Indices of sediment connectivity: opportunities, challenges and limitations

Published Version:
Heckmann, T., Cavalli, M., Cerdan, O., Foerster, S., Javaux, M., Lode, E., et al. (2018). Indices of sediment connectivity: opportunities, challenges and limitations. EARTH-SCIENCE REVIEWS, 187, 77-108 [10.1016/j.earscirev.2018.08.004].

Availability:
This version is available at: https://hdl.handle.net/11585/657185 since: 2021-11-30

Published:
DOI: http://doi.org/10.1016/j.earscirev.2018.08.004

Indices of sediment connectivity: opportunities, challenges and limitations

Tobias Heckmann, Marco Cavalli, Olivier Cerdan, Saskia Foerster, Mathieu Javaux, Elve Lode, Anna Smetanova, Damià Vericat, Francesco Brardinoni

PII: S0012-8252(17)30649-9
DOI: doi:10.1016/j.earscirev.2018.08.004
Reference: EARTH 2679

To appear in: *Earth-Science Reviews*

Received date: 23 December 2017
Revised date: 8 August 2018
Accepted date: 10 August 2018

Please cite this article as: Tobias Heckmann, Marco Cavalli, Olivier Cerdan, Saskia Foerster, Mathieu Javaux, Elve Lode, Anna Smetanova, Damià Vericat, Francesco Brardinoni , Indices of sediment connectivity: opportunities, challenges and limitations. Earth (2018), doi:10.1016/j.earscirev.2018.08.004

Indices of sediment connectivity: opportunities, challenges and limitations

Tobias Heckmann, Marco Cavalli, Olivier Cerdan, Saskia Foerster, Mathieu Javaux, Elve Lode, Anna Smetanova, Damià Vericat, Francesco Brardinoni

Abstract

Indices of connectivity are critical means for moving from qualitative to (semi-)quantitative evaluations of material (e.g., water, sediment and nutrients) transfer across the building blocks of a terrestrial system. In geomorphology, compared to closely related disciplines like ecology and hydrology, the development of indices has only recently started and as such presents opportunities and challenges that merit attention. In this paper, we review existing indices of sediment connectivity and suggest potential avenues of development for meeting current basic and applied research needs. Specifically, we focus on terrestrial geomorphic systems dominated by processes that are driven by hydro-meteorological forcing, neglecting seismically triggered events, karstic systems and environments controlled by eolian processes.

We begin by setting a conceptual framework that combines external forcings (drivers) and system (intrinsic) structural and functional properties relevant to sediment connectivity. This framework guides our review of response variables suitable for sediment connectivity indices. In particular, we consider three sample applications concerned with sediment connectivity in: (i) soil studies at the plot scale, (ii) bedload transport at the reach scale, and (iii) sediment budgets at the catchment scale. In relation to the set of response variables identified, we consider data availability and issues of data acquisition for use in indices of sediment connectivity.

We classify currently available indices in raster based, object or network based, and indices based on effective catchment area. Virtually all existing indices address the degree of static, structural connectivity only, with limited attention for process-based, functional connectivity counterparts.

Most recent developments in indices of sediment connectivity deal, to some extent, with different styles of anthropogenic and hydro-meteorological forcings and with the temporal variability of sediment connectivity, by incorporating additional variables and parameters in existing indices. We believe that, in order to use structural connectivity as explanatory or predictive tool, indices need to be interpretable in relation to geomorphic processes, material properties, and forcing styles and magnitude-frequency spectra. Improvements in this direction can be made through studies shaped to constrain structural-functional correlations across a range of hydro-meteorological scenarios, for example employing field-based techniques such as particle tracking and sediment provenance analysis, as well as numerical simulations.

We further consider existing indices in relation to spatial and temporal scales. The latter have immediate implications on the distinction and application between indices and models of sediment connectivity. In this context, we suggest that sediment connectivity over millennial or longer time scales should be dealt with models, as opposed to indices.

Keywords: structural and functional connectivity; geomorphic systems; sediment transfer; geomorphic coupling; scales; response variables

1 Introduction

Research on the linkage of system components and the consequences on system properties and behaviour is critical to many disciplines, including computer science, social sciences, economics and earth science. Landscape ecologists have pioneered analysis of landscape structure for assessing "landscape connectivity" that enables (or impedes) organisms to move across landscape patches for foraging, propagation and reproduction as early as in the 1970s (Tischendorf and Fahrig, 2000).

Connectivity research in hydrology and geomorphology has experienced considerable growth in the last decade (Parsons et al., 2015; Wohl et al., 2017). Building upon work concerned with hillslope-channel coupling (Brunsden and Thornes, 1979; Walling, 1983; Caine and Swanson, 1989; Harvey, 2001), and more recently in hydrology (e.g. Bracken and Croke, 2007) and geomorphology (e.g. Brierley et al., 2006; Bracken et al., 2015), we define hydrological and sediment connectivity as the degree to which a system facilitates the transfer of water and sediment through itself, through 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. Structural connectivity represents the spatial configuration of system components; functional connectivity is inferred from the actual transfer of water and sediment, i.e. the system's process dynamics (see also Wainwright et al., 2011).

Sediment connectivity emerges from the spatial configuration of landforms, as well as from the spatial arrangement of hydro-geomorphic processes that control the rates of water and sediment transfer (Slaymaker, 2006). Sediment connectivity is one of the building blocks of modern geomorphology, both for addressing basic scientific questions and for tackling more applied issues. This is exemplified by the conceptual frameworks of geomorphic process domains (and relevant transition zones, Montgomery and Dietrich, 1989; Stock and Dietrich, 2003; Brardinoni and Hassan, 2006) and sediment cascades (Burt and Allison, 2010), which both contain implicitly the notion of sediment connectivity. Geomorphic process domains are landscape subunits dominated by a specific suite of geomorphic processes; a sediment cascade is the downstream pattern of repeated entrainment, transport, and storage of sediment that link landforms over a given time period.

Connectivity is inherently a prominent component of **landscape sensitivity** (Brunsden and Thornes, 1979; Brunsden, 2001; Harvey, 2001; Michaelides and Wainwright, 2002; Fryirs, 2016) that moderates the propagation of geomorphic change within a basin in both the upstream and downstream directions. For example, a poorly connected, buffered catchment is expected to impede the downstream propagation of information, including energy, sedimentary waves and/or disturbance (e.g., Lane et al., 2017; Rainato et al., 2017), hence prevent postglacial recovery in formerly glaciated mountain settings (Brardinoni and Hassan, 2006).

The question of **sediment delivery** (Walling, 1983; de Vente et al., 2007) has been related to geomorphic coupling (e.g., Caine and Swanson, 1989), and later to sediment connectivity (Fryirs, 2013). The type of decoupling (dis-connectivity), controlled by the location of the corresponding landforms (i.e., their positioning relative to the direction of sediment transport), has been shown to be critical for sediment conveyance and yield (Fryirs et al., 2007a,b ; Brardinoni et al., 2009). In a more general context, the (dis-)connectivity of a system is part of the problem of **scale linkage**, that is, the transfer of findings from one scale of investigation to another. For example, hillslope -channel (de-)coupling moderates how smaller-scale properties and processes combine to influence properties or responses at a larger scale (Phillips, 1999; Slaymaker, 2006; Belmont and Foufoula-Georgiou, 2017). Vice versa large-scale imposed structures (e.g., glacial macroforms) can influence the spatial sequencing of channel morphology, hence the style and intensity of sediment transfer at the reach scale (Brardinoni and Hassan, 2007; Weekes et al., 2012).

Connectivity among spatial units (e.g., landforms) is an important driver of **system dynamics** (Peters and Havstad, 2006). In fact, heterogeneities, even when present in relatively small proportions, can have drastic impacts on the overall behaviour of a system, depending upon their spatial distribution (Turnbull et al., 2008). Changes in the coupling state of system components (i.e., **changes in connectivity**) may lead to changes in morphodynamics and to sediment budgets that are largely independent of external forcing (e.g., Wainwright, 2006).

The relevance of connectivity for geomorphic systems calls for connectivity assessment and quantification. Previous studies have mainly dealt with connectivity in a qualitative manner, for example by extracting and interpreting information from geomorphological maps or aerial photos, combined with fieldwork (Harvey, 2001; Schrott et al., 2002; Hooke, 2003; Brardinoni and Hassan, 2006). While a lot of progress has been made in measuring properties (e.g., topographic and geological attributes) and geomorphic features across scales, in most cases these are only partially related to connectivity. In fact, most case studies deal with structural or potential connectivity, and therefore are incomplete. Even though connectivity cannot be measured explicitly (Turnbull et al., 2018), a more comprehensive approach to assess (or constrain the degree of) connectivity should involve: (i) measuring structural connectivity, that is, the potential of a landscape to be connected through flow pathways; (ii) measuring sediment fluxes and associated changes in the landscape structure over a given timescale of observation, and (iii) physical tracing of sediment that enables connecting unambiguously sources to sinks, and therefore allows to better constrain functional connectivity (Brazier et al., 2015).

Two problems lead to the development of connectivity indices: First, the difficulty of directly measuring sediment delivery, hence inferring connectivity, in the field; while sediment yield (e.g., at a (sub)-catchment outlet) is readily measured, gross erosion has mostly been estimated based on models. Second, the need to predict the behaviour of geomorphic systems either in the future, or in study areas where proper measurements are unavailable. An index is defined as “a type of composite measure that summarises and rank-orders several specific observations and represents some more-general dimension” (Babbie, 2013). Specifically, a connectivity index would consist of several variables conceptually known to control the spatial organization and intensity of sediment fluxes in a landscape. Some of these variables, however, are difficult to measure at the required spatial and temporal scales. In these cases, proxy variables or indicators are needed, i.e., measurable variables used to represent associated, but non-measured or non-measurable factors or quantities. For example, terrain properties derived from Digital Elevation Models (DEMs) are used to represent hydrological, geomorphic and biological processes that are influenced by topography (Moore et al., 1991; Wilson and Gallant, 2000).

In ecology and hydrology, the quantitative investigation of connectivity has led to a variety of sophisticated indices reflecting the complexity of the connectivity concept (Calabrese and Fagan 2004; Ali and Roy, 2010). Reasons for this are to be found in the variety of assumptions, objectives and applications associated with different approaches to connectivity.

Metrics of landscape structure developed in ecology have been analysed in relation to hydrological processes (van Nieuwenhuyse et al., 2011), and the conditioning of hydrological connectivity on water-mediated sediment transport has been incorporated in hydrological connectivity indices in geomorphology (e.g., Reid et al., 2007). Although geomorphic coupling, and implicitly sediment connectivity, have been part of geomorphological research for decades (e.g. Brunsden and Thornes, 1979; Caine and Swanson, 1989; Harvey 2001; Hooke, 2003), attempts to assess sediment connectivity beyond the spatial configuration of structural attributes and the development of conceptual models are rare (e.g., Whiting and Bradley, 1993). The number of sediment connectivity indices (e.g., the IC by Borselli et al., 2008 and derivatives thereof, c.f. chapter 3) is apparently still inadequate to address the complexity of geomorphic systems and the range of relevant applications. Progress in the development of suitable indices requires a systematic review of the existing ones.

The purpose of this paper is fourfold:

- Establish a conceptual framework that combines the factors and drivers of sediment connectivity, particularly with regard to indices;
- Review existing sediment connectivity indices. Specifically, we focus on terrestrial geomorphic systems dominated by processes that are driven by hydro-meteorological forcing, neglecting seismically triggered events, karstic systems and environments characterised by wind erosion and eolian sediment transfer;
- Discuss fields of application of sediment connectivity indices in science and land management;
- Explore research needs regarding data, possible correlations of connectivity indices with system behaviour, and approaches towards new indices.

2 Assessing sediment connectivity through indices: Concept, scales, and response variables

Sediment connectivity emerges at different spatial scales (Brierley et al., 2006); consequently, different aspects of sediment connectivity are relevant for different scientific problems. In this paper, we have selected three spatial scales by which we will structure both the conceptual framework and the discussion of response variables for connectivity indices. The choice of these scales is pragmatic, it implies data availability at a suitable resolution, and acknowledges that the processes operating at different scales may be different (while sharing the same external forcings), which needs to be reflected in different sets of response variables for connectivity indices. Furthermore, each scale is linked to a "typical" application for which sediment connectivity is critical:

(i) Runoff generation and soil erosion occur at the **plot/hillslope** scale, and connectivity affects the corresponding fluxes towards the channel network.

(ii) In the channel network, longitudinal connectivity can be seen as the linkage among **channel reaches** with respect to sediment transfer.

(iii) Lateral (i.e., hillslope-channel) and longitudinal (i.e., within-channel) linkages combine, or interact, at the **catchment** scale, determining the transfer of sediment to the catchment outlet. At this scale, we use the example of sediment cascades and budgets.

The issue of scale is closely related to the delineation of "fundamental units", i.e., spatial or functional elementary entities of a landscape, and the way they are linked to each other with respect to water and sediment transfer (see Turnbull et al., 2018, and Poeppl and Parsons, 2018, for a discussion of fundamental units). We argue that, in geomorphology, an intuitive fundamental unit is the landform, or the (sub-)catchment, depending on the scale of interest. The relative positioning of neighbouring landforms along potential flow paths (e.g. toposequences, Otto et al., 2009), especially in relation to the architecture of the channel network, determines structural connectivity. The (basic or applied) problem that is addressed determines whether connectivity needs to be assessed between landforms, hillslopes and channels, channel reaches, portions of catchments, or between catchments (c.f. section 2.2.3). Consequently, the response variables making up a specific connectivity index need to be determined for each respective fundamental unit.

Section 2.1 introduces the conceptual framework (Figure 1Figure 2) that leads our collection of response variables (section 2.2). The question of how these variables can be measured for use in indices of sediment connectivity is addressed in section 2.3.

2.1 Conceptual framework

Before introducing our conceptual framework, we show in Figure 1 a more figurative, schematic depiction of sediment (dis-)connectivity in a terrestrial geomorphic system. We included relevant factors of lateral and longitudinal (dis-)connectivity that we use in the subsequent conceptual framework (Figure 2), and that are partially being used in connectivity indices: Forcing, landscape structure and intrinsic properties, different geomorphic processes, and human impact. In general, Figure 1 highlights the importance not only of different landscape elements and their properties, but also of their spatial configuration.

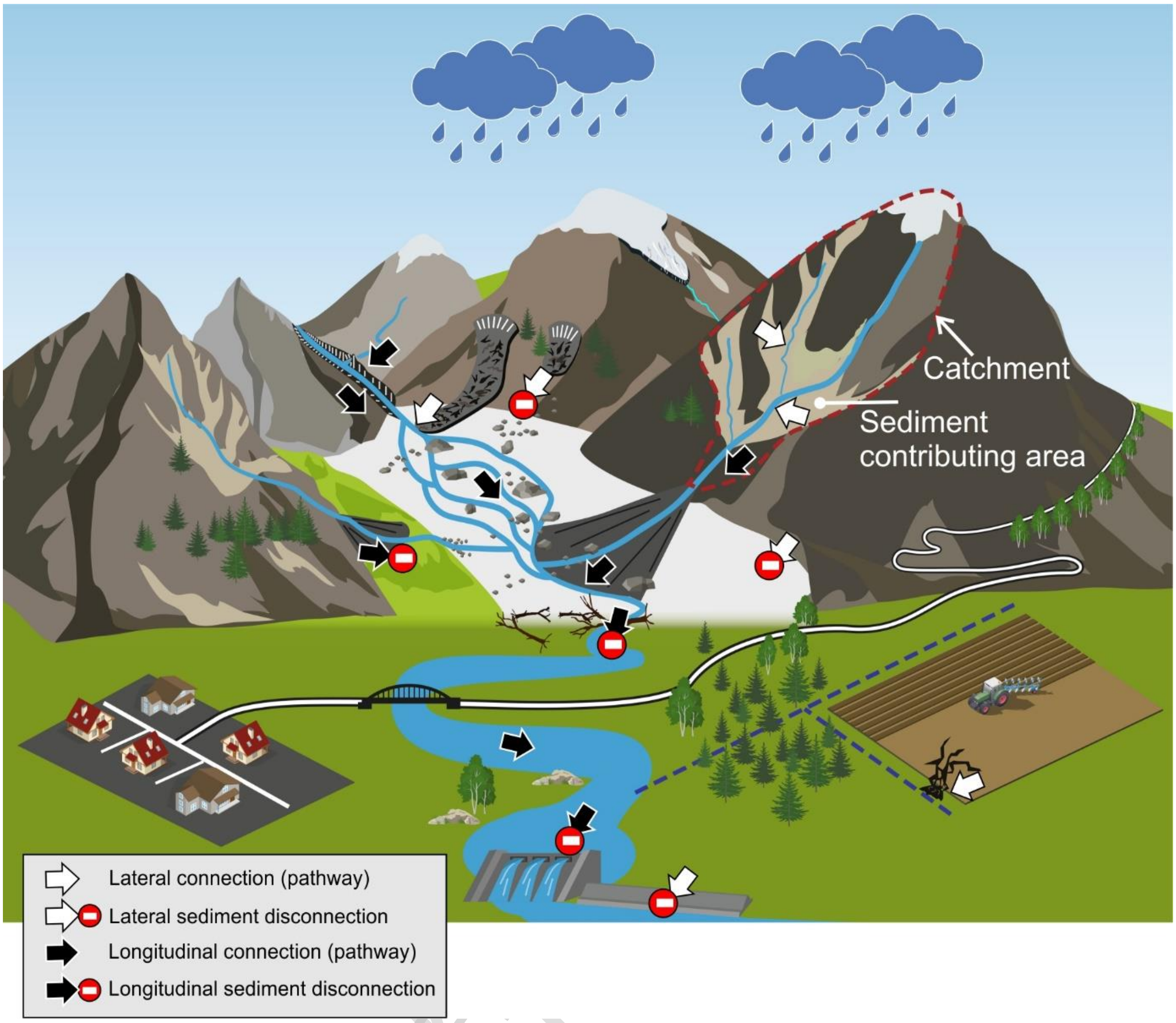


Figure 1: Schematic depiction of sediment (dis-)connectivity (lateral e.g. hillslope-channel, longitudinal along channel network) and its most relevant factors. (i) Forcing, e.g. precipitation and snow/glacier meltwater discharge. (ii) Intrinsic properties: Topography (slope, valley form/width/confinement etc), landforms indicating (dis-)connectivity (alluvial fans, fluvial terraces etc), type and spatial pattern of landuse/landcover, material properties. (iii) Geomorphic processes linked to sediment cascades (sources-pathways-sinks), e.g. fluvial, graviational etc. (iv) Human impact through agricultural landuse, settlement and infrastructure, direct impact on channels (dams, dikes) etc. The sediment contributing or effective catchment area is a subset of the hydrological catchment area (dashed red outline) and is further explained in section 3.2).

Figure 2 shows a conceptual model of sediment connectivity. While structural connectivity is determined by the spatial arrangement of landscape units and their properties, functional connectivity is established through the actual transfer of sediment. The latter is effected by geomorphic processes that emerge from the interaction of their drivers and landscape properties. In the following paragraphs, we briefly summarise this conceptual framework for the plot/hillslope, the channel reach and the catchment scale.

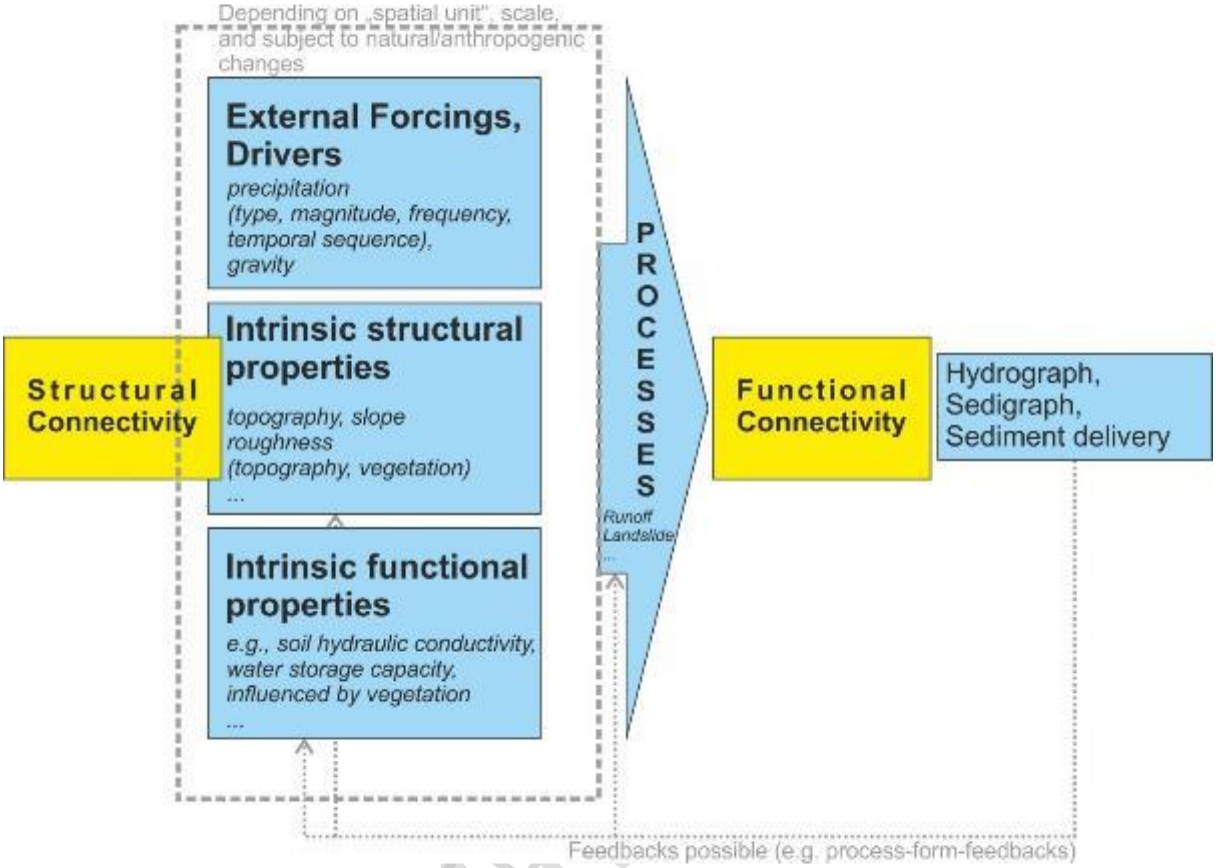


Figure 2: Conceptional model of water or sediment connectivity, influencing factors and drivers (based on a draft by M. Javaux)

External forcing

As the most relevant geomorphic processes that we consider in this paper are those driven, or at least mediated, by water, the most important forcings are related to climate, specifically to precipitation. For example, the temperature-mediated type of precipitation (e.g., snow and rain), its amount and intensity-duration (e.g., Cammeraat, 2002) affect surface runoff generation and subsequently water discharge. Antecedent conditions influenced by the sequencing of hydrometeorological events, or the melting of a snowpack, play an important role in runoff generation and regulate base and peak flows at all scales. While a catchment typically receives no sediment input from across its divides (exceptions may include karstic, volcanic and eolian-dominated systems), run-on of water and sediment has to be considered at the plot and channel reach scales.

