing area (m^2).

The downslope component D_{dn} takes into account the flow path length that a particle has to travel to arrive at the nearest target or sink:

$$D_{dn} = \sum \frac{d}{WS} \quad (3)$$

where d_i is the length of the flow path along the cell according to the steepest downslope direction (m), and *W* and *S* are the weighting factor and the slope gradient of the cell, respectively.

The weighting factor *W* in Eq. 2 and 3 is intended to represent the impedance to sediment transport and can be expressed in different ways. Cavalli et al. [12] refined the original index by Borselli et al. [14] in order to adapt it to the mountain environment and to better exploit high-resolution DEM. In particular, they proposed to use a surface roughness index [15] in place of the USLE/RUSLE C- factor adopted in [14] as weighting factor. Other modifications encompass the calculation of the slope along the flow direction and of the drainage area using the multiple flow D-infinity approach [16], replacing the single-flow direction algorithm used in the original version to capture flow paths on hillslopes where divergent flow occur. More details on the theoretical basis and the methodology can be found in Cavalli et al. [12]. A standalone freeware software (SedInConnect 2.3, [13]) implementing new features, as the possibility to normalize W according to Trevisani and Cavalli [17], was also developed to facilitate index computation. The software is available at https://github.com/HydrogeomorphologyTools/SedInConnect_2.3.

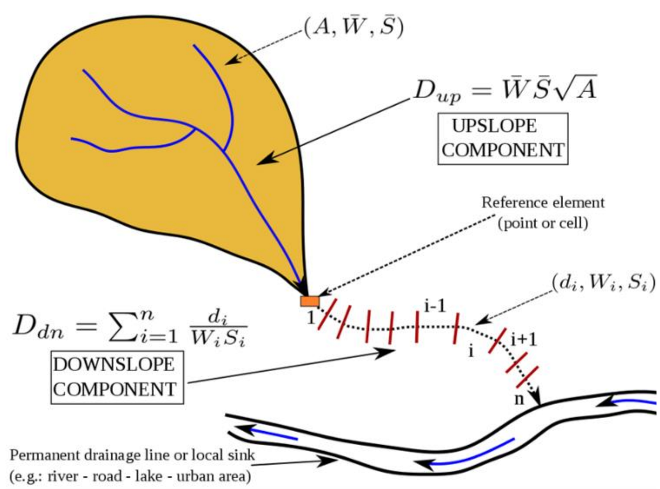

Figure 2. Representation of the components of the index of connectivity (from [13])

III. Recent Applications and Conclusions

The version by Borselli et al. [14] was successfully applied to understand soil erosion patterns [18] and specific sediment yield variations [19]. Using a land-use based weighting factor permits to study the effects of different land use and land abandonment scenarios on sediment connectivity e.g. [20, 21]. Even if not meant for this purpose, *IC* has proven useful also for estimating hillslope sediment delivery ratio (SDR) [22]. Jamshidi et al. [23], developed an algorithm integrating the SDR estimation approach by Vigiak et al. [22] to assess annual variability in sediment yields related to changes in vegetation. Hamel et al. [24] integrated *IC* into a new version of the InVEST model, a model aiming at quantifying and map ecosystem services, showing a great potential to quantify the sediment retention service. *IC* supported the interpretation of radioactive dose rate measurements after the Fukushima Dai-ichi Nuclear Power Plant accident in nearby catchments [25]. Another interesting application of this version of *IC* was carried out by Foerster et al. [26] in the Spanish Pyrenees. In [26], *IC* was computed in two catchments in contrasting seasons estimating the weighting factor based on fractional vegetation cover from hyperspectral data. This approach permitted to effectively identify hot spot erosion areas.

The herein presented version implementing roughness index as W factor, after its first application in two small adjacent catchments of the Eastern Alps [12], was extensively applied in different contexts especially in the mountain environment. Notable applications include the analysis of hillslope–channel coupling in a catchment in SW Turkey [27], sediment transfer dynamics in a formerly glaciated alpine valley [28], the impact of volcanic eruptions on sediment connectivity [29, 30] and sediment connectivity in proglacial areas [1, 31, 32]. *IC* has been successfully used in combination with sediment sources and/or landslide inventories in order to characterize such areas and optimize sediment management and to focus on the most critical hotspots [33, 34]. A valuable feature of *IC* arose from an application to 22 catchments in the Eastern italian Alps: if averaged at catchment scale, *IC* values can help distinguishing among different dominant processes (debris flow, bedload transport and intermediate behavior) [35]. Similar results were found in the Austrian Alps where *IC* was used together with other morphometric parameters to identify dominant processes acting in headwater catchments [36]. Most recently, the increasing availability of multitemporal high-resolution data offered the opportunity to integrate the time variable into the connectivity analysis [37, 38]. It is worth noting that the index values show a systematic decrease with increasing resolution [35, 39] and it has a strong dependency on catchment size. Furthermore, the use of different weighting factors can lead to different connectivity patterns. It is thus recommended to carefully choose the weighting factor according to the specific research aims. These limitations should be taken into account to produce reliable results that, given the simple index structure, must be always validated in the field.

In conclusion, *IC* has proved very promising for rapid spatial characterization of sediment dynamics both at catchment and regional scales. The reported applications demonstrate that a reliable assessment of sediment connectivity via a geomorphometric approach, especially when integrated with a sediment sources inventory, is useful for giving management priorities. This represents a key issue when dealing with sediment management and has important linkages with hazard and risk assessment and in relation to priorities of intervention at the catchment scale. Being a topography-based index, *IC* is focused on structural aspects of connectivity, and quality and resolution of DEMs may have significant impact on the results. Future development should consider process-based connectivity and incorporate temporal variability directly into the index. First attempt has been made by Kalantari et al. [40] who modified *IC* including a functional weighting factor based on surface runoff estimate by curve numbers and considering spatially and temporally variable forcing. Further research in this direction will help to conceive a new geomorphometric approach combining system configuration, processes and external forcing towards an improved caractherization of sediment and hydrological connectivity.

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