Intrinsic properties and structural connectivity

Intrinsic structural properties relate to the fundamental units and materials that compose homogenous plots and/or channel reaches; they affect structural connectivity.

Topographic properties include elevation, slope gradient, slope aspect, plan and profile curvature, and roughness. While slope is arguably the most important one, here we elaborate the example of roughness because it illustrates the multi-scale and complex nature of topographic control on connectivity; additionally, it is influenced by vegetation. Depending on the focus of investigation, roughness is typically assessed at the millimetre (soil aggregates), centimetre-to-decimetre (microdepressions and sediment grains) to metre (landforms and channel units) scale. The microtopography of the soil surface has been used to assess connectivity (Gascuel-Odoux and Bruneau, 1990; Antoine et al., 2009; Peñuela et al., 2015) and is one of the key parameters in modelling soil erosion at the plot or hillslope scale. In channel reaches, roughness associated with grain size of channel bed material and the arrangement of the grains (bedforms) moderate in-channel hydraulics and bedload transport.

At the catchment scale, the channel network forms “both the skeleton and the circulatory system” of a landscape (Perron et al., 2012); hence, catchment properties such as the drainage density, the distribution of flow lengths, and the location of sediment sources relative to the channel network (Figure 1) add to the list of connectivity-related properties.

Material properties include, but are not limited to, grain sizes, aggregate stability, soil moisture and hydraulic conductivity. Vegetation provides aerial protection (plot scale), constitutes interception storage (catchment scale), and modifies roughness (e.g., vegetation cover on hillslopes; large wood in channels) and material properties (all scales).

Processes and functional connectivity

Structural connectivity, i.e., the topology of landscape units, however, does not necessarily imply that sediment is indeed transferred from one unit to another. Whether this happens or not depends on the activity of processes that emerge from the combination of the aforementioned structural and functional properties and the external forcings (see also Bracken et al., 2015). Specifically, some of the properties are linked to drivers (e.g., elevation => temperature => precipitation type) while some others directly influence processes (e.g., slope gradient => flow velocity and transport capacity). These processes transfer water and sediment across the landscape, along flowlines and sediment pathways, respectively; functional connectivity emerges from the spatial interaction of processes. This notion is reflected in the concept of toposequences (sequences of landforms along a topographic gradient) and their relationship with sediment cascades (Burt and Barber, 2010) as some toposequences are disconnected with respect to sediment transport (see also Meßenzehl et al., 2014, and references therein).

Depending on the system under study, a range of geomorphic processes has to be included in the sediment connectivity assessment. In high-mountain areas, for example, mass wasting processes may play a significant role in sediment connectivity (e.g., Brardinoni et al. 2009; Heckmann and Schwanghart, 2013; Meßenzehl et al., 2014; Figure 1). Along these lines, Bracken et al. (2015) developed a framework in which a combination of hydrologically-driven and gravity-driven processes (with their magnitude and frequency) leads to scenarios of sediment connectivity in which sediment detachment and transport are controlled hydrologically (i.e., runoff) or non-hydrologically (e.g., by co-seismic mass wasting; Li et al., 2016) in varying proportions.

Finally, the water and sediment dynamics within a system, and the structural and functional connectivity of its components, lead to characteristic time-integrated signatures that can be recorded at the outlet of the respective spatial unit as hydrographs and sedigraphs.

Human impact

Human impact affects lateral and longitudinal sediment connectivity in both directions through interfering with the aforementioned properties and processes (Figure 1; for comprehensive accounts see Wohl, 2006, 2015; Pöppl et al., 2017). This takes place on multiple scales, from the river channel and its corridor to the catchment scale. The most conspicuous anthropogenic change of connectivity takes place in rivers, in the form of dams, reservoirs, levées, channelization, bank stabilisation, wood removal and water abstraction. The effects on lateral and longitudinal sediment connectivity are sometimes unintended side-effects, sometimes intentional within frameworks of river restoration (Kondolf et al., 2006). At the hillslope to catchment scale, landcover changes (de- or afforestation and urbanisation), agricultural landuse including tillage/ploughing, topographic engineering (e.g., terraces, roads and embankments), and artificial drainage through ditches and pipes affect sediment connectivity through their effects on runoff and sediment generation, routing and dynamics. Examples in the following sections highlight the opportunities of using indices to investigate the consequences of, e.g., landcover changes (sections 4.2.2, 4.4.1, Figure 12), for connectivity.

2.2 Response variables for indices

In this section, we identify response variables governing (hydrological and specifically sediment) connectivity, structured across three spatial scales. Typical scientific problems related to the respective scales helped in addressing these variables, namely erosion at the plot/hillslope scale (2.2.1), fluvial sediment transport at the reach scale (2.2.2), and sediment cascades and budgets at the catchment scale (2.2.3).

2.2.1 Initiation of sediment connectivity: The plot scale

The plot scale often represents the elementary response unit of the catchment-scale sediment cascade, and as such, exerts a first-order impact on the rates of sediment connectivity at larger scales. This is illustrated by recent work on the influence of local soil surface characteristics on connectivity and runoff and erosion processes (e.g., Le Bissonnais et al., 2005). For example, Descroix et al. (2012) demonstrated that changes in the hydrograph of the Niger River could be explained by an increase of the connectivity at the plot scale caused by the spreading of soil surface crusts.

Conversely, we know that in large low-relief catchments, complex responses may arise from the disconnection between the dominant sediment sources at the plot scale and the channel network, preventing the sediment to reach the latter or the main floodplain (Trimble, 1999). Characteristic temporal and spatial scales (here: resolution) to study connectivity at the plot scale range between 5 minutes and a day and between one mm to 10 cm, with temporal extent comprised between a rainfall event and several years, and a spatial extent from 10^0 to 10^5 m².

External forcings

Numerous types of processes that influence sediment connectivity take place at the plot scale: (1) local raindrop splash, where the external forcing is mainly the kinetic energy of the rainfall (Ek); (2) sheet erosion governed by the rainfall characteristics and by laminar flow (defined by the transport capacity TC); and finally (3) concentrated erosion, where the processes are controlled by the hydraulic characteristics of the overland laminar or turbulent flow (that can be defined by stream power ω). The relevant parameters for characterizing the dynamics and magnitude of these forcings are the general slope gradient, the run-on characteristics (intensity and magnitude/frequency) and the rainfall characteristics like volume, kinetic energy, magnitude/frequency of the rainfall time series and sesonnality. Being local, these characteristics can be available in the context of experimental work but are barely available at high resolution for large areas under natural conditions. Therefore, empirical parameters, derived from statistical relationships between these variables and more readily available ones may be used (e.g., pedotransfer functions in the soil science community). In addition, anthropogenic activities are a strong external force, in particular in cultivated areas, where the tractive energy of agricultural machineries induce the downslope movement of large quantities of soil (tillage erosion). Relevant parameters characterizing anthropogenic activities are the tillage transport coefficient (ET) (function of tool, speed, direction and depth of the tillage) and slope (S).

Intrinsic properties of the system

The intrinsic structural properties of the system that influence connectivity are related to the slope and curvature of the surface that will determine flow velocity and divergence/convergence, and to surface microtopography (roughness and depression storage). At the plot scale, microtopography is the property that has the highest impact on connectivity and as such is contained in several indices of connectivity (e.g., Darboux et al., 2001; Antoine et al., 2009). Microtopography can be characterized by its spatial distribution characteristics (e.g., semi-variograms and, fractal dimension), the standard deviation of its height, and its anisotropy. Functional properties of the soil (e.g., hydraulic conductivity, water storage capacity, hydrophobicity, and erodibility) are governed by soil surface characteristics (roughness), the microtopography and the soil cover. Soil surface characteristics are affected by soil texture, organic matter, calcium and iron contents, and soil cover by plants or stones. Additional important features for soil surface characteristics are surface crusting, presence of cracks and biopores, and soil structure (e.g., aggregates and clods). The microtopography can be characterized by the spatial distribution, the standard deviation of local relief, and its anisotropy. Soil cover is typically partitioned into basal cover (e.g., litter, biological soil crust and mulching) and aerial/vegetation cover (e.g., interception and stemflow).

Response variables summarizing forcing-resistance interactions: indices

Because of its limited spatial extent, sediment connectivity at the plot scale can often be represented by single lumped (non-distributed) variables. This is the case for highly anthropogenic environments like agroecosystems where the natural spatial variability is smoothed. Key variables in these environments include the standard variation of microtopograpy perpendicular to the slope (structural connectivity); vegetation cover (structural and functional connectivity) or soil surface characteristics (functional connectivity). Soil surface characteristics are also used to represent sediment connectivity in natural environments, like in arid areas where it is a driving factor for the development of banded-like vegetated patterns. In more heterogeneous environments, connectivity can be determined by means of geostatistical indices that describe the patchiness together with the spatial extent of intrinsic features able to attenuate or amplify external forcings.

2.2.2 Sediment transport in channels: The reach scale

External forcings

Precipitation (e.g., water inputs), temperature (e.g., snowmelt-driven water inputs and loss through evapotranspiration), sediment inputs (e.g., landslides or debris flow entering the channel reach, sediment supply from tributaries and floodplains), and anthropogenic disturbance (e.g., dams, canals, dikes and in-channel mining activities) control local channel hydraulics and the magnitude-frequency of water discharges (Q) entering a channel reach. Q being the main "response variable" controlling water and sediment dynamics at the reach scale.

For the definition of connectivity indices we are interested in characteristic discharges within the magnitude-frequency spectrum, which, depending on the specific objectives, may include: (i) High-magnitude low-frequency discharges (variables: Q_{100}, Q_{200}, that is, discharge with a return period of 100 or 200 years, respectively) that are associated with overbank flows and therefore hold geo-hazard implications and applications; (ii) Low-magnitude high-frequency discharges (variable: Q_{min}) determine habitat conditions for the survival and the functioning of indigenous riverine biota and therefore are useful for eco-hydrology applications; and (iii) Intermediate events (variable: $Q_{bankfull}$) which, being formative events, conduct most of the geomorphic work and are in dynamic equilibrium with the current morphological and geometric configuration of a given channel reach.

Suitable indices of connectivity should also consider different seasonality scenarios. For example, seasonality affects the annual length of periods with no water (or frozen water) in the channel (variable: *number of days per year*), as well as the hydrograph shape that changes dramatically depending on forcing typology (e.g., snowmelt vs rainfall-induced floods), and the sequencing of floods (variables: *number of peak flows per season*; *average seasonal hydrograph duration*).

Intrinsic properties of the system

The main intrinsic properties of a channel reach include topography (TOP), bed material size (GSD), and vegetation (VEG). The spatial variability of topography (ground elevation) in a given reach is considered in both the longitudinal (variable: *slope gradient*) and the transversal (variables: *channel width* and *depth*) directions. Additionally, in both directions, surface roughness (variable: *roughness length*) plays a key role in controlling channel hydraulics, which in turn influence bed shear stress and, consequently, critical conditions for bed entrainment and transport. Finally yet importantly, the proportion of channel bed/banks exposed as bare bedrock (variable: *percent* or *area in bedrock*), including bedrock type, are important as they affect flow resistance, abrasion, sediment transport, and rock detachment from the bed.

Bed material size is evaluated in terms of *grain size distribution* (GSD) and *armoring ratio* (AR). Where AR is expressed as the ratio between $D_{50\text{-}s}$ (median grain diameter, s=surface) and $D_{50\text{-}ss}$ (ss=subsurface), which can be considered a measure of vertical sediment connectivity. For defining useable indices we are interested in characteristic particle percentiles (D_i) within the surficial grain size distribution, which depending on the specific objectives of the study, may include: (i) The coarsest fractions of the GSD (e.g., percentiles D_{84}, D_{90}, D_{95} or D_{max}) that determine grain resistance to flow (in ordinary flow conditions) and geo-hazard potential due to channel instability (i.e., in extreme flow conditions that mobilize such percentiles) and catastrophic runout; (ii) The finest percentiles of the GSD (variables: D_{16}, D_{22}) that control in-channel habitat conditions (e.g., fine gravel for fish spawning and oxygenation for fry survival); and (iii) The median fraction of the GSD (variable: D_{50}), which moves during the most frequently recurring flows associated with Q_{bf} (e.g., engineering applications for designing canals, and landscape evolution models).

The effects of vegetation on sediment connectivity are exerted by living plants growing on the channel bed (e.g., stabilization of islands) or on the wet banks (e.g., root cohesion to the banks), and by wood pieces. Both components impart additional resistance to water flow and determine flood conveyance (e.g., Abu-Aly et al., 2014). Woody debris has complex dynamics, at ordinary flow it moves and can form logsteps (see Figure 1), acts as a site of sediment storage, and decreases local channel slope. During extreme flow events (or due to a major bank failure or a landslide/debris flow) a number of logs are suddenly delivered to the channel and can form a logjam. In places, logjams can impart complete downstream sediment disconnection and delayed water connectivity. Following this logic, the current load of vegetation/wood in a channel reach is evaluated by considering *plant/wood density* (e.g., the number of live trees, and/or wood pieces (above a certain threshold size: *large wood* (LW)), by channel reach surface area), the number of *channel spanning logjams* and their degree of integrity. The potential wood load to the channel reach is evaluated by considering: (i) Land cover and land use conditions along the riparian buffer (e.g., forest cover extent, forest management type) control: the amount of wood delivery to the channel (e.g., increased flow resistance) and size of woody debris, hence the potential for the formation of channel-spanning logjams (e.g., channel occlusion); and (ii) Plant species typology, which controls wood decay, hence the persistence of a logstep/logjam structure.

Response variable summarizing forcing-resistance interactions: indices

The key parameters that are customarily used for characterizing sediment transport potential arising from the interactions between forcings and intrinsic system properties (i.e., channel boundary conditions) opposing resistance to flow by means topography/sediment/vegetation properties, include: (i) Boundary shear stress (τ), which depends on water slope and water depth (or hydraulic radius); (ii) Critical shear stress (τ^*) for particle entrainment; (iii) Total stream power (Ω), which depends on mean annual water discharge and channel slope; and (iv) Specific stream power (ω), which additionally takes into account bankfull channel width. An additional list of compound variables is available, for example Ω/D_{84} which provides a ratio between external forcing (Q is included in Ω) and grain resistance exerted by coarse grain size fraction (e.g., Wohl, 2004).

2.2.3 Sediment cascades and budgets: The catchment scale

External forcing and intrinsic properties of the system

Catchment-scale sediment connectivity emerges from the linkage of catchment components with respect to sediment transport, comprising lateral (i.e. within-hillslope and hillslope-to-channel) and longitudinal (i.e. within-channel network) coupling (Brierley et al. 2006, Fryirs et al. 2007a,b). A catchment can be subdivided into components defined by, for example, pixels of a DEM; landform entities or types delineated on a geomorphological map (e.g., Schrott et al., 2002; Otto et al., 2009); slope units (van den Eeckhaut et al., 2009); hydrological response units (Flügel, 1995); subcatchments; or process domains (Montgomery, 1999; Brardinoni and Hassan, 2006). The "geomorphic cell" is a spatial entity recently proposed for the analysis of connectivity (Poeppl and Parsons 2018).

In general, all forcings identified on the plot/hillslope and channel reach scale also apply to the catchment scale. As the catchment size increases, some forcing factors cannot be considered homogenous any more, so that their spatial distribution needs to be accounted for, for example precipitation sum, intensity, and type (given sufficient vertical extent of the study area).

The same is true for the intrinsic properties, e.g. topography (variables: *elevation, slope, roughness, curvature* etc), lithology, soil- and landcover-related properties. Most importantly, the spatial distribution (i.e. location, size and topological sequence along flowlines) of these properties modifies the impact of small-scale connectivity (plot/hillslope, channel reach) on catchment connectivity, and hence on its runoff response and associated sediment yield (e.g., Cammeraat, 2002; Fryirs et al. 2007a; Nippgen et al., 2011). Jencso et al. (2009) highlight the importance of hillslope-channel coupling in translating hillslope-scale runoff generation into catchment response by showing that the "the fraction of the network connected to its uplands controls runoff magnitude" (see also Emanuel et al., 2014). Similarly, Pöppl et al. (2012) showed that riparian vegetation may effectively decouple the channel network from its catchment area. Valley form (specifically valley width and confinement; see Figure 1) determines the amount of accommodation space for sediment storage and hence influences sediment connectivity (Nicoll and Brierley, 2016; Fryirs et al., 2016).

Some properties related to catchment-scale connectivity are determined directly at the (sub-)catchment scale, e.g. (sub-)catchment size and shape, or the distribution of flow lengths, that govern the amount and concentration of runoff. Jencso et al. (2009), for example, observed that the duration of hydrological connectedness in their study area was linearly related to the size of the contributing area. Additional properties are related to the channel network, its geometry and density. Drainage density has been shown to play an important role in describing connectivity in low-relief landscapes (Gay et al., 2015). Recent work has shown the importance of network structure on the propagation and superposition of sediment pulses (Czuba and Foufoula-Georgiou 2014, 2015; Gran and Czuba, 2017).

Response variable summarizing forcing-resistance interactions: indices

Consistent with the framework proposed by Bracken et al. (2015), variables representing hydrologically and gravitationally driven processes are needed to assess catchment-scale connectivity. The previous paragraphs have highlighted the importance of the spatial distribution of forcing and intrinsic properties. Precipitation (see subsections 2.2.1 and 2.2.2) and substrate properties drive surface runoff, which is the actual driver of sediment transfer (by running water). At the catchment scale, this variable requires modelling, using either DEM-based flow accumulation as a proxy variable (e.g. Jencso et al., 2009) or rainfall-runoff models (e.g., Lane et al., 2004; Reid et al., 2007) including snowmelt. Sediment pathways effected by mass movements require an account of the spatial distribution, magnitude (runout length) and frequency of such processes (Guzzetti et al., 2006; Heckmann and Schwanghart, 2013), and their topological relationship with the channel network (Korup, 2005).

Topographic variables (e.g., slope, curvature and roughness) are readily derived from increasingly available digital elevation models. Additionally, landcover information is used to represent, among others, the terrain impedance to surface flow and sediment transfer. Surface substrate information relates to connectivity if sediment availability plays a role. The “effective catchment area” (Fryirs et al., 2007b), i.e. the area actually contributing sediment, and related concepts (the upslope component of the IC index; Borselli et al., 2008 and the “sediment contributing area”, Haas et al., 2011; Heckmann and Schwanghart, 2013) are implicitly related to sediment connectivity (c.f. section

3.2). In these concepts, both hydrological forcing and potential sediment transfer are represented by the upslope contributing area (or a subset) as a proxy (Figure 1).

2.3 Response variables and data acquisition

Many of the response variables listed above, which represent forcing and intrinsic properties associated with sediment connectivity, can be acquired or derived through remote sensing and/or direct techniques. While for each response variable an accurate spatially and temporally continuous representation of the real world situation would be ideal, in practice, customarily available data are often limited in terms of spatial and temporal resolution, completeness and/or accuracy. For example, at the reach scale ideally one would like to have continuously distributed terrain information derived from Digital Surface Models (DSM). Practically, we are often left with direct measurements obtained by topographic surveys conducted at selected channel points or along cross sections. Yet, data acquisition technologies, particularly in remote sensing, have recently experienced a tremendous development in terms of spatial, spectral and temporal resolution (Toth and Jóźków 2016). Moreover, data availability has increased substantially and thus gives prospect to a wider range of applications in water and sediment related issues. Several authors have pointed out the high capabilities of remote sensing, particularly at the catchment scale (e.g., Vrieling 2006), while Bracken et al. (2013) call for the potential of developing hybrid approaches combining a range of direct and remotely-based methods to improve the quantification of process specific sediment fluxes.

Remote sensing enables a spatially explicit data acquisition at different spatial resolutions and revisit frequencies. Acquisition platforms can generally be grouped into satellites, planes, Unmanned Aerial Vehicles (UAVs) and terrestrial devices, typically carrying either passive panchromatic, multi-spectral or hyperspectral cameras, active sensors such as LiDAR or Radar, or a combination of the aforementioned. A recent detailed review of the state-of-the art remote sensing technologies is provided in Toth and Jóźków (2016). Various terrain, soil and vegetation properties useable for sediment connectivity assessment can be retrieved from remote sensing data (see reviews in Mulder et al., 2011; Smith and Pain, 2009; and Schaepman et al., 2009). Primary properties highly relevant to sediment connectivity are land cover, topographic information and surface roughness. Land cover and land use is typically obtained from satellite and airborne imagery at the catchment scale, while topography is typically derived from spaceborne photogrammetry, interferometric SAR or airborne LiDAR at the catchment scale; and Terrestrial Laser Scanning (TLS) or UAV-based digital photogrammetry (e.g. Structure-from-Motion; SfM) techniques at the reach scale. Surface roughness, as one of the key factors controlling sediment connectivity, is governed by different surface properties at the plot, reach and catchment scale. Accordingly, it should be derived through different acquisition technologies depending on scale.

Soil roughness at the plot scale is preferably inferred from high-resolution TLS, while subaerial surface roughness at the reach scale is ideally derived from area-wide high-resolution topographic data sets obtained by airborne (Cavalli et al., 2008) or terrestrial LiDAR, or SfM techniques (e.g. Brasington et al., 2012). Using high-resolution DEMs, even properties of the grain size distribution of surface sediments can be estimated (e.g., Pearson et al., 2017). At the catchment scale roughness is, apart from topography, mainly driven by land cover and particularly vegetation density and pattern to be ideally derived from multi-temporal airborne or spaceborne imagery. The type of information obtained by means of these techniques may differ substantially and thus will affect the representation of the respective response variables. One example is the impact of vegetation on the acquisition of topographic data. Due to the multi-pulse ability, airborne LiDAR allows to distinguish ground form vegetation and thus to obtain both Digital Terrain and Digital Surface Models. However, most of the data sets acquired by means of UAV-based SfM or photogrammetry capture topography data in vegetated areas at canopy height and hence ground surface covered with dense vegetation is rarely represented in these data sets.

Direct data acquisition technologies are often limited to small areas and, consequently, data acquired using such techniques require regionalisation by means of interpolation or spatial modelling. Although data interpolation at plot-to-reach scale may provide accurately reasonable results if sufficient point-wise measurements are available, such techniques may lead to high uncertainty at larger scales. For instance, in a stream channel reach, the availability of spatially distributed data on bed texture would be ideal, however this is rather difficult to obtain by direct data acquisition technologies. The way to overcome this limitation will be determined by the size of the reach in relation to the variability of the response variable under investigation. In a homogenous gravel bar, several randomly distributed bulk samples may be sufficient to compute the grain size distribution of each, extract relevant statistics (e.g. D_{50}), and interpolate them to have a continuous map of a variable that represents bed texture or roughness. This procedure, however, might be rather time-consuming for larger or heterogeneous areas. In these cases, spatially distributed data require indirect or remote sensing technologies. In this particular example, digital image processing from high resolution aerial imagery can provide reasonably accurate maps of the median surface grain sizes over multiple scales (e.g., Carbonneau et al., 2003; Verdu et al., 2005), if appropriate calibration (and validation) is provided using direct point-wise measurements. Additionally, the enormous density of the point clouds extracted from airborne LiDAR, TLS or SfM, enables the assessment of ground roughness based on sub-grid statistics of bed elevations. In this context, Smith (2014) pointed out that the detrended standard deviation of elevations extracted from high density point clouds is increasingly recognized as a roughness metric across the Earth Sciences. Although this metric is directly related to bed texture, it may differ from direct measurements due to the effects of the shape and form of the particles, and the local topographic changes associated to bedforms. Therefore, it could be considered a proxy measure that needs some validation by direct measurement. Finally, some direct methods are exclusively applicable at the point scale as for instance water discharge. Any attempt to obtain spatially distributed flow data requires taking into account the (potentially) non-linear nature of the contributing area-discharge relation, and need to be supported by rainfall-runoff modelling that in turn can be parameterized from remotely-sensed initial conditions (e.g., Xu et al., 2014).

3 Review of existing indices

In this chapter, we give an overview of existing approaches for assessing sediment connectivity through indices. In addition, we review a number of hydrological connectivity indices that have been applied to sediment connectivity. For an extended review on hydrological indices, the reader is referred to Ali and Roy (2010). Our overview distinguishes raster-based connectivity indices *sensu stricto* from approaches delineating an “effective catchment area”, which implement concepts of connectivity, and network-based indices.

3.1 Raster-based connectivity indices

Since the late 1980s, thanks to the rapid improvement of GIS technology and the growing availability and quality of DEMs, several methodologies were developed for modelling, through a spatially distributed approach, the influence of topography on shallow landsliding, erosion and sediment yield. Following empirical findings on the stream power law (Wolman, 1954; Leopold and Wolman, 1957) and topographic thresholds of process transitions (Patton and Schumm, 1975; Dietrich and Montgomery, 1988; Montgomery and Foufoula-Georgiou, 1993), several combinations of upslope area and local slope, have been used to implement topography-based models and indices. For example, to identify landslide-prone areas (Montgomery and Dietrich, 1994) or to estimate sediment transport potential (Montgomery and Buffington, 1997, 1998).

Slope-area indices rely on the concept of stream power (Ω) developed in the context of hydrology and fluvial geomorphology but applicable also to unchannelled areas. Stream power represents the rate of energy expenditure and is usually expressed as:

$$\Omega = \rho g Q \tan\beta \quad (1)$$

where ρ is water density, g gravitational acceleration, Q discharge and β slope (in degrees). Considering ρ and g being constant and assuming that Q is a power function of the upslope catchment area (A), A multiplied by tanβ represents a general formulation of a stream power index (Wilson and Gallant, 2000). Stream-power based approaches were also applied for modelling the topographic potential for erosion and deposition, and for evaluating the impedance to sediment conveyance (Moore and Burch, 1986; Mitasova et al., 1996). Wilson and Gallant (2000) provided the most comprehensive review of existing approaches and software tools for terrain analysis in the environmental sciences available so far. Recently, d'Haen et al. (2013) employed Ω as an index of longitudinal connectivity (see also Kuo and Brierley, 2014; in their study, however, specific stream power is computed using the width of the valley, not of the active river bed).

These concepts have been incorporated in two stream power-based indices to evaluate the impedance to sediment fluxes at the catchment scale and along the channel network in alpine environments (Dalla Fontana and Marchi, 1998; Marchi and Dalla Fontana, 2005). Both indices are based on a comparison between a simple stream power index (SPI) and a fixed threshold (usually the threshold used to define the location of channel heads). SPI is defined as:

$$SPI=A^{0.5}\,S \tag{2}$$

where A is the drainage area and S the local slope.

The DEBAS index (stream power DEficit on BASin slopes) (Dalla Fontana and Marchi, 1998; Marchi and Dalla Fontana, 2005) expresses the influence of the location of the elementary unit (i.e., DEM pixel) within the catchment on the possibility that the eroded sediment reaches the outlet; this is directly related to definitions of connectivity, e.g. that by Hooke (2003). Values of the index progressively increase by one unit starting from the outlet (where the value is set to 0) in the upstream direction as long as the SPI is lower than a fixed threshold (that usually corresponds to a threshold representing the initiation of the channel network). High DEBAS values represent a low degree of linkage between local erosion processes and sediment yield at basin scale. Similarly, but with a specific focus on the channel network, the DENET (stream power DEficit on channel NETwork) indicator highlights spatial patterns of low-efficiency sediment transport processes. In this case, the computation, consisting in summing contiguous cells with SPI values lower than the threshold, has a downstream direction.

Walling and Zhang (2004; see also McHugh et al., 2002) presented a GIS-based procedure for the estimation of lateral (i.e., hillslope to channel) connectivity at large spatial scales. In this approach, a connectivity index was initially calculated as a function of the sediment transport capacity modified by a slope shape and a drainage pattern factor. The sediment transport capacity parameter is derived using variables related to runoff potential, slope gradient, land-use and sediment characteristics. The approach applied to the whole territory of England and Wales with a 1 km resolution showed promising results, although the authors highlighted the need for methodological improvements.

Jain et al. (2010) introduced a fourfold classification of connectivity depending on physical contact (yes/no, equivalent to structural connectivity) and transfer of material (yes/no, equivalent to functional connectivity). They applied different connectivity indices to physically connected ($C_{pc} = A * i_m$) and physically disconnected ($C_{dc} = E/d$) system compartments in a geomorphological map of the Ganga river system; these indices depend on the area of physically connected components (A), the rate of material transfer (i_m), energy in the system that is available to move sediment (E) and the distance between compartments (d). These indices, however, are only of conceptual nature and were not computed actually.

In recent years, the growing need for the quantitative characterization of the linkage between landscape units that could benefit from high resolution topographic data has led to a growing interest in geomorphometric indices in order to qualitatively address sediment connectivity. A particularly successful index, named Index of Connectivity (IC) was developed in the context of soil erosion studies and applied in an agricultural catchment in Tuscany (Italy) by Borselli et al. (2008, see Figure 3 and Figure 4). IC is a distributed GIS-based index mainly focused on the influence of topography on sediment connectivity, taking into account also some land cover-related information. The map of IC aims at representing the potential connectivity between catchment components. IC is defined as:

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) \qquad (3)$$

where D_{up} and D_{dn} are the upslope and downslope components of connectivity, respectively (Figure 3). IC is defined in the range of [-∞, +∞], with connectivity increasing for larger IC values.

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

$$D_{up} = \overline{W}\,\overline{S}\sqrt{A} \qquad (4)$$

where W is the average weighting factor (dimensionless) of the upslope contributing area, S is the average slope gradient of the upslope contributing area (m/m) and A is the upslope contributing area (m²).

The downslope component D_{dn} considers the potential flow path length that sediment has to travel in order to reach the nearest target or sink, and is expressed as:

$$D_{dn} = \sum_i \frac{d_i}{W_i S_i} \qquad (5)$$

where d_i is the length of the flow path along the *i*th cell (m), W_i and S_i are the weighting factor and the slope gradient of the *i*th cell, respectively.

The weighting factor, which represents the impedance to sediment movement, was estimated by referring to a factor used in soil loss equations: the C-factor of USLE–RUSLE models that takes into account land use cover. Borselli et al. (2008) defined also a field connectivity index (FIC), which can be used to validate IC results.

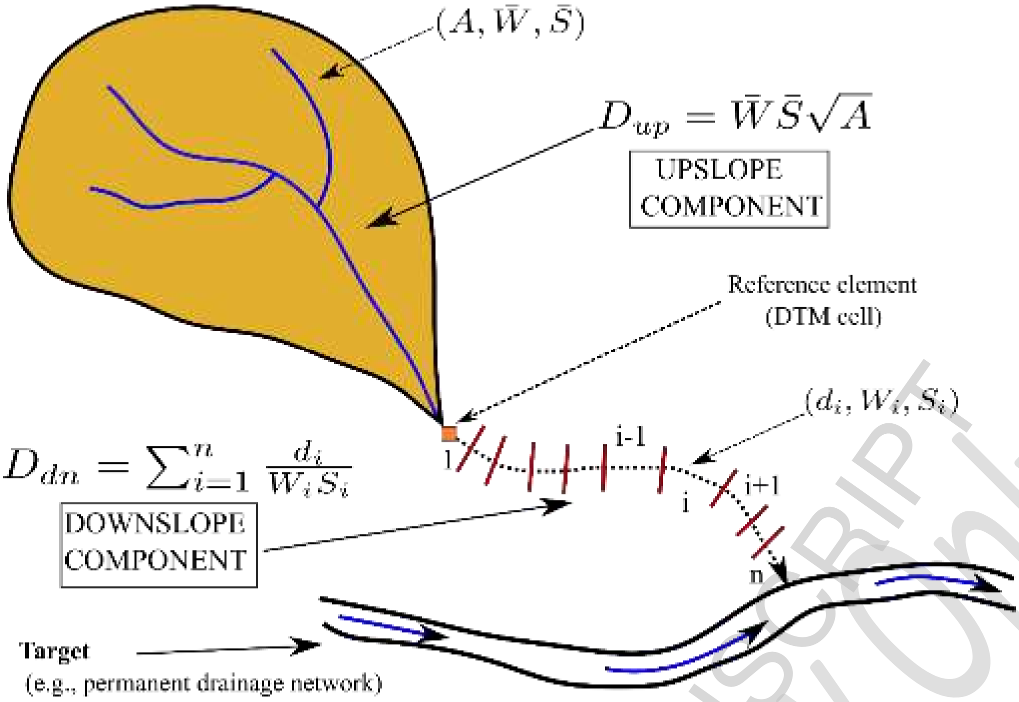


Figure 3: Upslope and downslope components of the Index of Connectivity (after Borselli et al. 2008)

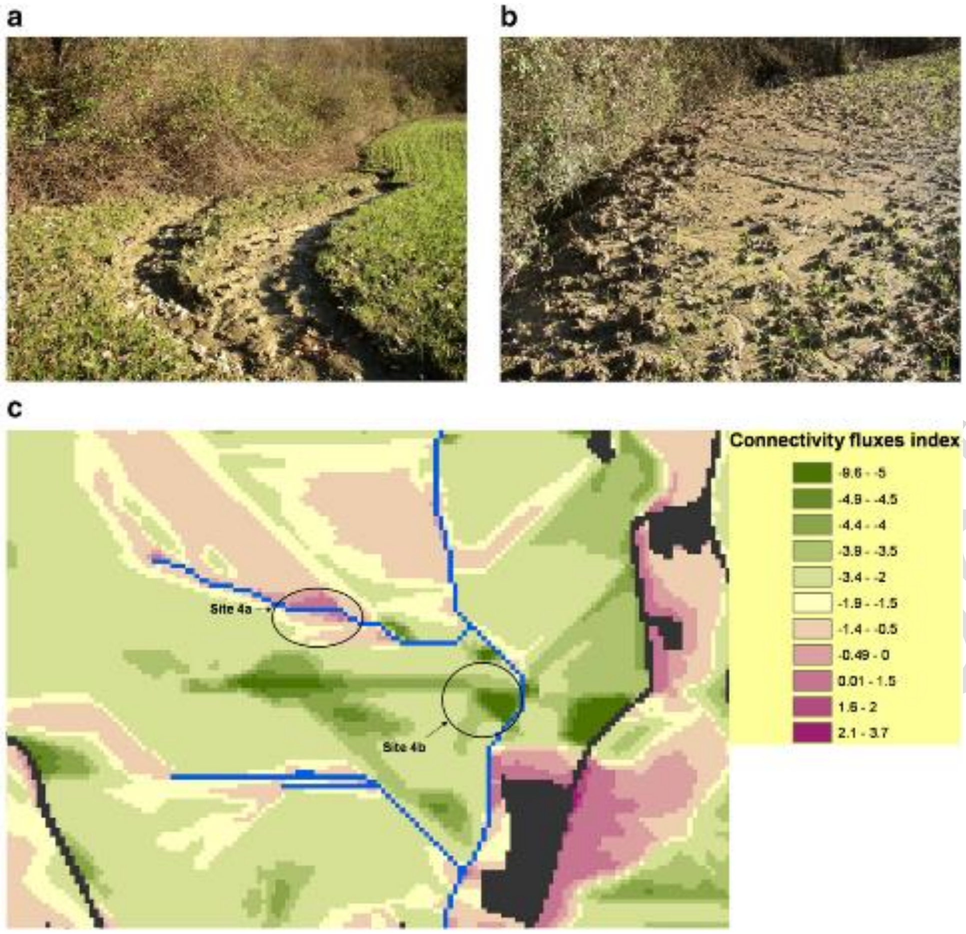


Figure 4: Photographs showing the direct connection of a channel and an adjacent field (a) and colluvial deposits evidencing decoupling (b). An IC map shows high and low values for areas 4a and 4b, respectively. Source: Borselli et al., 2008 PERMISSION

Cavalli et al. (2013) proposed a new version of IC with refinements and modifications to deal with main processes dominating sediment dynamics in mountain catchments and to apply IC with high-resolution DEMs. Moreover, they proposed to use IC with different targets in order to evaluate the potential connection between hillslopes and features of interest such as the catchment outlet, the main channel network, roads, lakes, or a given cross section along the channel. The main refinements made to the original index are related to slope, contributing area and weighting factor computation: Slope is computed along the direction of flow, and contributing area is calculated using the D-infinity approach (Tarboton, 1997) to capture divergent flow paths on hillslopes (the original version used the D8 approach that does not account for divergent flow). The modified weighting factor is derived based on a local measure of surface roughness computed from high-resolution DEMs (Cavalli and

Marchi, 2008). Using a flow-directional surface metric may further improve the effectiveness of surface roughness computation (Trevisani and Cavalli, 2016).

Advantages in using a surface roughness indicator (W) in IC computation include that: i) the weight is estimated objectively; ii) it avoids the use of tabled data; and iii) it allows IC to be applied straightforwardly, requiring only the DTM as data input. After its first application in two small adjacent catchments of the Eastern Alps, this version was widely applied in different contexts.

Chartin et al. (2016) modified IC by implementing a rainfall erosivity factor in addition of the C factor used in the original version of IC (Borselli et al., 2008); together with a temporally variable C factor, this allowed the authors to better address connectivity in study periods that were affected by rainfall (typhoons) of different intensity. Hooke et al. (2017) combined W (=C according to Borselli et al., 2008) with a factor derived from the curve number method to compute a “connectivity breaker factor” for use in the original IC framework; thus, their index makes it possible to account for different antecedent moisture conditions. Kalantari et al. (2017) used curve numbers for “a more functional approach”, in order to account for other factors than topography, which they state is especially important in lowland areas. Specifically, curve numbers reflect the runoff generation potential on surfaces with different landuse and groups of soil types; they are used to estimate surface runoff Q on the basis of gridded daily precipitation (which makes their IC variant dynamic). W is then computed as the ratio of local Q and Qmax (maximum Q within study area), or through a multiplication of normalised Q and roughness according to Cavalli et al. (2013). Several authors developed options to use both topographic roughness and landcover-related flow impedance to compute the W factor of IC. Lizaga et al. (2017) compute the W factor using the normalised product of topographic roughness (computed as the standard deviation of slope), the RUSLE C factor, and the “total aerial biomass” estimating forest density with the help of LiDAR point cloud data. Ortiz-Rodriguez et al. (2017) apply topographic roughness (according to Cavalli et al., 2013) to bare areas, and the C factor (according to Borselli et al., 2008) to vegetated and agricultural areas; they state that this “joint IC” does not overestimate connectivity in bare areas. Persichillo et al. (2018) use (1-

Manning's *n*) to compute W, with *n* either extracted from tables as a function of landcover or estimated using Manning's equation.

Another IC modification was proposed by Gay et al. (2016) in order to integrate landscape infiltration and saturation properties to consider lowland processes in the assessment of connectivity. The authors demonstrated that existing topographic indices fail to represent existing sediment connectivity in lowland areas; in their adaptation, runoff processes are accounted for through the IDPR index (index of the development and persistence of the drainage network; Mardhel et al., 2004) that is related to drainage density. IDPR is rescaled to [0,1] with a linear or sigmoid function, and is included in the IC computation as an additional factor where slope does not exceed 7°. Gay et al. (2016) report that the implementation of IDPR led to a better differentiation of IC in flat areas, and assign the IDPR an "interesting potential to reflect connectivity in lowland areas". In fact, the IDPR index itself can be seen as a proper index of (hydrological) connectivity, indicating whether surface/subsurface or deep percolation contribute to water transfer (Dupas et al., 2015).

Grauso et al. (2018a) proposed a "simplified connectivity index" (SCI) that is calculated for a group of i=1…N unit areas draining into a common outlet located at a distance d_i that is measured along flow paths on a DEM. Each unit area is characterised by a specific soil loss SL_i that is usually estimated from a model. Both d_i and SL_i are normalised by the maximum values, d_{max} and SL_{max}, found in the study area, and SCI is computed as

$$SCI = -log\left(\frac{\sum_{i=1}^{N}\frac{SL_i/SL_{max}}{d_i/d_{max}}}{N}\right) \qquad (6)$$

Note that SCI is based on (modelled) specific soil loss, which does not conform with the hypothesis that connectivity only relates to the proportion of eroded sediment being delivered, not on its net amount (e.g., Heckmann and Vericat, 2018).

Wohl et al. (2017; Figure 5) highlight the importance of the spatial characterization of sediment connectivity in analysing sediment fluxes. They propose a "fast and simple proxy", i.e., an index of (mostly longitudinal) connectivity for river reaches that is computed from a GIS-based weighted overlay of a number of spatially distributed variables: river reach gradient, lithology, elevation (related to flood generation), vegetation, and human influence (diversion, roads). It was found that stream gradient (a morphometric parameter easily derived from DEMs) was most indicative of the relative longitudinal connectivity. Figure 5 highlights that the index correctly reflects observed connectivity by the examples of a beaver meadow, a reservoir (both associated with poor connectivity) and a high-gradient reach with cascades (indicative of high connectivity).

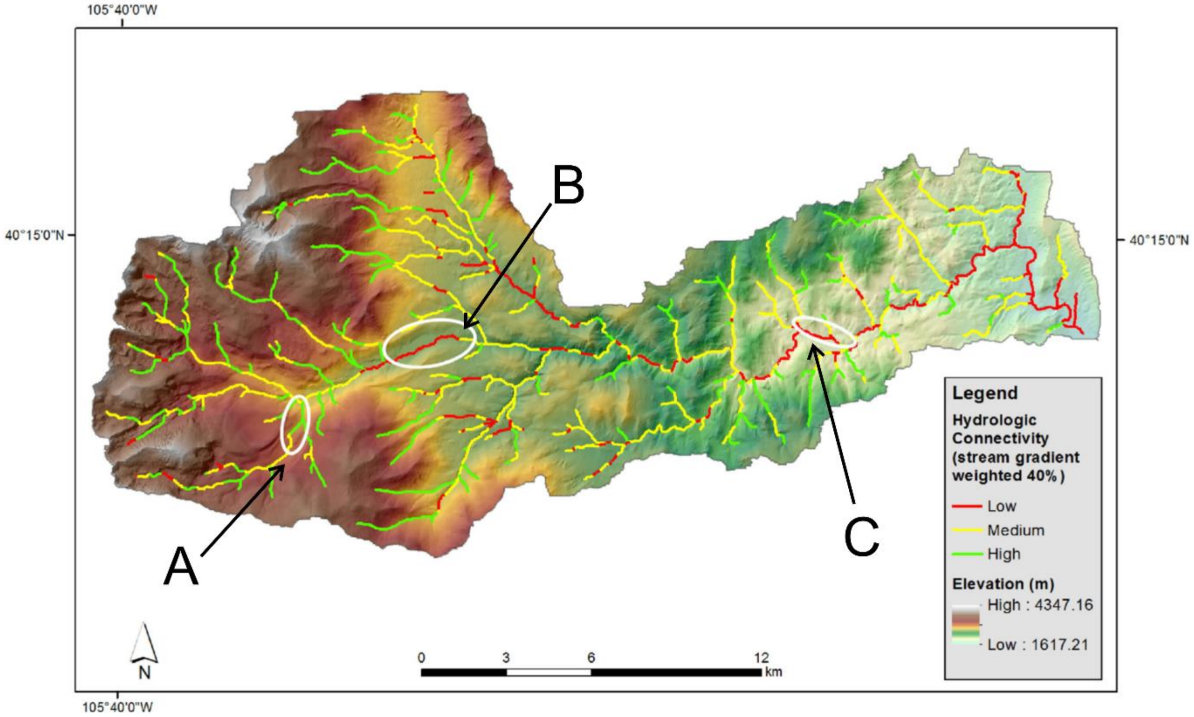


Figure 5: River reaches in the North St. Vrain catchment, Colorado, classified according to an index of longitudinal connectivity. Letters depict reaches used to calibrate the weighting of different factors. A: waterfalls in a steep reach, assumed to be unconditionally coupled. B: Beaver meadow, C: Reservoir. Source: Wohl et al. (2017, letters added) PERMISSION

In a new approach to assess the connectivity of flow paths through mountainous terrain, Lane et al. (2017) apply a sink filling algorithm iteratively, with an increasing “maximum depth” threshold, to a high-resolution DEM and monitor the corresponding size of the contributing area of selected sub-catchment outlets. They hypothesise that small sinks are spurious, conditioned by DEM noise, and term the resulting disconnection of flow pathways "methodological disconnection". In contrast, "process disconnection" of flow pathways is promoted by real sinks whose depth is larger than the noise-induced DEM roughness. The depth filling threshold at which the contributing area (calculated from the sink-filled DEM) no longer increases is then used to quantify the "level of process disconnection along the flow path". This threshold will be low if there is a large number of very shallow sinks that can be attributed to DEM noise; it will be high in the presence of more, deeper, landform-induced sinks. This approach is conceptually similar to the relative surface connection function (RSCf) used by Antoine et al. (2009, see also Antoine et al., 2011) and Peñuela et al. (2015) to include sub-grid information on soil microtopography in hydrological models. This function describes how the percentage of area connected to the outlet (of a raster cell) increases with increasing level of fill of the depression storage. One of the characteristic points that define this function (Peñuela et al., 2015) is an inflection in the connected area-depression storage relation, called the connectivity threshold, above which the connected area increases sharply with only small increases in depression storage filled. In Lane's et al. (2017) approach, the transition between "methodological disconnection" and "process disconnection" is inferred at an inflection where the size of the contributing area starts to rapidly increase with increasing sink filling depth, and process connectivity is achieved where the contributing area increases no more as the sink filling depth increases.

In hydrology, Lane et al. (2004; Figure 9) modified the topographic wetness index used in TOPMODEL (Beven and Kirkby, 1979) that implements the "variable contributing area" concept of runoff generation and transmission to the channel network. Hydrological connectivity is established only where the model indicated continuously saturated flow paths towards the channel network; part of this procedure involved assigning to each raster cell the lowest topographic wetness index value encountered along the steepest descent flow path to the channel network.

Recently, Mahoney et al. (2018) presented a three-stage watershed erosion model featuring a "probability of sediment connectivity" that could be regarded as a sediment connectivity index. The first stage involves a dynamic hydrological model that estimates soil moisture and runoff depth across the study area. In a second stage, this model and geomorphological information (sediment availability, geomorphic processes and the presence of impediments to sediment transport) are combined to assign each raster cell probabilities of sediment availability, detachment, and transport by hydrological and non-hydrological processes, and presence of buffers. These probabilities are intersected (mathematically by multiplication and summation) to yield a "probability of sediment connectivity". The result of stage two can be viewed as a connectivity index, which is then used in a third stage in combination with an erosion model.

3.2 Effective catchment area approaches

The raster-based indices mentioned in the previous paragraph are based on the "variable contributing area" concept, acknowledging that not all runoff-producing areas ("active" areas) are coupled to the channel network, and hence "contributing" (Antoine, 2004; Nippgen et al., 2015). Geomorphological research dealing with sediment transfer and delivery (Walling, 1983; de Vente et al., 2007) has used similar concepts. Here, the aim is to spatially delineate a portion of the catchment that effectively contributes to sediment delivery from various sources to the channel network or the catchment outlet (Figure 1). This is generally achieved by using flow-routing algorithms on DEMs that delineate the contributing area of selected targets, constrained by disconnections. The latter can be inferred from geomorphological and/or land cover maps, and from the DEM itself, mostly by using slope thresholds below which sediment transfer is assumed to be ineffective (e.g., 4° for coarse sediment transport in channels; Church, 2010).

Fryirs et al. (2007) mapped landforms indicative of disconnections (buffers, barriers, blankets) and used a DEM (with a slope threshold of 2°; see also Lisenby and Fryirs, 2017a) to delineate the "effective catchment area" (ECA), which is the area that may actually contribute sediment to a specified outlet and is directly related to sediment connectivity. Similarly, Nicoll and Brierley (2016) automatically delineated the ECA by using an 8° slope threshold on the contributing area of a narrow channel buffer. The 8° threshold was selected by trial and error after the thresholds proposed by

Fryirs et al. (2007) yielded ECAs that were markedly different from the field situation, highlighting the need for careful selection of the threshold. Kumar et al. (2014) used the approach with variable thresholds (set to account for different magnitudes of hydrological forcing), to investigate IC-based sediment connectivity on a Megafan in India. Souza et al. (2016) use a set of slope thresholds to differentiate between major (<0.5°) and minor (0.5-2°) disconnecting elements, non-limiting gradients (2-25°) and those not allowing for sediment storage, therefore acting as boosters to sediment transmission (> 25°).

The ECA rationale also forms the basis of an earlier application by Heinimann et al. (1998) to extract a continuously steep portion of a channel buffer in a debris torrent susceptibility model; the result was called the “sediment contributing area” (SCA; see also Wichmann et al. 2009; Haas et al., 2011; Figure 1 and Figure 13).

The result of ECA approaches is the location and extent of an area. While this area directly results from the connectivity concepts implemented in the maps and algorithms, it is not a specific measure or index of connectivity as defined above (Babbie, 2013). However, it is possible to compare the effective catchment area to the size of the unconstrained (hydrological) contributing area; for example, Fryirs et al. (2007b) reported that the effective catchment area of sub-catchments of the Upper Hunter River catchments amounts to 3-73 % of their respective area.

3.3 Object- and network-based connectivity assessment

Most connectivity indices are based on raster data, and many are computed for raster cells. However, (dis-)connectivity operates not at the raster cell but at the landform scale (see section 2.1), and single raster cells bear no geomorphological significance (c.f. a similar discussion in landslide susceptibility modelling, e.g., van den Eeckhaut et al., 2009). Gascuel-Odoux et al. (2011) suggest to represent “space as closely as possible in terms of functional objects in relation to the processes involved, thus avoiding a single cell-based discretization with topographic attributes”. As a consequence, objects such as landforms (sediment storage, Schrott et al., 2002; buffers, barriers and blankets, Fryirs et al., 2007), agricultural fields (Gascuel-Odoux et al., 2011), river reaches (Wohl et al., 2017) and valley segments (Wohl and Beckman, 2014) have been addressed in hydrological and sediment connectivity studies. Singh et al. (2017) propose ‘connectivity response units” (CRUs) as a connectivity-related analogue to hydrological response units (HRUs, c.f. Fluegel, 1995), but highlight the differences between hydrological and sediment connectivity. In their work, CRUs are delineated using IC maps that are (i) smoothed using a diffusion kernel in order to homogenise the spatial pattern, and (ii) classified using Jenk’s natural breaks algorithm. Recently, Poeppl and Parsons (2018) proposed the “geomorphic cell” as a fundamental unit for studying connectivity; contrary to the previously named spatial units, their proposal remains purely conceptual. They suggest that geomorphic cells should be delineated within a GIS framework, but remain vague as to how this can be achieved, especially as to how their approach differs from a “unique condition” segmentation approach (see discussion of mapping units in Guzzetti et al. 1999).

Quiñonero-Rubio et al. (2013) attempted to combine multi-scale (hillslope, channel, subwatershed) factors of connectivity mapped with different techniques (fieldwork, remote sensing, modelling) into a catchment scale connectivity index (CCI). The factors are hillslope transport capacity (modelled), channel flow conditions (perennial vs. ephemeral; field and orthophoto maps), stream power (DEM-based), tributary confluence (tributary-main stem coupling; field and orthophoto maps) and sediment retention (trap efficiency of dikes; field and orthophoto maps).

Landscape structure, i.e. the spatial configuration of landforms, has been analysed with respect to sediment connectivity mostly based on geomorphological maps, and in a qualitative fashion (Harvey, 2001; Hooke, 2003). Schrott et al. (2003) derived a flowchart-like model representation of sediment cascades in an alpine catchment from a geomorphological map. Otto (2006) and Meßenzehl et al. (2014) mapped toposequences and sediment cascades. Korup (2005) presented a framework to classify the geomorphic coupling of landslides to the channel network on the basis of areal, linear, point-like, indirect, or no intersections (see Figure 1; one of the landslides is coupled to the channel network). Li et al. (2016) investigated connectivity caused by earthquake-triggered landslides and found a positive correlation between landslide area and landslide-channel connectivity (intended as landslides topologically connected to the main channel network). Sidle et al. (2004) evaluated the influence of forest logging roads and skid trails on sediment connectivity in a semiquantitative manner by categorising single intersections of water and sediment pathways with the road/trail network as being fully, moderately or not connected.

The approach by Poeppl et al. (2012) is based on DEM-based flow pathways between (potential) sediment sources and the channel network. The authors correlated topographic and landcover-related properties of these flow paths to their coupling to the channel network (as assessed in the field). The resulting logistic regression model could be seen as an index of sediment connectivity when applied to a network of automatically delineated flow paths.

The perception of a catchment as a cascading system whose compartments are linked by sediment fluxes (e.g. Chorley and Kennedy, 1971; see also Figure 1) suggests networks as an intuitive data structure to study connectivity. Indeed, ecologists have been using graph theory to assess landscape connectivity for quite some time (Bunn et al., 2000; Urban and Keitt, 2001; Pascual-Hortal and Saura, 2006; Minor et al., 2008; Galpern et al., 2011; Laita et al., 2011; Segurado et al., 2013). Recently, there have been attempts to assess the structure of alpine catchments using a graph representation of a geomorphological map (Otto and Löwner, 2008; Götz et al., 2013; Heckmann et al., 2014; Cossart, 2016). In these approaches, landforms form the nodes, and edges represent existing or potential sediment pathways inferred from field evidence by geomorphological expertise, for example by identifying features indicative of active or potential sediment transfer. Cossart and Fressard (2017) proposed the first network-based sediment connectivity index and applied it to a synthetic, didactic and to a real catchment where the nodes represent locations in the study area that can be aggregated by the landform to which they belong (Figure 6). The nodes are connected by directed edges representing sediment fluxes. In order to keep the approach simple, the authors chose not to assign more than one outgoing edge to each node, thus avoiding divergent sediment pathways. The proposed index IC combines two graph-theoretic metrics for nodes, namely the flow index F_i and the Shimbel index of accessibility index A_i. F_i is a centrality measure evaluating the number of paths in the graph that include node *I* and reach the outlet. The index is computed as the ratio F_i/A_i for each node *i*. Key results of the analysis of the Celse-Nière catchment in the French Southern Alps (see also Cossart et al., 2018) include that only 56% of all paths are connected to the outlet, and that the system is highly fragmented (referring to the number of connected components of the graph). Important links are identified as hotspots of geomorphic changes (see also Czuba and Foufoula-Georgiou, 2015); this relates to the fact that connectivity has been associated with sensitivity to and propagation of change (e.g., Fryirs, 2017).

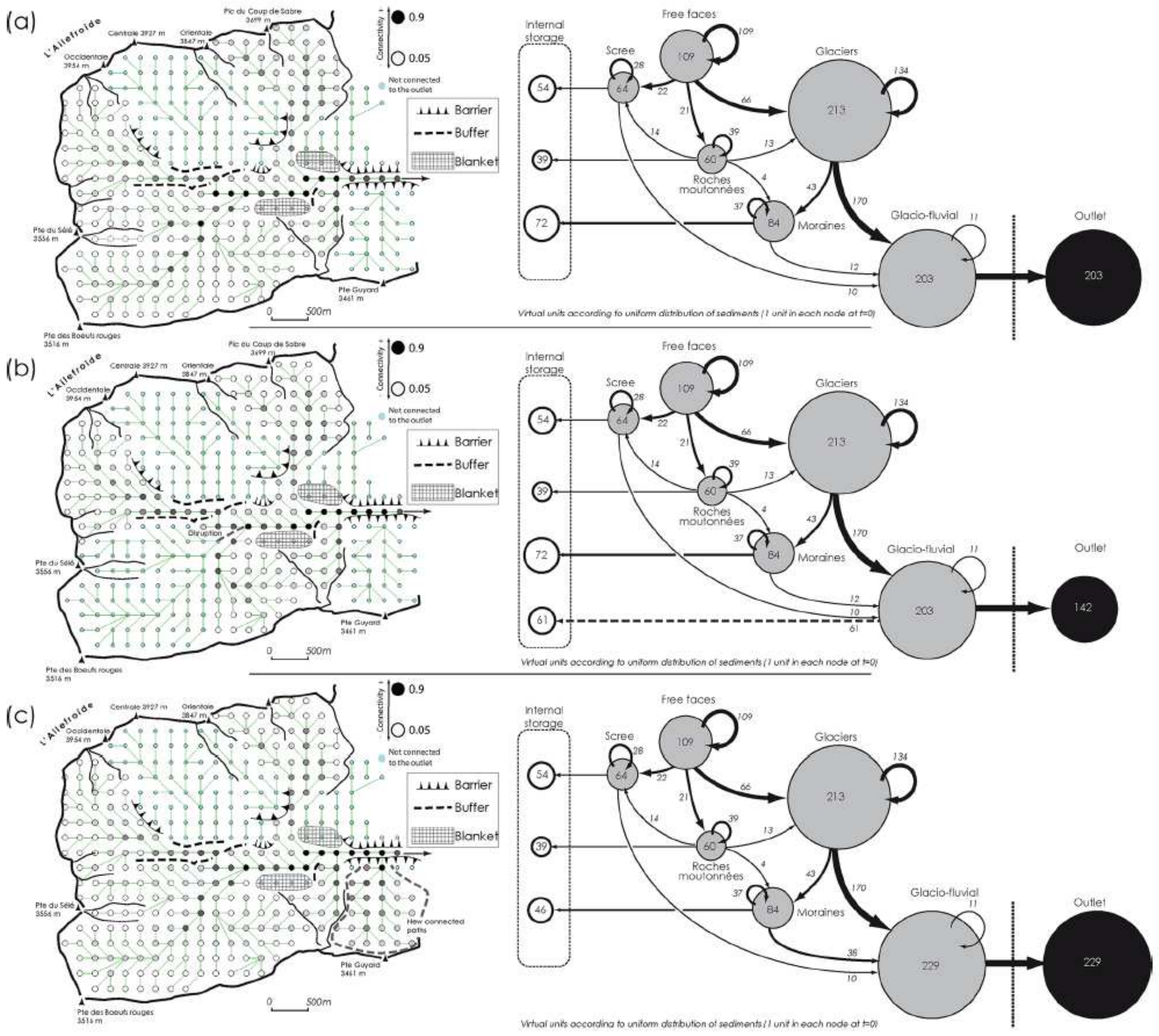


Figure 6: Connectivity assessment of the Celse-Nière catchment, French Alps, under current conditions (a), with a simulated disruption (b), with a simulated reconnection (c). The column on the left shows the network of sediment pathways according to flow directions, and disrupted by buffers, barriers and blankets according to a geomorphological map. The nodes are

coloured according to their connectivity index value. The column on the right shows simulated rates of sediment transfer between system compartments, assuming uniform distribution of sediment across nodes at t=0. Source: Cossart and Fressard (2017) PERMISSIONS

Heckmann and Schwanghart (2013) based their investigation of coarse sediment connectivity in an Alpine catchment on spatial models of sediment sources and pathways. A graph is constructed whose nodes (raster cells of the DEM) are connected by edges that represent sediment pathways operated by different geomorphic processes (slope wash, linear erosion, rockfall and debris flows). The subgraphs related to the single processes were merged into a single graph. Graph theory provides a multitude of measures to quantitatively analyse such networks (c.f. Heckmann et al., 2015). For example, Heckmann and Schwanghart (2013) analysed node properties (by classifying source, sink and link nodes) and the distribution of edge sequences interpreted as sediment cascades, leading to a still structural, yet more process-based perspective on sediment connectivity. Besides addressing the spatial distribution of the size of the sediment contributing area (by multiple processes), however, they did not derive a proper connectivity index. More recently, this approach was modified to use landscape units from a geomorphological map to aggregate rockfall trajectories modelled on a raster DEM (Heckmann et al., 2016). By assigning stochastic rockfall rates to the trajectories, the resulting graph of landforms linked by rockfall sediment pathways allowed for the assessment of functional connectivity, and resulted in a spatially distributed rockfall sediment budget.

There is a number of studies in fluvial geomorphology that investigate longitudinal connectivity within the channel network, especially in braided river systems (e.g., Zah et al. 2001; Gomez et al., 2013; Marra et al., 2014) and deltas (Tejedor et al., 2015ab; Passalacqua, 2017). These studies use network representations of water and sediment pathways in which the channels form edges that connect sources, tributary junctions or bifurcations, and sinks. Different measures can be used to quantitatively describe properties of certain edges, or of the whole network (c.f. Heckmann et al., 2015). Zah et al. (2001), for example, compute a network connectivity index for each edge from the ratio of upstream and downstream connections to the main channel; Marra et al. (2014) use a centrality measure from graph theory to assess the relative importance of network edges. Such structural indices bear significance for both discharge and sediment flux, however applications to sediment connectivity are still rare. Connor-Streich et al. (2018), for example, propose a graph-theory toolbox that could be used for a multi-scale characterisation (and segmentation) of braided river systems with applications related to fluvial morphodynamics. Lehotský et al. (2018) construct a graph in which gravel bars mapped from aerial photos of a braided river form nodes; through a GIS analysis, the latter are linked to downstream neighbours if the Euclidean distance falls short of 200 m. Based on these data, the authors compute the Integral Index of Connectivity (IIC, Pascual-Hortal and Saura 2006), a patch-based connectivity index originally developed for habitat patches in landscape ecology.

4 Discussion

Our discussion of existing indices starts with a comparative evaluation of connectivity indices, continues with the discussion of spatial and temporal scale issues, the relationship between indices and models, and aspects related to the application of indices, for example in catchment management. We conclude by discussing future perspectives for the development and application of new sediment connectivity indices.

4.1 Comparison of indices

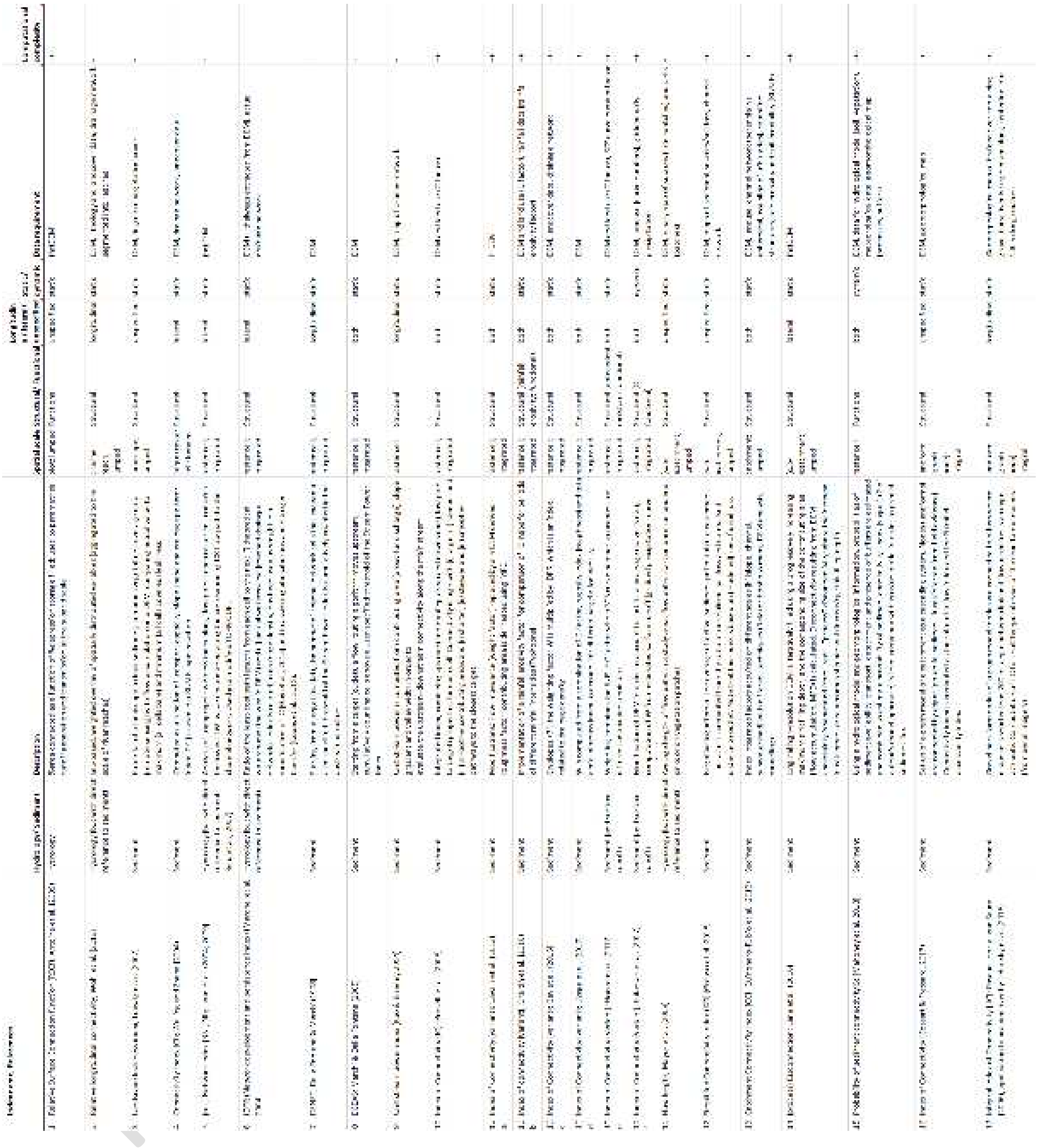
Our comparative evaluation of indices considers the spatial scale/s of application, the type (i.e., functional or structural) and directional component (i.e., longitudinal or lateral) of connectivity addressed, the explicit incorporation of time dependence (i.e., static or dynamic indices), as well as data requirements and computational complexity (Table 1).

Spatial scale refers to the spatial unit at which the index is computed (section 4.2.1). We distinguish between “integrated” and “lumped” indices. Integrated indices are computed at the scale of a raster cell, where computation is based on information (e.g., contributing area, average slope, and pathway to target) derived from upstream and/or downstream raster cells. In this context, network indices are classified as integrated ones, because relevant metrics may take into account (up- and downslope or -stream) nodes, edges, paths and graph structure. Lumped indices are computed for geomorphic units such as landforms (e.g., talus cones, fans and terraces) or catchments that include sub-scale information.

In terms of data requirement and computational complexity, low requirements refer to a small number of simple datasets (e.g. a DEM, a landcover map), medium requirements apply to integrated indices involving more complex datasets, for example flow routing, and high requirements include indices that need running a model beforehand. As topography plays a major role in connectivity, all indices make use of DEMs; however, terrain features, which often are not (or only incompletely) represented in the DEM (for example due to resolution, c.f. section 4.2.1), need to be implemented via additional factors such as the channel network.

The first observation from Table 1 is that there is not a large number of sediment connectivity indices. Six of the 23 indices represent modifications of the IC index originally developed by Borselli et al. (2008). A need to design new indices, however, cannot be justified from this observation alone, but needs to be based on a discussion of properties of present-day indices.

Table 1: Comparison of existing connectivity indices; see text for criteria and explanations.



Regarding the conceptual distinction between lateral and longitudinal connectivity (e.g. Brierley et al., 2006), four indices target lateral connectivity, four longitudinal connectivity, ten indices include both, and five indices are unspecified with respect to this conceptualisation. The IC (Borselli et al., 2008) and its derivatives are flexible, depending on the choice of the target (as implemented by Cavalli et al., 2013): When the channel network is the target, the index represents lateral connectivity, while both forms of connectivity are represented when the sediment pathway to the target (here: catchment outlet) includes the channel network.

Most indices exclusively address structural connectivity. This is also reflected in the data requirements: Most indices include neither factors representing functional properties nor external forcing (c.f. Figure 2). The implementation of a rainfall erosivity factor (Quiñonero-Rubio et al., 2013; Chartin et al., 2016) or a curve number factor (Hooke et al., 2017) to compute the weight W in IC may be seen as attempts to move in this direction. The modified IC proposed by Kalantari et al. (2017) uses curve numbers (as a proxy for functional properties governing surface runoff generation) together with spatially and temporally variable forcing and is, therefore, the only index in Table 1 that addresses both structural and functional connectivity, and includes forcing. With respect to structural connectivity, it has to be noted that most of the indices use flow directional analysis of DEMs, therefore the direction of connectivity is implemented. This represents an advantage over omnidirectional indices that merely address neighbourhood/adjacency of landscape units (see Ali and Roy, 2010). The relative surface connection function (and the indices derived from it; Antoine et al., 2009) is related to functional connectivity, as the development of connectivity with the filling of depression storage is described quantitatively (c.f. also the index conceived by Lane et al. 2017).

The relationship of structural connectivity indices to functional connectivity has been evaluated in some studies. Mayor et al. (2008), for example, state that the strongest relationship of the flow length index and runoff exists for high-magnitude events, and that the relationship decreases in strength with decreasing rainfall magnitude. A positive relationship with sediment yield was found, but that was only significant for the highest rainfall magnitudes. As the capacity of structural indices to explain or predict functional connectivity is vital for their application, we discuss this issue in detail in section 4.4. One problem of static structural connectivity indices is that they do not account for forcing events of different magnitude that lead to different degrees of functional connectivity. Thresholds used for the delineation of the effective contributing area, for example, have to be chosen carefully to fit the properties of the study area (Lisenby and Fryirs, 2017a), material properties (grain sizes), and have to be interpreted in consideration of event magnitudes. This is also related to temporal scales of connectivity (Harvey, 2002; Fryirs et al., 2007a; Fryirs, 2013), as forcing events are characterized by a different frequency of occurrence (see section 4.2.2). Dynamic models are seen as important tools to investigate the linkage of structural connectivity indices with functional connectivity under different forcing scenarios; this is discussed in detail in section 4.3.

As can be seen from the data requirements, virtually all indices collated in Table 1 are static and do not include time explicitly. The IC modified according to Kalantari et al. (2017) is the only example of an index that accounts for spatially and temporally varying external forcing. However, some studies have computed the IC index for different points in time to investigate seasonal (Foerster et al., 2014; Figure 7) to decadal (Lopez-Vicente et al., 2017a; Lizaga et al., 2017; Persichillo et al., 2018) changes of structural connectivity due to landuse/landcover changes, based on multitemporal landcover maps. Such analyses are facilitated by the increasing opportunities to gather remotely sensed topographic and landuse/landcover data (c.f. section 2.3). Some of these techniques could enable the implementation of parameters presently not included in indices, for example data related to surface material that is known to affect particle thresholds of motion and travel distances through the catchment (c.f. Lane et al., 2017).

Finally, the computational complexity of most of the indices is low to medium, which facilitates the implementation of the algorithms in GIS packages or management software tools. The IC, for example, can be computed using a free ArcGIS toolbox and a stand-alone software tool that were developed within the framework of the EU project SedAlp (Cavalli et al., 2014; Crema and Cavalli 2018). The Matlab-based Brain Connectivity Toolbox (Rubinov and Sporns 2010) has been used by researchers for the network-based assessment of geomorphic systems (braided rivers: Marra et al. 2014, lava channels: Dietterich and Cashman 2014). The software package iGraph (Czardi and Nepusz 2016) implemented in an R package was used by Heckmann and Schwanghart (2013).

The "probability of sediment connectivity" proposed by Mahoney et al. (2018) assumes a special position as it is coupled to a hydrological model and is therefore both dynamic and linked to functional connectivity. In that respect, we consider this a valuable development that deserves future research in terms of refinement (fuzzy or Bayesian treatment of single probabilities as the authors suggest), application (the authors combine the index with an erosion model in order to predict sediment fluxes) and validation.

4.2 Indices and scales

As discussed earlier, connectivity, and more particularly functional connectivity, clearly depends on spatial and temporal scales. In this context, we understand spatial scale as referring to the fundamental spatial units between which connectivity is assessed; this is associated with the typical length scale of connectivity (see section 2.1). Temporal scale refers to the time period for which connectivity is assessed (and therefore does not change substantially) using an index. In general, the review by Wohl (2017) shows that connectivity in river systems is being investigated at the spatial scale of 10^{-2}-10^{3} km or 10^{-6}-10^{3} km^{2}, respectively, and at temporal scales of days to thousands of years.

Spatial and temporal scales are not independent of each other. Depending on spatial scale (that is, the size of a study area), an event with a certain return period can have different geomorphic effects: Small subareas can be fully connected, but particle travel distance (e.g., Mao et al., 2017ab) during that event could be too short for connecting more distant subareas within a larger catchment. For clarity, we chose to discuss spatial and temporal scales separately.

4.2.1 Spatial scales

In this section, spatial scales are addressed from two perspectives: The first aspect relates to **spatial resolution**, reflecting the fact that most indices are computed from gridded geodata: (mostly raster-based) DEMs represent topographic properties and are used to establish structural connectivity via flow routing algorithms, and remote sensing imagery is an important source of landcover information. Lisenby and Fryirs (2017b) used DEMs of different resolution (1m, 5m, and 25 m) in order to find out what DEM resolution was most appropriate for, among others, delineating the ECA (c.f. section 3.2). They found that using a DEM1 (cell size 1m) led to numerous disconnections and hence to an underestimation of ECA; the DEM25 was found to be the most suitable one for delineating the ECA, due to averaging out spurious disconnections. Nicoll and Brierley (2016) showed that important features are not captured or mis-represented in coarser DEMs (DEM90 in comparison to DEM30). Cantreul et al. (2018) computed IC for a small experimental catchment in the Belgian loess belt using photogrammetric DEMs with resolutions between 0.25 and 10 m. They showed a systematic decrease of IC values with increasing resolution, which they attributed to (i) longer and more tortuous flow paths and (ii) higher slope values computed for finer DEMs. In the end, Cantreul et al. (2018) recommend using DEM1, a resolution that is increasingly available for large areas from LiDAR surveys; this resolution was shown to represent a compromise between level of detail and computing efficiency: Coarser DEMs do not resolve relevant terrain features (such as field limits, grass strips, zones of water stagnation and more complex, secondary flow paths), while a 0.25m resolution yields only a small improvement of fine-scale features representation, but requires 16 times larger memory, hence much more processing time. López-Vicente and Álvarez (2018) recommend different DEM resolutions for IC computation, depending on the purpose of investigations: In their 27.4 ha study area, they found a 20 cm resolution to best represent those terrain features that are closely related to short- and medium-term soil redistribution. Long-term redistribution, however, was best reflected by IC computed from a DEM1. We may conclude from this discussion that the optimum resolution depends on a multitude of factors, including the importance of small-scale features, relevance to the phenomenon under study, DEM uncertainty (see Lane et al. 2017), and computational demand, which affects both resolution and extent of the required data. Given availability of DEMs or acquisition equipment, respectively, the choice of resolution for connectivity assessment is therefore a non-trivial one. Finer resolution does not automatically mean a better basis for connectivity assessment, and tends to decrease index values (or to increase the frequency of disconnected areas). We propose testing data of different resolution against independent empirical measurements (which is in any case a main conclusion of our review) in order to better assess the role of DEM resolution.

A second aspect of spatial scale is the **area of reference** for which an index is computed. Different "fundamental spatial units" were named in section 3.3, arguing that they should bear a relationship to the processes that accomplish connectivity, and to the research problem (basic or applied). Most indices are computed at the scale of raster cells; hence, in order to address the sediment connectivity of more process-based landscape units using indices, two alternatives arise. First, to design indices that directly relate to such landscape units; similar solutions have been described in section 3.3 (see also Table 1). However, the question of what is the fundamental spatial unit (e.g., a landform or a catchment) remains largely unresolved and is subject to future research (Turnbull et al., 2018; Poeppl and Parsons, 2018). Second, in a sort of upscaling approach, studies have attempted to aggregate pixel-based indices for larger spatial units in order to assess the connectivity of these larger areas. Conceptually, this task appears difficult, as one could argue that the connectivity of a large area cannot result from the simple sum of its individual components. For example, Cerdan et al. (2004), while modelling overland flow in cultivated catchments, found a simple upscaling method that uses the average of plot-scale values to characterise the hydrological behaviour of a catchment to be inappropriate, resulting in a strong overestimation of the runoff coefficient.

Two main general explanations are often reported for similar discrepancies. First, even in the case of a relatively homogeneous landscape under homogeneous climate forcing, a decreasing trend in the runoff and erosion response is often observed when moving from the plot/field to the catchment scale. It can be explained by the spatial pattern of hydrological response units and their connection to the flow network system (Cammeraat, 2004). Specifically, the relative position and the connectivity between areas producing surface runoff/erosion and the infiltrating/deposition areas represent the link between field and catchment scales (Cerdan et al., 2004; Bakker et al., 2008; Gumiere et al., 2011). Second, additional processes can emerge at larger spatial scales, such as water drainage in karst areas (Rodet and Lautridou, 2003; Schilling and Helmers, 2008), transmission losses in stream channels (Gu and Deutschman, 2001; Lange, 2005), and/or spatial variability in climatic conditions. The implication of this scale dependency of geomorphological processes is that connectivity indices should focus on the parameters that are representative of the processes operating at the scale of application.

Nevertheless, several studies have attempted to upscale pixel-based IC maps to (sub-)catchments using aggregation. Brardinoni et al. (2015) investigated the mean IC for 22 catchments of a sector of the Venosta valley (Italy) and found a strong relationship between mean IC and catchment size, and an association of mean IC with dominant processes (debris flows vs. bedload transport; c.f. section 4.4.2). Gay et al. (2016) computed their revised IC at the raster cell scale, and then aggregated the IC map for catchments, using the mean IC to characterise catchment-scale connectivity. Ortiz-Rodriguez et al. (2017) proposed a new “lateral hydrological efficiency” index that is related to potential (water and) sediment delivery from (sub-)watersheds. It is computed by normalising each watershed’s median IC using the observed range of IC within the total study area, and by multiplying this value with $\log_{10}$ of the respective watershed area. De Walque et al. (2017) tested multiple quantiles of IC (aggregated for subcatchments) in a logistic regression model for the prediction of muddy flood hazard; they found that increasing quantiles of IC were increasingly more related to the dependent variable, and the 95% quantile of IC was among the best predictors. While this application is only implicitly related to connectivity, this observation suggests that it could be the highest (and not the average, or lowest) IC within a larger area that is most representative of the area’s sediment connectivity. We suggest that future studies systematically investigate the predictive or explanatory power of different quantiles of the IC distribution for observed or measured catchment behaviour (e.g., sediment delivery) in order to corroborate this finding.

Upscaling to larger areas, however, is constrained by the size of the study area. Vigiak et al. (2012), for example, concluded that the IC is applicable to catchments with homogeneous climatic conditions (c. 3000 km² in their Australian study region). It is plausible that an index based on static topographic and landcover-related parameters cannot reflect differences in connectivity that are driven by large-scale variability in climatic conditions. In a homogeneous catchment, there might be a quantifiable relation between different magnitudes of functional connectivity and a (structural) connectivity index (e.g. Lane et al. 2009; see also section 4.3). Different forcing, either in terms of large-scale climatic spatial variability or in terms of events affecting only part of the wider study area, will lead to different connectivity under otherwise (topographic and land-use) similar conditions.

4.2.2 Temporal scales

System properties, forcing, and geomorphic processes are subject to change at different temporal scales. Static indices computed using time invariant parameters only do not reflect this temporal variability – at least for those parameters that can not be assumed constant at the temporal extent of a given investigation. Harvey (2002) addressed the importance of temporal scale on geomorphic coupling in fluvial systems. Wohl et al. (2018) transferred the concept of Schumm and Lichty's (1965) classic paper to connectivity driven by different geomorphic processes on steady, graded and cyclic temporal scales. In our paper, we identified essentially the same temporal scale at which connectivity should be assessed using indices (chapter 2) on all spatial scales; depending on the purpose of the investigation, it varies between minutes (e.g., event duration) and a few decades. The extent of years to decades is considered to be most relevant for disconnections: Wohl et al. (2018) state that sediment transport is connected and continuous on longer time scales; Lu et al. (2005) explain that, on millennial scales, the sediment delivery ratio should approach unity, indicating full connectivity.

The applicability of connectivity indices is particularly constrained by the temporal scale at which the structural properties of the system change significantly: Process-form feedbacks imply that geomorphic processes (i.e., sediment fluxes) produce new landforms or alter existing ones. In so doing, they modify structural connectivity, which in turn will affect functional connectivity, by altering sediment pathways and rates of transfer. These changes may occur gradually - for example, an active rock glacier can gradually occlude a mountain stream -, but also catastrophically through high-magnitude, low-frequency events. An example is the effect of landslide dam formation or breaching (Costa and Shuster, 1988; Morche et al., 2007; Frattini et al., 2016) on sediment connectivity and pathway diversion. Another example is represented by forested streams, where logjams can form gradually, as the result of wood recruitment during multiple floods, or suddenly, following the encroachment of a debris flow at a tributary junction (e.g., Hogan et al., 1998; Abbe and Montgomery, 2003; Hassan et al., 2005).

It is difficult, chiefly depending on the characteristics of the study system, to estimate a critical temporal scale beyond which such changes are likely to be effective. The increasing capability of remote sensing methods to generate high-resolution and high-accuracy topographic and landcover data (as important factors of connectivity and constituents of related indices) facilitates the investigation of connectivity and its changes even within short periods. Peñuela et al. (2016), for example, monitored the evolution of soil roughness on field plots on a monthly basis and investigated the corresponding changes in connectivity indices derived from the RSCf connectivity function (e.g. Antoine et al., 2009; Peñuela et al., 2015). Due to natural or anthropogenic landuse / landcover changes, connectivity indicated by IC has been shown to vary on seasonal (Foerster et al., 2014; Figure 7) to decadal (e.g. Lopez-Vicente et al., 2017a) temporal scales.

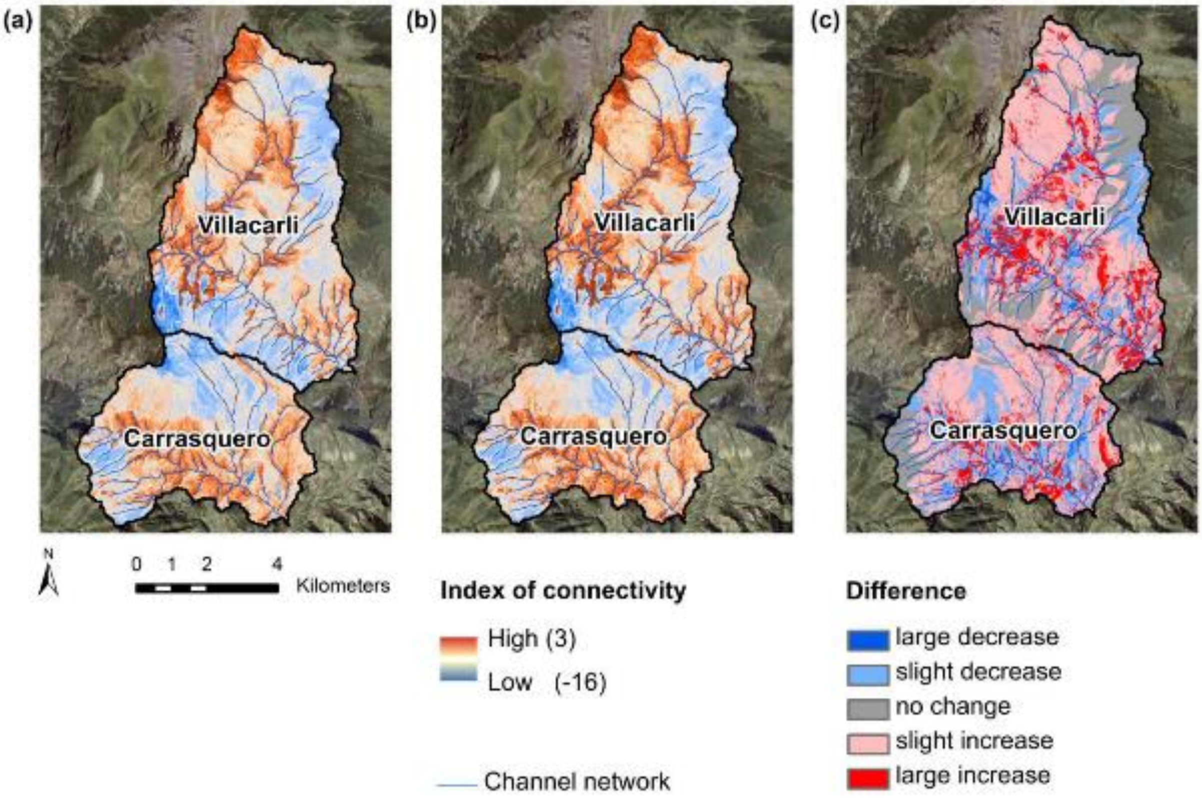


Figure 7: IC maps of the Isábena catchment, Spanish Pyrenees representing the remotely sensed state of vegetation (and corresponding C factors) for the months of April (a) and August (b). The spatial distribution of seasonal connectivity changes is visualised in map c. Source: Foerster et al. (2014). PERMISSIONS

Bracken et al. (2015) sketched three general pathways of connectivity changes triggered by infrequent events: (i) decrease of connectivity through disconnection of formerly connected components, (ii) return to previous conditions after a “pulse” of increased connectivity, and (iii) increased connectivity following the (re-)connection of previously disconnected components. Where changes in connectivity are persisting (scenarios i and iii), the structure of the system changes – consequently, an index computed using pre-event data no longer describes the post-event topography. We argue that such changes are beyond the temporal scope of connectivity indices and pertain more to the realm of landscape evolution in relation to tectonic and climatic (e.g., glaciation) forcing that operate at much longer temporal scales. Scenario ii also relates to the influence of forcing events of different magnitude; they will lead to different functional connectivity while structural connectivity may remain constant. Higher thresholds are crossed with increasing event magnitude (and correspondingly longer time periods during which such an event is likely to occur), and an increasing proportion of a catchment is coupled to the outlet (c.f. Harvey, 2002). Duvert et al. (2011), for example, report that a structural impediment to sediment transfer (in their study: the abrupt decrease in slope at the junction between piedmonts and an alluvial plain) was overcome by flood events establishing functional connectivity. In section 4.3, we suggest using models to investigate the relationship of structural and functional connectivity under different forcing magnitudes. Marchamalo et al. (2016) argue that fairly simple mapping approaches can be used for field-validating connectivity models or indices. They assessed functional connectivity during forcing events by mapping connected pathways in terms of water and sediment. In their study, rainfall, both in terms of event magnitude and 30 days sum, correlated with the length and number of mapped flow and sediment pathways. While these studies corroborate the relationship of forcing and functional connectivity, it largely remains to be studied to what degree this is also valid for connectivity indices.

4.3 Indices and models

Connectivity indices are computed from factors hypothesised to influence connectivity; in that respect, they are conceptual models of connectivity. In this paragraph, we distinguish models from indices through two main properties (following Nunes et al. 2018; Figure 8), the spatial resolution and the degree of process representation. In the following paragraphs, we will focus on synergies resulting from the use of indices in modelling (arrow A in Figure 8) and the use of models to assess indices (arrow B).

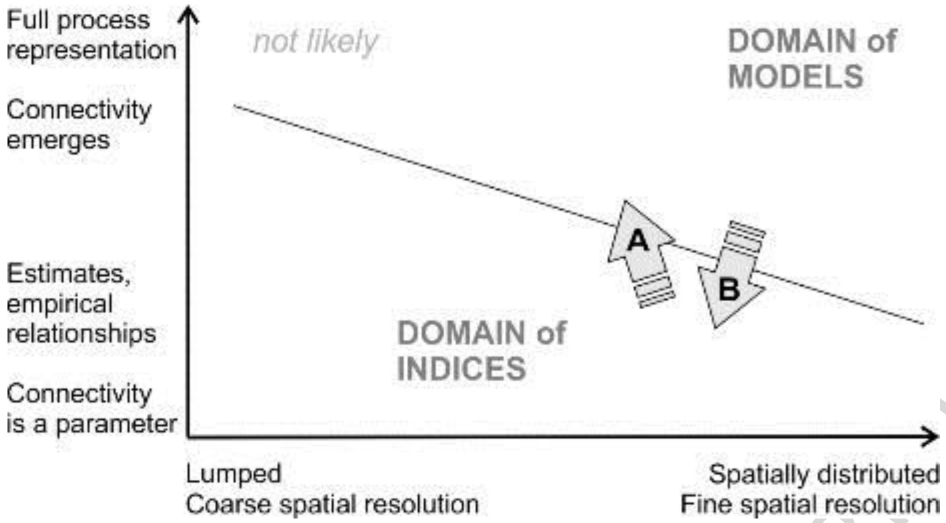


Figure 8: Models and indices are characterised by their spatial units and resolution (x axis), the degree to which processes are accounted for (y axis). Connectivity either emerges from the spatiotemporal interaction of processes, or is parameterised, for example by an index. Arrows A and B show potential uses of indices in models (A; see section 4.3.1) or vice versa (B; section 4.3.2).

4.3.1 Application of indices in models:

Typically, a model aims to simulate the spatial distribution and temporal development of the processes (e.g., runoff, sediment transport) whose spatiotemporal and functional interaction leads to the emergence of connectivity (c.f. Fig.1). An ideal deterministic model that perfectly represents all of these processes would perfectly explain connectivity and would abolish the need to use conceptual understanding and/or statistical relationships to build indices. Favis-Mortlock (2013) questions whether the addition of physics-based detail, that leads to an increase in model complexity and data requirements, is a remedy for models failing to represent, for example, within-watershed flow paths. Where (full) process representation cannot be achieved, for example when the scale of the modelling unit exceeds that of the processes (“lumped” models in Figure 7), connectivity would have to be a model parameter, for example through a connectivity index (arrow “A” in Figure 4).

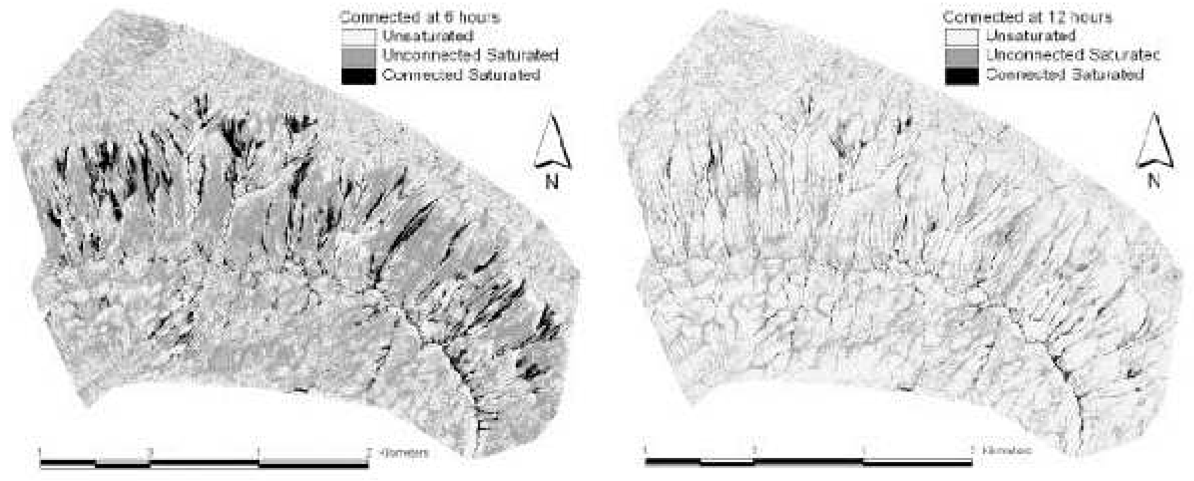


Figure 9: Predictions through time (t=6 hours, left; t=12 hours, right) of unsaturated, unconnected saturated and connected saturated areas for a storm event, modelled using the network index. Source: Lane et al. (2004) PERMISSIONS

The network index (Lane et al., 2004) version of TOPMODEL was successfully used by Reid et al. (2007) to assess the delivery of landslide-borne sediment to the channel network; in their study, landslides predicted by SHALSTAB were coupled to the channel network only where the modified TOPMODEL predicted continuously saturated flow paths between the channel network and the landslide locations. Lane et al. (2009) used the network topographic index in the CRUM2D model to investigate the spatiotemporal development of saturated, but disconnected areas (see also Figure 9). Antoine et al. (2011) used the Relative Surface Connection function as a “subgrid function” to improve the prediction of discharge dynamics. They (and references therein) stated that connectivity was “a key factor to be introduced in current modeling tools to bring our models and predictions a step forward”. Jamshidi et al. (2014) combined an IC-based estimation of SDR (Vigiak et al., 2012) with a RUSLE-based erosion model to assess annual variability in sediment yield related to changes in vegetation; their results led to a sustainability assessment of land management practises (i.e., single-tree selective logging). Similarly, Hamel et al. (2015) estimated sediment yield by multiplying modelled erosion (RUSLE) with SDR in order to assess the sediment retention potential in the Cape Fear Catchment, North Carolina; they identified a high sensitivitiy of the model regarding the parameters for the sigmoid function translating IC to SDR (Vigiak et al. 2012). Mahoney et al. (2018)

use their “probability of sediment connectivity” in combination with an erosion model to predict sediment flux.

4.3.2 Application of models to support indices:

Existing sediment connectivity indices are static and based on structural properties; hence, the question is to what degree they are able to explain or predict system behaviour especially with respect to functional connectivity that, among others, depends on the magnitude of forcing.

This relationship could be investigated by comparing records of sediment fluxes across different catchments characterised by connectivity indices. Models can be used to generate such records, with interesting options to vary systematically forcing magnitudes (even for unobserved scenarios), and structural and functional properties of the study areas. Under the assumption that models are able to account for the decisive factors and processes, modelled scenarios would help to assess the explanatory and predictive abilities of connectivity indices. Conversely, Wohl et al. (2018) suggest using connectivity metrics for the validation of numerical models: “If we can quantify connectivity pathways through a landscape, we can then use those metrics to evaluate similarity of the couplings and transport pathways in numerical results”.

Baartman et al. (2013) used the LAPSUS landscape evolution model to evaluate functional sediment connectivity in 6 natural and 9 synthetic landscapes of identical size under different rainfall scenarios (normal, torrential, extreme). For each landscape and each forcing scenario, functional connectivity was assessed by the modelled SDR. Landscape complexity was measured with a simple index combining overall relief, slope variability and stream order; note that, in this case study, landscape complexity functions as a connectivity index (with the aim of predicting functional connectivity). Baartman et al. (2013) found a non-linear inverse relationship between the morphological complexity index and SDR (Figure 10), especially for high-magnitude events. We suggest a similar experimental setup, with different connectivity indices replacing the complexity index as the independent variable.

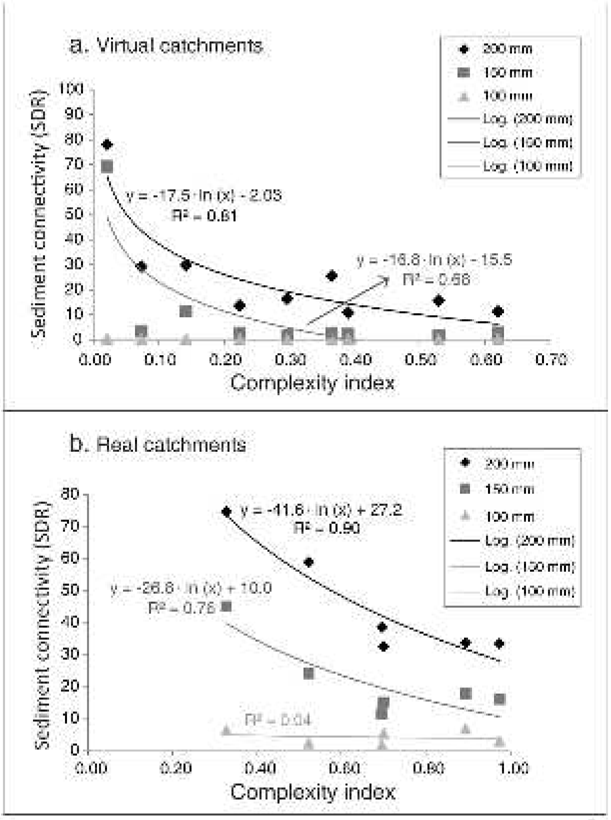


Figure 10:Correlation between the morphological complexity index and SDR (as a measure of functional connectivity) for virtual (a) and real (b) catchments. Source: Baartman et al. (2013) PERMISSIONS

In this context, Neugirg (2016), for example, used LAPSUS to investigate the dependence of SDR on the mean IC of six different catchments of comparable size (44-58 km²) and 8 different precipitation scenarios. He found a positive relationship with r² between 0.41 and 0.93. This relationship, however, did not exist at the subcatchment scale (10^0 km²); therefore, the existence of a possible scale dependence deserves further research. Considering that SDR always refers to a contributing area, while IC integrates contributing areas and flow paths to the target (here: catchment outlet), IC values need to be aggregated; here, it should be investigated whether other properties of the IC distribution (e.g. high percentiles, c.f. de Walque et al., 2017) are more significant predictors than the average.

The modelling study by Neugirg (2016) also revealed that an IC threshold, above which raster cells were experiencing sediment transfer, systematically decreased with increasing event magnitude. This can be interpreted as first evidence that even a static index can be (at least qualitatively) linked to event magnitude in terms of connectivity, for example by stating that lower-rated terrain was likely to be connected with high-magnitude events. Lane et al. (2009) found that the network topographic index (Lane et al., 2004) was indeed related to (time averaged) connectivity in terms of propensity to and duration of connection, and improved the estimation of sediment transfer and delivery to the channel network. Peñuela et al. (2016) used photogrammetric high-resolution DEMs of three 30 m² plots on agricultural fields in the Belgian Loess belt and the FullSWOF_2D model (Delestre et al., 2014) to model overland flow dynamics. Connectivity was assessed using characteristic points of the RSCf (Antoine et al., 2009) computed for the DEMs. Peñuela et al. (2016) found that modelled overland flow dynamics were highly correlated to the RSCf indices. Moreover, they were able to show that the decrease of roughness and the formation of rills increased connectivity during the investigation period of two years.

A series of dynamic, network-based modelling approaches has been developed to investigate connectivity-related issues within channel networks, such as sediment transfer and delivery (Czuba and Foufoula-Georgiou, 2014; Schmitt et al., 2016; Gran and Czuba, 2017; Schmitt et al., 2017), and sensitivity to change (Czuba and Foufoula-Georgiou 2015). These approaches explain the behaviour observed in the dynamic models with structural (and functional) properties of the channel network and are very relevant, especially in linking connectivity to the propagation of changes (see also Coulthard and van de Wiel, 2017). We argue that they could also be used to investigate the significance of static indices, either network-based (Heckmann et al., 2014; Cossart and Fressard, 2017) or others (e.g., IC). Presently, most of the above modelling approaches at the fluvial network scale address mainly sand (0.062-2mm), and in some instances silt and clay, leaving aside the transfer of gravel and coarser grain sizes, which control most of the morphological change in mountain channels. In this context, CASCADE (Schmitt et al., 2016) can deal with gravel as well; however, each model run can be implemented for a single grain size only.

Further studies, based on models but also on fieldwork, are needed to investigate the validity of connectivity indices, both with respect to (i) the interpretation of index maps and (ii) their use as model parameters. We admit that the distinction of models and indices outlined above is somewhat vague; however, models and indices, as we see them, also differ with respect to their computational complexity and their way of communicating the results to the user. The output of a model, e.g. sediment yield, bears some relationship with connectivity, while a map depicting the spatial distribution of a connectivity index addresses connectivity explicitly (though more qualitatively). In the following section, we outline how indices, also in combination with models, can be applied for basic and applied scientific problems.

4.4 Application of indices

In landscape ecology, Goodwin (2003) asked whether connectivity was "the dependent or the independent variable"; in his literature review he found that 78% of the papers use connectivity measures to explain ecological processes (connectivity as the independent variable), while the remaining investigate which processes or properties govern the level of connectivity (connectivity as the dependent variable). The same question can be asked with respect to indices of sediment connectivity, and we think that connectivity indices can find useful applications in both ways.

4.4.1 Connectivity as a study target: Indices as dependent variables

Sediment connectivity itself can be the aim of a study, or the dependent variable; for this purpose, it has to be quantified. Regarding functional connectivity, this refers to the question whether connectivity can be measured (Brazier et al., 2015), for example by the SDR (see section 4.3; Baartman et al., 2013; Hoffmann, 2015; Heckmann and Vericat 2018). Most connectivity indices can be interpreted as measures of structural connectivity; consequently, the independent variables are factors of these indices that were preselected to represent the researcher's conceptual understanding of connectivity. As long as index values are not viewed in context with connectivity-related observations or measurements in the field (e.g., Borselli et al., 2008; Figure 4; Meßenzehl et al., 2014, see also section 4.4.2), indices lend themselves primarily as relative metrics, focusing on the spatial pattern (differences within or between study areas), temporal evolution (multitemporal analysis of the same area), and the effect of changing conditions. One difficulty of index maps is that (except for ECA/SCA approaches) the indices do not have meaningful absolute values (such as, for example, negative values for low connectivity and positive values for high connectivity). Therefore, the interpretation of values representing the transition from low to high connectivity is up to the user. Classification in, for example, high/moderate/low connectivity can be aided either by the statistical distribution (natural breaks: Cavalli et al., 2013; Kalantari et al., 2017; quantiles: Gay et al., 2015). In any case, care must be taken when setting up and interpreting colour-scales (e.g., a blue-white-red one as in Cavalli et al., 2013) for index maps. The inter-catchment comparison of IC can be facilitated by standardising (z-transforming; Persichillo et al., 2018) or normalising (to the range [0,1], Nicoll and Brierley, 2016) the IC maps.

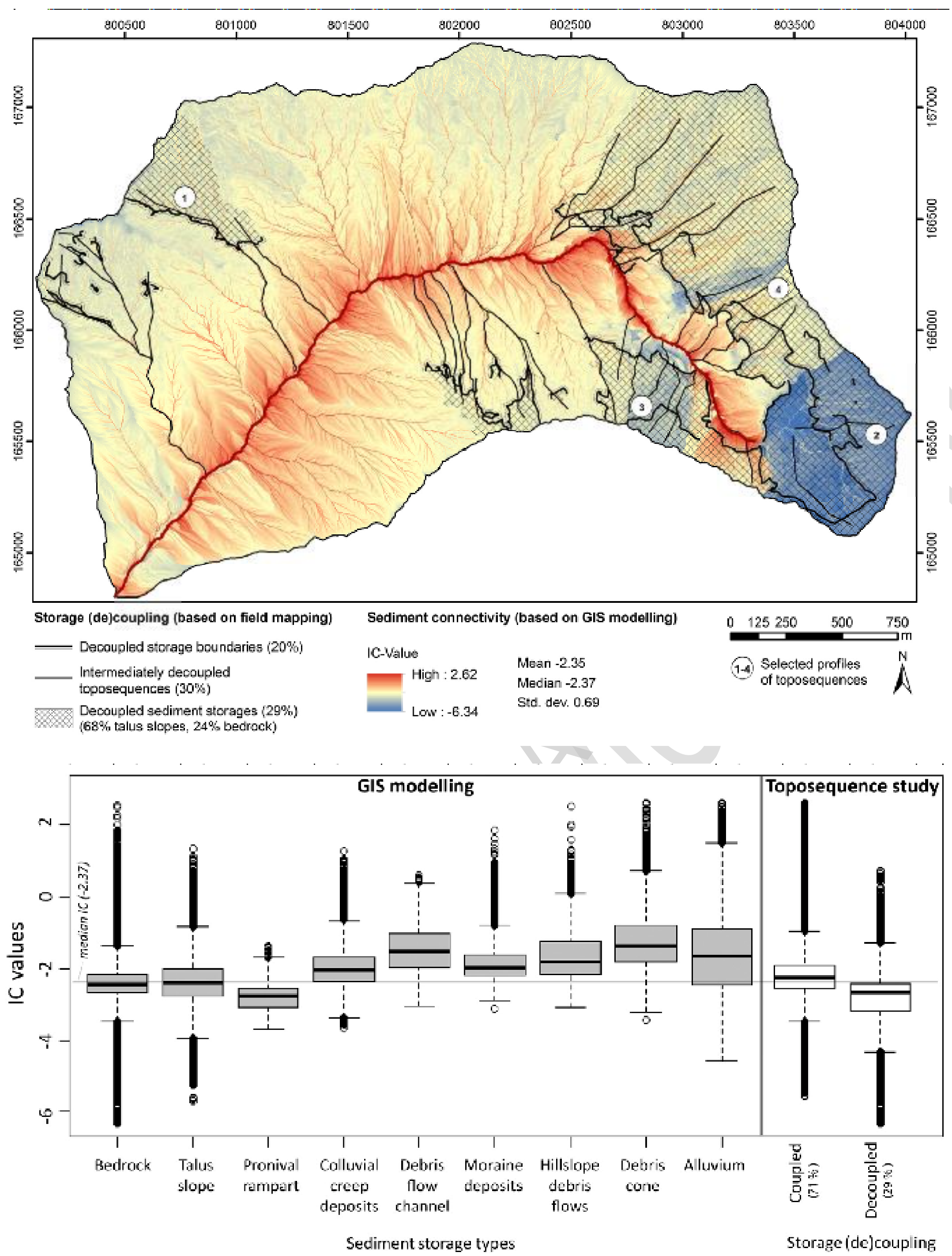


Figure 11: Top: IC map (after Cavalli et al., 2013) of the Müschauns Valley, Swiss Alps, together with decoupled sediment storages from a geomorphological map. Bottom: Distribution of IC values for different landforms (left), and for coupled/decoupled portions of study area from a field-based „toposequence" study (right). Souce: Meßenzehl et al. (2014) PERMISSIONS (2 FIGs have been combined here)

IC was used in combination with geomorphic field mapping to investigate sediment cascades of a formerly glaciated alpine valley in Switzerland (Messenzehl et al., 2014; Figure 11). While IC was found to reflect well the decoupling impact of the inherited, glacially shaped topography (e.g. in hanging valleys), the authors report that IC also failed to identify actually decoupled parts of the area where disconnectivity is not reflected in surface geomorphometry. As a consequence, an index-based appraisal of sediment connectivity should be complemented by a field-based expert assessment of diagnostic features indicative of (de-)coupling, for example fluvial undercutting of storage landforms, in order to enhance the geomorphological significance of the results (see, for example, Theler et al., 2010). Nicoll and Brierley (2016) applied IC and another approach mainly based on geomorphic mapping for assessing landscape connectivity and analyzing sediment dynamics in a sub-catchment of the upper Yellow River. The IC, while showing a general good agreement with field observations, especially on low-relief large decoupled alluvial fans, was found incapable of characterizing connectivity of some sediment stores mapped in the field. Reasons for such a discrepancy are likely related to the coarse resolution of the DEMs (i.e., 30 and 90 m) employed, which cannot reliably capture the spatial variability in surface morphology and roughness (see section 4.2). Rainato et al. (2017) compared multitemporal maps of sediment sources with an IC map; they found that, due to a low-gradient section, the disconnectivity of their study area (Rio Cordon, Italy) resembled that typical of formerly glaciated valleys. Tarolli and Sofia (2016) investigated the potential delivery of landslide-borne sediment to the road and channel network by implementing the latter as targets in the computation of IC. The IC maps were found to confirm earlier work based on extensive fieldwork (Wemple et al., 2001), highlighting the potential of digital topographic analysis for large-area yet high-resolution insights in “the possible outcomes of sediment production”.

The analysis of the effects of changing conditions on connectivity is an important application where the index represents the final result. Lopez-Vicente et al. (2013) compute IC maps for different (past, present and future) landuse scenarios and found a decrease in connectivity with vegetation recovery on abandoned fields and with decreasing number of anthropogenic structures. Foerster et al. (2014; Figure 7) assessed sediment connectivity for two adjacent sub-catchments in contrasting seasons, estimating the IC weighting factor based on fractional vegetation cover and topography derived from hyperspectral and LiDAR data. Results showed that IC aided to identify hot spot areas of erosion and the effects of erosion control measures. Similarly, Lopez-Vicente et al. (2017a) conducted a multitemporal analysis based on land cover scenarios derived from historical orthophotos between 1945 and 2012; in their study area, connectivity decreased as a consequence of afforestation, but also increased where stonewalls and terraces had collapsed (Figure 12; see also Hooke et al., 2017).

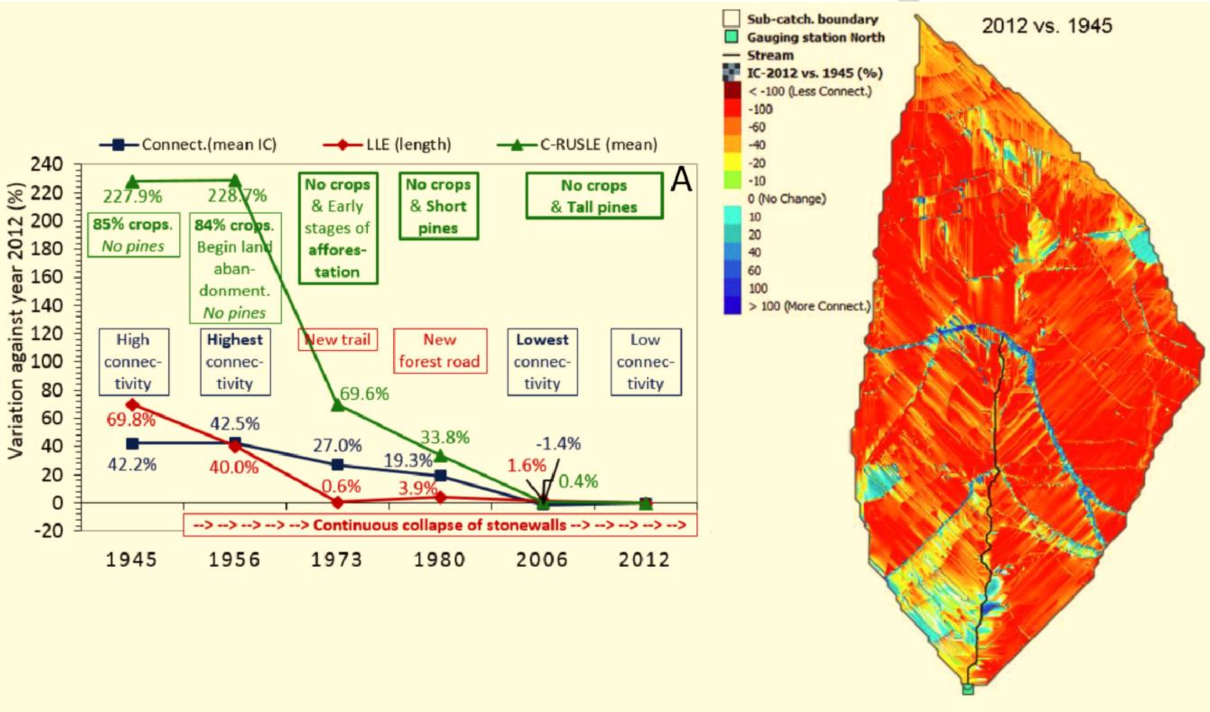


Figure 12: Spatial pattern of changes in IC in the Araguás catchment, Spanish Pyrenees, between 1945 and 2012. The diagram on the left highlights the effect of landuse and landcover dynamics and the development of infrastructure at different points in time. The latter is also evident in the map (right) showing total changes between 1945 and 2012. Source: López-Vicente et al. (2017a). PERMISSIONS

Lopez-Vicente et al. (2017b) investigated connectivity changes in two Japanese catchments that were caused by different land management scenarios (tree thinning, establishment of new skid trails). Calsamiglia et al. (2018) computed IC in an artificially drained agricultural landscape and compared the index map to a hypothetically unchanneled scenario where artificial channels were removed from the underlying high-resolution DEM. Persichillo et al. (2018) computed IC for three scenarios related to human impact in the Oltrepò Pavese area (Northern Appeninnes, Italy): First, they used four maps of the drainage network as target for IC in order to investigate the effects of a man-made reduction of drainage density between 1980 and 2009. Second, the road networks mapped at four points in time between 1954 and 2007 were used as targets, reflecting the densification of the road network. Third, weighting factors (computed using Manning's *n*) were changed based on different landuse scenarios. Scatterplots then allowed for the evaluation of the effects of these anthropogenic changes to the degree of connectivity (IC) between shallow landslides and the road and stream networks. Martínez-Murillo and López-Vicente (2018) use IC to show that post-fire establishment of skid trails for salvage logging increases connectivity. Cossart et al. (2018) used network indices (Cossart and Fressard 2017) to study the effects of anthropogenic infrastructures on structural connectivity; starting from a landscape scenario without anthropogenic elements, they included such structures step-by-step in order to assess the consequences of each component in terms of connectivity reduction or increase. In their multitemporal study of a braided river system across 60 years, Lehotský et al. (2018) used a network-based connectivity index to assess the temporal variability of longitudinal connectivity and found a decreasing trend.

The propagation of changes, for example enhanced sediment yield due to paraglacial morphodynamics, is particularly relevant in proglacial, that is recently deglaciating areas (e.g., Lane et al., 2017). IC maps have been used to assess the likelihood of this happening, either in combination with field observations (Cavalli et al., in press) or DEMs of difference revealing actual surface changes (Micheletti and Lane, 2016). Goldin et al. (2016) computed IC for the current topography and a future scenario to analyse the evolution of connectivity patterns due to the retreat of the Zinal glacier (Southern Swiss Alps). Finally, IC was also used to investigate the impact on connectivity exerted by man-made structures such as the rail and road network. Kumar et al. (2014) and Stangl et al. (2016) strived to remove anthropogenic elements from DEMs to compare the IC based on the actual and the 'natural' topography.

4.4.2 Connectivity as a means to an end: Indices as independent variables

Wohl (2017) stated that, "given that restoring natural or desired levels of connectivity is increasingly a goal of river management, the quantitative predictive ability [of connectivity indices] is likely to be critically important". Hence, the capability of indices to explain or predict observable phenomena or processes (that is, their suitability as independent variable) needs to be investigated.

Section 4.3.1 has shown that indices can be part of models, for example as a parameter to account for sub-scale processes (Antoine et al., 2011), or to predict sediment delivery (Reid et al., 2007; Vigiak et al., 2012; Hamel et al., 2015) or muddy flood susceptibility (de Walque et al., 2017). In the study by Sougnez et al. (2011), a specific connectivity index (computed by dividing IC by catchment area) explained 22% of the observed variance in specific sediment yield. Application of IC has proven useful also for estimating hillslope SDR, in a semiarid catchment of south-east Australia, where Vigiak et al. (2012) compared four metrics for the regionalisation of SDR in terms of pattern distributions and efficiency in matching sediment yield at five monitoring stations. Results showed that IC was the most effective metric in predicting specific sediment yield in small-to-medium catchments with homogeneous climate. Dupas et al. (2015) correlated rates Phosphorous and Nitrogen transfer, among others, with the IDPR index. They found that it explained phosphorus fluxes (because it is mobilised by erosion from P stocks and transported via surface and subsurface runoff) while it could not explain nitrogen fluxes (because N leaches through deeper pathways less associated with the terrain surface). Brardinoni et al. (2015) found that IC was related to the dominant process affecting the main channel (debris flows vs. bedload transport) in 22 catchments in the Venosta valley, Italy: IC mean values are higher for debris flow basins (drainage area from 1 up to about 10 km^2) while larger basins whose main channel is mostly affected by bedload are characterized by low IC values. Medium size basins display an intermediate situation. Similarly, Heiser et al. (2015) used IC, among other parameters, in a statistical model to determine the dominant flow process types in steep headwater catchments. IC has also been applied in more qualitative studies: Hooke et al. (2017) stratified 58 plots that had been monitored for erosion and deposition since the year 2006 according to their connectivity (assessed using a modified IC) and found that "the very high connectivity sites particularly [had] greatest changes". Calsamiglia et al. (2017) report that 73% of the agricultural terrace wall collapses took place along highly connected flow pathways that were indicated by very high IC values above the 80% quantile. Furthermore, they evaluated IC spatial patterns with respect to functional connectivity (active areas, classified into sources, pathway links and sinks) they had mapped in the field during and after specific storm events. By k-means clustering of IC, elevation, and location (x, y coordinates) of raster cells in two study areas, Crema and Bossi (2017) delineated spatially coherent homogeneous subareas which they found were associated with the main geomorphic processes, for example debris flows. The latter two studies suggest that IC could be used for a general geomorphological classification of (sub-)catchments. Bordoni et al. (2018) included IC in a generalised additive model predicting road sections susceptible to landslides in a study area in the Italian Appennines. Conoscenti et al. (2018) found that a modified IDPR index (c.f. Gay et al. 2016) was a useful factor in the assessment of gully erosion susceptibility in to Sicilian catchments. The simplified connectivity index SCI proposed by Grauso et al. (2018a) was found to correlate only poorly with specific sediment yield of 45 catchments in Southern Italy (Grauso et al. 2018b). The authors argue that this might have been caused by using post-1990 data on soil loss for index computation, while the sediment yield data refer to the period 1950-1990 with likely different landuse.

While not representing proper indices of connectivity, ECA or SCA (section 3.2) approaches are closely related because they implement concepts of sediment connectivity; they can be used in models to predict sediment yield. The SCA (following Heinimann et al., 1998; see also Wichmann et al., 2009) was demonstrated to correlate well with the mean annual sediment yield measured by sediment traps in different alpine catchments (Haas et al., 2011; Sass et al., 2012; Huber et al., 2015; Neugirg et al., 2016; Figure 13). It has to be noted that the hydrological catchment area of the sediment trap had no significant correlation with measured sediment yield (Haas et al., 2011), except where the former was very steep (Neugirg et al., 2016). These observations highlight the importance of including connectivity in sediment yield studies (see also de Vente et al., 2006), either implicitly, through the delineation of ECA or SCA, or explicitly through the use of connectivity indices. Furthermore, they confirm that ECA or SCA approaches not only implement a conceptual model of connectivity but yield results that are related to functional connectivity. Sediment fingerprinting (Guzmán et al., 2013) could be used to verify the provenance of in-channel or exported sediment from sources within the ECA/SCA. D'Haen et al. (2013), for example, used IC as a proxy for hillslope – channel coupling and stream power estimations as a proxy for the within-channel connectivity to study sediment dynamics. Complementing their connectivity assessment with sediment fingerprinting, they could identify seasonal changes in sediment provenance that reflect the discharge regime of the river: Rainstorms lead to hillslope-channel coupling, but within-channel coupling was effective mainly during springtime peak discharge.

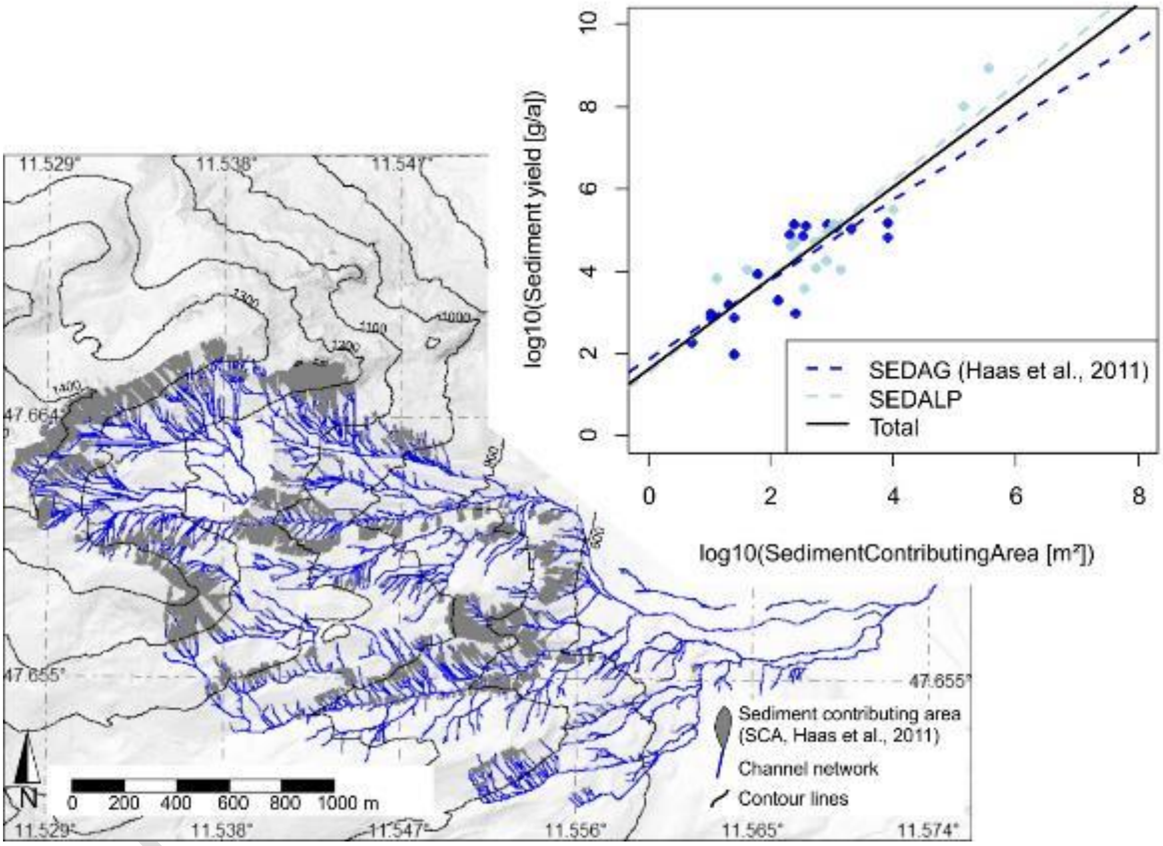


Figure 13: Sediment contributing area (SCA) within the Murbach catchment, Bavarian Alps, delineated on a 1 m DEM according to Haas et al. (2011). Upper right: Correlation of log SCA and log sediment yield measured in several study areas oft he SedAlp (Huber et al., 2015) and SEDAG project (Haas et al., 2011).

Indices are not only useful as independent variables in models. A combination of connectivity index maps with maps or measurements of other spatially distributed properties or processes can enrich the investigation or prediction of on-site processes with an assessment of their off-site relevance. Recent studies carried out geomorphometric analyses of sediment connectivity using IC to evaluate the connection of sediment sources to the channel network (Cavalli et al., 2016; Surian et al., 2016; Tiranti et al., 2016; Rainato et al., 2017). Tiranti et al. (2018), for example, combined a map of potential sediment sources with an IC-derived connectivity classification to evaluate sediment supply for debris flows in a 22 km² catchment in the Italian Alps. Sediment delivery from sediment sources (e.g., soil erosion) to the channel network may cause issues related to their quantity (aggradation, reservoir siltation) or quality (granulometry, adsorbed nutrients and pollutants). Shore et al. (2013) used the network index (Lane et al., 2004) for the delineation of critical (i.e. well-connected) source areas at the field and subcatchment scales. Chartin et al. (2016) computed a modified IC to support the interpretation of spatial and temporal patterns of erosion, transfer and deposition of sediment contaminated with 137Cs after the Fukushima Dai-ichi Nuclear Power Plant accident. In a study by Barneveld (2015, and personal communication, 2017), connectivity indices revealed that (modelled) soil erosion was high in some poorly connected parts of the catchment and vice versa. Consequently, the implementation of mitigation measures where a model predicts high soil erosion does not automatically lead to an adequate sediment management, because highly coupled areas with less erosion but effective sediment transfer might be overlooked. Lopez-Vicente et al. (2015) also combined a soil erosion assessment with the IC, but they associated the IC more with deposition potential and mentioned only briefly the ability of IC to identify erosion-prone patches with low sediment connectivity. The Brittany and Loire River Basin Agency has recently been confronted with a similar issue when trying to explain the water quality issues with the sole help of a soil erosion map. Indeed the dense hedges network still existing in Brittany prevent the eroded material on the slopes to reach the rivers, whereas the networks of manmade canals and ditches in the lowland areas create a direct connection between the fields and the ponds and lakes (Vandromme et al., 2015).

4.4.3 Possible fields of application in watershed (sediment) management

Sediment connectivity plays a major role in basic and applied problems concerning the quantity (that is, erosion, transfer, deposition) and quality of sediment. The two are interdependent and both related to the continuum of sediment transfer through a catchment (Apitz and White 2003; Grant et al., 2017), from upland sources to the river corridor, and between river reaches, until the outlet is reached. Integrated catchment-scale (sediment) management therefore calls for connectivity assessment (Brierley et al., 2006; Skolaut et al., 2015; Wohl, 2017) due, for example, to the linkage of reach-scale morphodynamics and catchment-scale sediment fluxes (Wohl et al., 2018); we argue that this can be supported by connectivity indices.

Reflecting the opportunities outlined in the previous subsections and section 4.3, we see the following major directions of application of indices, whether as a part of models or “stand-alone”, in management. They are all related to the reaction of a catchment, or part of it, to changes, be they natural or anthropogenic, actually occurring, predicted, or planned (within a management scenario). Moreover, they all include the use of the connectivity concept to identify and prioritise management needs, for example by evaluating different options (finding the “best bank for the buck”; e.g., Brardinoni et al., 2015; Hamel et al., 2015; Tarolli and Sofia, 2016; Belmont and Foufoula-Georgiou, 2017; Ghafari et al., 2017):

First, to predict the downslope/downstream consequences of processes (or changes) occurring at the local (hillslope, river reach, subcatchment) scale, for example concerning landcover/landuse, the channel network, or morphodynamics (e.g. activation of sediment sources by landsliding). This is associated with the identification of sensitive parts of the landscape (Brierley et al., 2006). If a process/change is occurring at multiple locations within a catchment, connectivity assessment can help to identify, rank, and prioritise areas to which funding should be allocated best/first because they generate the most severe impact (e.g. landslides potentially affecting the road network; Bordoni et al. 2018). Similarly, connectivity analysis may support the identification of upstream causes of processes (or changes) observed upstream/upslope of a particular location; this is related to the identification and possible prioritisation of critical source areas (e.g., Shore et al., 2013). The network-based analysis of dynamic sediment connectivity (Czuba and Foufoula-Georgiou, 2015) led to the identification of "hotspots", defined as river reaches with a possible accumulation of sediment waves from different parts of the catchment.

Second, to identify "hotspots" of connectivity itself (Hooke et al., 2017) and options of changing connectivity (where ? how ?) when the enhancement/restoration (e.g., Skolaut et al., 2015; Magilligan et al., 2016) or decrease (e.g., Hooke et al., 2017) of sediment connectivity has already been identified as a management goal. Wohl et al. (2018), however, stress that these management goals can be highly contingent upon different stakeholder perspectives.

According to the SedAlp final report (Skolaut et al., 2015), „sediment continuity has a notable impact on several management issues in alpine river basins and poses multiple use conflicts related to e.g. small hydropower, ecology, fishing, flood control, morphology, or the good status according to the EU Water Framework Directive.". Legal requirements and recommendations of the Water Framework Directive (WFD; Directive 2000/60/EC), include the minimisation of sediment transport in fluvial systems; measures and monitoring of sediment together with the monitoring of water matrix are suggested to be conducted prior to the compilation of status improvement of the rivers (Guidance document No. 25). Increasing loads of fine sediment bringing adsorbed contaminants to terrestrial water systems is one of the concerns in EU Freshwater Fish Directive (2006/44/EC), because sediment quality is related to environment quality standards (2008/105/EC) and sediment quantity to the ecological status. Connectivity indices can be integrated with factors of both, sediment quality and ecological status in order to support the directive's monitoring protocols and mitigation measures. We suggest to integrate connectivity indices with maps of fine sediment sources (e.g. McHugh et al., 2002). Flood risk management (FRM) plans and activities are based on a thorough understanding of linkages between sediment and habitats at all stages of flood events. Incorporating topography-based connectivity assessment is crucial to support decision making in FRM and important to meet goals of protection of habitats and species in the directives on habitats

(79/409/EEC) and birds (79/409/EEC). This short list of examples highlights that sediment connectivity also has strong ecological connotations, and hence related indices are potentially important tools for a holistic environmental management framework.

4.4.4 Connectivity indices in practice: Actual use

In light of these potential fields of application, an important question is whether stakeholders are aware of the existence of connectivity indices and their potential uses. Interviews with 85 stakeholders from land and water management across Europe showed that more than half of interviewed stakeholders considered connectivity to be important for management (Smetanova et al., 2018). Despite the demand of more precise spatial information on sediment fluxes, sources, sinks, transfer routes, water quality, effect of sediment on infrastructure, etc., the interviews revealed that sediment connectivity indices are presently not being used. This is in spite of the fact that connectivity indices meet also the stakeholders' requirements regarding simple, cost-, data- and labour-effective tools to assess connectivity. For example, topography-based connectivity indices require data (remote sensing, DEM, spatial data; Table 1) that are applied by stakeholders twice more often than environmental modelling (Smetanova et al., 2018). Such data form already part of ready-to-use GIS-based tools with complete guidelines and proven successful application for management and decision-support (Skolaut et al., 2015; Crema and Cavalli, 2018; http://www.naturalcapitalproject.org/invest/). Based on the examples outlined above, we suggest that sediment connectivity indices be used as tools for a wide range of management issues by relevant regional or national environmental agencies and made available to a variety of stakeholders. However, we identify a need for (i) more research in the explanatory or predictive capacities of indices (see section 4.3) in context of management, and (ii) more and better communication of indices to stakeholders in order to promote the application of indices.

4.5 Perspectives and Research Needs

The overarching static nature of existing indices justifies the need to (i) develop dynamic counterparts and/or (ii) carry out studies to examine the relation between static indices and functional connectivity across hydro-meteorological forcing scenarios. Such analyses will improve our understanding of the linkages between indices and observed (or modelled) system response, which has rarely been addressed so far. In geomorphology, this refers to variables like sediment transport, yield (e.g. Sougnez et al., 2011) or change in storage that can be measured and monitored, but also to more abstract system properties like landscape sensitivity, which is related to the propagation of changes, or the ability to recover from disturbance (Brunsden and Thornes, 1979; Brierley et al., 2006; Fryirs, 2017).

In other disciplines, strong qualitative and quantitative evidence exists on the correlation between connectivity and sensitivity (e.g. Albert et al., 2000), for example in hydrology (e.g. Knudby and Carrera, 2005) and landscape ecology (e.g., McCluney et al., 2014). For network approaches in landscape ecology (see e.g. a review by Grubesic et al., 2008), Jordán and Scheuring (2004) emphasized that "the main question is how to link certain graph properties to understanding and predicting the behaviour of an ecosystem". This question needs to be addressed for sediment connectivity indices too, where “geomorphic coupling” has long been contextualised with sensitivity (e.g. Brunsden and Thornes, 1979; Fryirs, 2017). Nakamura et al. (2002) investigated how geomorphological processes potentially inflicting disturbance on stream and riparian ecosystems propagate in ‘disturbance cascades’ through a channel network, and how the fluvial network structure provides refugia and resilience. Even though using a fragmentation index known in landscape ecology (and not a proper sediment connectivity index), Vanacker et al. (2005) showed that comparatively little landcover changes had a significant impact on river morphology and explained this finding with changes in the “spatial organisation and connectivity of land-use systems within the catchment”. Recently, Coulthard and van de Wiel (2017) used a landscape evolution model to investigate how land-use changes in one half of a catchment can affect the geomorphology of the other half; they observed the propagation of changes in both up- and downslope direction. Regarding sensitivity, it is important to point out that, in landscape ecology, a well-connected system is resilient (e.g. Taylor et al., 1993) because organisms may use alternative linkages between habitat patches when either these patches or single links fail. On the contrary, a well-connected geomorphic system appears to be sensitive to changes, as changes are readily propagated between its components.

The potential of network approaches for comparative sediment connectivity assessment of multiple catchments is very promising (Heckmann et al., 2015); similar conclusions have been drawn by Connor-Streich et al. (2018) in context of network analysis of braided rivers. The network approach enables "to keep the whole in mind while studying the parts and vice versa" (Jordán and Scheuring, 2004; see also Cossart and Fressard, 2017), something that is inherent to the connectivity concept. The network data structure allows for multi-scale analysis, e.g. the landforms arranged within a subcatchment, or the subcatchment structure of the whole study area. Technically, this means that a network analysis may be focused on nodes, edges, pathways, graph components, or the whole graph. Parts of the network can be aggregated to investigate connectivity at a larger spatial scale (e.g., Heckmann et al., 2016), and the consequences of structural changes effected by the addition or deletion of edges can be assessed in "what if" scenarios (Cossart and Fressard 2017, Cossart et al. 2018; see also Matisziw and Murray, 2009 and Segurado et al., 2013 for landscape ecology examples). By now, only one published sediment connectivity index belongs to this category (Cossart and Fressart, 2017), highlighting the opportunities for future research. In contrast, static (Heckmann and Schwanghart, 2013; Heckmann et al., 2014) and dynamic network-based modelling approaches (e.g. Czuba and Foufoula-Georgiou, 2015; Schmitt et al., 2016) have shown their potential for the investigation of sediment transfer and other connectivity-related research problems, including sensitivity.

5 Summary and Conclusions

Sediment connectivity is an important property of geomorphic systems, influencing sediment fluxes and delivery, the propagation of and sensitivity to changes. Moreover, the concept is capable of linking scales (plot/hillslope, reach, channel network, and catchment) and even disciplines (e.g.

hydrology, ecology, geomorphology; Tetzlaff et al., 2007; Bracken et al., 2015) for holistic approaches to landscape research and management (Brierley et al., 2006).

As sediment connectivity is hardly measurable (Brazier et al., 2015; Turnbull et al. 2018), indices have been proposed for the assessment of spatiotemporal patterns of connectivity, the investigation of connectivity drivers and changes, and for use in explanatory or predictive frameworks. Due to the increasing availability of DEMs and other remote sensing data that can serve as proxy for quantifying the most relevant factors controlling sediment connectivity, a number of sediment connectivity indices has been developed. Existing indices can be grouped in three categories: Raster based, object or network based, and based on effective catchment area. Our review shows that all indices represent static, structural connectivity; however, first attempts exist to work with temporal variation and different styles of forcing, mostly through the implementation of additional variables in existing indices. The specificity of indices and their application with respect to grain size variability is only partially addressed and represents a challenge for future research.

In order to use structural connectivity as explanatory or predictive variables, indices need to be interpretable in relation to geomorphic processes, material properties, and forcing styles and magnitudes. This relationship can be investigated by measurements (e.g., Hooke et al., 2017; Heckmann and Vericat, 2018), particle tracking (e.g., Dell'Agnese et al., 2015), sediment provenance analyses (e.g., d'Haen et al., 2013), and models (e.g., Baartman et al., 2013). However, many published examples employing connectivity indices do not relate index values to system properties or behaviour beyond – clearly valuable - qualitative, expert-based field assessment (Borselli et al., 2008; Cavalli et al., 2013) or comparison with geomorphological maps (Meßenzehl et al., 2014). Tentatively, and to be ascertained and corroborated by future research, some field-based (Peñuela et al., 2016) and model-based studies (Baartman et al., 2013) point to a possible direct correlation between connectivity indices and sediment transfer, sediment yield, or sediment delivery ratio. More research is also needed concerning the effect of connectivity on catchment sensitivity (c.f. Fryirs, 2017); we suggest that this task can be pursued best using landscape evolution models (e.g., Coulthard and van de Wiel, 2017) rather than applying connectivity indices alone.

Recent research has spotted a discrepancy between availability and actual application of sediment connectivity indices in management, highlighting the need for communicating the opportunities that indices offer to stakeholders involved in land management at various scales. Applied research should promote the implementation of connectivity assessment in decision-support systems, given that tools for the automated and/or semi-automated computation of indices are already available.

6 Acknowledgements

This paper forms part of the activities of the EU-funded COST action "CONNECTEUR" (http://connecteur.info). Working group 4 (on "useable indices of connectivity") thanks CONNECTEUR for funding two workshops in Eichstaett and Tallinn during which this paper has been developed. Damià Vericat is supported by a Ramon y Cajal Fellowship (RYC-2010-06264). Authors acknowledge the support from the Economy and Knowledge Department of the Catalan Government through the Consolidated Fluvial Dynamics Research Group (2014 SGR 645), and the CERCA Programme.

7 References

Abbe TB, Montgomery DR. 2003. Patterns and processes of wood debris accumulation in the Queets river basin, Washington. Geomorphology 51: 81-107.

Abu-Aly TR, Pasternack GB, Wyrick JR, Barker R, Massa D, Johnson T. 2014. Effects of LiDAR-derived, spatially distributed vegetation roughness on two-dimensional hydraulics in a gravel-cobble river at flows of 0.2 to 20 times bankfull. Geomorphology 206: 468–482.

Ali GA, Roy AG. 2010. Shopping for hydrologically representative connectivity metrics in a humid temperate forested catchment. Water Resources Research 46(12).

Ambroise B. 2004. Variable'active' versus'contributing' areas or periods: a necessary distinction. Hydrological Processes 18(6): 1149–1155.

Antoine M, Javaux M, Bielders C. 2009. What indicators can capture runoff-relevant connectivity properties of the micro-topography at the plot scale? Advances in Water Resources 32(8): 1297–1310.

Apitz, S., White, S., 2003. A conceptual framework for river-basin-scale sediment management. J Soils and Sediments 3 (3), 132–138. 10.1065/jss2003.08.083.

Baartman J, Masselink R, Keesstra SD, Temme AJAM. 2013. Linking landscape morphological complexity and sediment connectivity. Earth Surface Processes and Landforms 38(12): 1457–1471.

Babbie ER. 2013. The practice of social research. Wadsworth Cengage Learning: Belmont, CA.

Bakker, M.M., Govers, G., van Doom, A., Quetier, F., Chouvardas, D., Rounsevell, M., 2008. The response of soil erosion and sediment export to land-use change in four areas of Europe: the importance of landscape pattern. Geomorphology 98: 213–226.

Barneveld R. 2015. Modelling the erosion process using Norwegian methods. Conference on the possibilities of territory adaptation to the impacts of climate change. University of Brno/Czech Republic, November 19th, 2015

Belmont, P., Foufoula-Georgiou, E., 2017. Solving water quality problems in agricultural landscapes: New approaches for these nonlinear, multiprocess, multiscale systems. Water Resour. Res. 53 (4), 2585–2590.

Beven KJ, Kirkby MJ. 1979. A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrological Sciences Bulletin 24(1): 43–69.

Bordoni, M., Persichillo, M.G., Meisina, C., Crema, S., Cavalli, M., Bartelletti, C., Galanti, Y., Barsanti, M., Giannecchini, R., D'Amato Avanzi, G., 2018. Estimation of the susceptibility of a road network to shallow landslides with the integration of the sediment connectivity. Nat. Hazards Earth Syst. Sci. Discuss., 1–34. 10.5194/nhess-2017-457.

Borselli L, Cassi P, Torri D. 2008. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. Catena 75(3): 268–277.

Bracken LJ, Wainwright J, Ali GA, Tetzlaff D, Smith MW, Reaney SM, Roy AG. 2013. Concepts of hydrological connectivity: Research approaches, pathways and future agendas. Earth-Science Reviews.

Bracken LJ, Croke J. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrological Processes 21(13): 1749–1763.

Bracken LJ, Turnbull L, Wainwright J, Bogaart P. 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. Earth Surface Processes and Landforms 40(2): 177–188.

Brardinoni F, Cavalli M, Heckmann T, Liébault F, Rimböck A. 2015. Guidelines for assessing sediment dynamics in alpine basins and channel reaches: Final Report of the SedAlp Project, Work Package 4: Vienna.

Brardinoni F, Hassan MA. 2006. Glacial erosion, evolution of river long profiles, and the organization of process domains in mountain drainage basins of coastal British Columbia. Journal of Geophysical Research 111(F1).

Brardinoni F, Hassan MA. 2007. Glacially-induced organisation of channel-reach morphology in mountain streams. *Journal of Geophysical Research*, 112, F03013, doi:10.1029/ 2006JF000741.

Brardinoni F, Hassan MA, Rollerson T, Maynard D. 2009. Colluvial sediment dynamics in mountain drainage basins. Earth and Planetary Science Letters 284(3-4): 310–319.

Brazier, R.E., Damia Vericat, Cerda, A., Brardinoni, F., Batalla, R.J., Masselink, R., Wittenberg, L., Nadal-Romero, E., López-Tarazón, J.A., Estrany, J., Keesstra, S.D., 2015. Can we measure connectivity ? in: Geophysical Research Abstracts. EGU General Assembly, Vienna.

Brierley G, Fryirs K, Jain V. 2006. Landscape connectivity. The geographic basis of geomorphic applications. Area 38(2): 165–174.

Brunsden D. 2001. A critical assessment of the sensitivity concept in geomorphology. Catena 42(2–4): 99–123.

Brunsden D, Thornes JB. 1979. Landscape Sensitivity and Change. Transactions of the Institute of British Geographers 4(4): 463–484.

Bunn AG, Urban DL, Keitt TH. 2000. Landscape connectivity: A conservation application of graph theory. Journal of Environmental Management 59(4): 265–278.

Burt TP, Allison RJ (eds). 2010. Sediment Cascades. John Wiley and Sons: Chichester, UK.

Caine N, Swanson FJ. 1989. Geomorphic coupling of hillslope and channel systems in two small mountain basins. Zeitschrift für Geomorphologie N.F. 33(2): 189–203.

Calabrese JM, Fagan WF. 2004. A comparison-shopper's guide to connectivity metrics: Frontiers in Ecology and the Environment. Frontiers in Ecology and the Environment 2(10): 529–536. doi: 10.1890/1540-9295(2004)002[0529:ACGTCM]2.0.CO;2.

Calsamiglia, A., Fortesa, J., García-Comendador, J., Lucas-Borja, M.E., Calvo-Cases, A., Estrany, J., 2017. Spatial patterns of sediment connectivity in terraced lands: Anthropogenic controls of catchment sensitivity. Land Degrad Dev 128, 122. 10.1002/ldr.2840.

Calsamiglia, A., García-Comendador, J., Fortesa, J., López-Tarazón, J.A., Crema, S., Cavalli, M., Calvo-Cases, A., Estrany, J., 2018. Effects of agricultural drainage systems on sediment connectivity in a small Mediterranean lowland catchment. Geomorphology. 10.1016/j.geomorph.2018.06.011.

Cammeraat ELH. 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. Agriculture, Ecosystems and Environment 104(2): 317–332.

Cammeraat LH. 2002. A review of two strongly contrasting geomorphological systems within the context of scale. Earth Surface Processes and Landforms 27(11): 1201–1222.

Cantreul, V., Bielders, C., Calsamiglia, A., Degré, A., 2018. How pixel size affects a sediment connectivity index in central Belgium. Earth Surf. Process. Landforms 43, 884–893. 10.1002/esp.4295.

Carbonneau PE, Lane SN, Bergeron NE. 2003. Cost-effective non-metric close-range digital photogrammetry and its application to a study of coarse gravel river beds. International Journal of Remote Sensing 24(14): 2837–2854.

Cavalli M, Marchi L. 2008. Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR. Natural Hazards and Earth System Science 8(2): 323–333.

Cavalli, M., Tarolli, P., Marchi, L., Dalla Fontana, G., 2008. The effectiveness of airborne LiDAR data in the recognition of channel-bed morphology. Catena 73 (3), 249–260.

Cavalli M, Heckmann T, Marchi L. in press. Sediment connectivity in proglacial areas. In Geomorphology of Proglacial Systems: Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes, Heckmann T, Morche D (eds). Springer International Publishing.

Cavalli M, Tarolli P, Dalla Fontana G, Marchi L. 2016. Multi-temporal analysis of sediment source areas and sediment connectivity in the Rio Cordon catchment (Dolomites). Rendiconti Online della Società Geologica Italiana 39: 27–30.

Cavalli M, Trevisani S, Comiti F, Marchi L. 2013. Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. Geomorphology 188: 31–41.

Cerdan, O., Le Bissonnais, Y., Govers, G., Lecomte, V., van Oost, K., Couturier, A., King, C., Dubreuil, N., 2004. Scale effect on runoff from experimental plots to catchments in agricultural areas in Normandy. Journal of Hydrology 299: 4–14.

Chartin C, Evrard O, Laceby JP, Onda Y, Ottlé C, Lefèvre I, Cerdan O. 2016. The impact of typhoons on sediment connectivity: Lessons learnt from contaminated coastal catchments of the Fukushima Prefecture (Japan). Earth Surface Processes and Landforms.

Chorley RJ, Kennedy BA. 1971. Physical Geography: A Systems Approach. Prentice-Hall: London.

Church M. 2010. Mountains and Montane Channels. In Sediment Cascades, Burt TP, Allison RJ (eds). John Wiley and Sons: Chichester, UK; 17–53.

Connor-Streich, G., Henshaw, A.J., Brasington, J., Bertoldi, W., Harvey, G.L., 2018. Let's get connected: A new graph theory-based approach and toolbox for understanding braided river morphodynamics. WIREs Water 13, e1296. 10.1002/wat2.1296.

Conoscenti, C., Agnesi, V., Cama, M., Caraballo-Arias, N.A., Rotigliano, E., 2018. Assessment of Gully Erosion Susceptibility Using Multivariate Adaptive Regression Splines and Accounting for Terrain Connectivity. Land Degrad. Develop. 29, 724–736. 10.1002/ldr.2772.

Cossart E. 2016. L'(in)efficacité géomorphologique des cascades sédimentaires en question: Les apports d'une analyse réseau. Cybergeo.

Cossart É, Fressard M. 2017. Assessment of structural sediment connectivity within catchments: Insights from graph theory. Earth Surface Dynamics 5(2): 253–268.

Cossart, E., Viel, V., Lissak, C., Reulier, R., Fressard, M., Delahaye, D., 2018. How might sediment connectivity change in space and time? Land Degrad Dev 3, 350. 10.1002/ldr.3022.

Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. Geol Soc America Bull 100 (7), 1054–1068. 10.1130/0016-7606(1988)100<1054:TFAFON>2.3.CO;2.

Coulthard TJ, van de Wiel MJ. 2017. Modelling long term basin scale sediment connectivity, driven by spatial land use changes. Geomorphology 277: 265–281.

Crema, S., Cavalli, M., 2018. SedInConnect: A stand-alone, free and open source tool for the assessment of sediment connectivity. Comp. Geosci. 111, 39–45. 10.1016/j.cageo.2017.10.009.

Crema, S., Bossi, G., 2017. Clustering sediment connectivity maps to distinguish hillslope processes. Rendiconti Online della Società Geologica Italiana 42, 23–26.

Csardi, G., Nepusz, T., 2006. The igraph Software Package for Complex Network Research. InterJournal Complex Systems.

Czuba JA, Foufoula-Georgiou E. 2014. A network-based framework for identifying potential synchronizations and amplifications of sediment delivery in river basins. Water Resources Research 50(5): 3826–3851.

Czuba JA, Foufoula-Georgiou E. 2015. Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change. Water Resources Research 51(3): 1401–1421.

Dell'Agnese, A., Brardinoni, F., Toro, M., Mao, L., Engel, M., Comiti, F., 2015. Bedload transport in a formerly glaciated mountain catchment constrained by particle tracking. Earth Surf. Dynam. 3 (4), 527–542. 10.5194/esurf-3-527-2015.

D'Haen K, Dusar B, Verstraeten G, Degryse P, Brue H de. 2013. A sediment fingerprinting approach to understand the geomorphic coupling in an eastern Mediterranean mountainous river catchment. Geomorphology.

Dalla Fontana G, Marchi L. 1998. GIS indicators for sediment sources study in Alpine basins. IAHS Publication 248: 553–560.

Darboux, F., Davy, P., Gascuel-Odoux, C., Huang, C., 2001. Evolution of soil surface roughness and flowpath connectivity in overland flow experiments. Catena 46 (2-3), 125–139. 10.1016/S0341-8162(01)00162-X.

Descroix, L., Genthon, P., Amogu, O., Rajot, J.-L., Sighomnou, D., Vauclin, M., 2012. Change in Sahelian Rivers hydrograph: The case of recent red floods of the Niger River in the Niamey region. Global and Planetary Change 98-99, 18–30.

Delestre O, Cordier S, Darboux F, Du M, James F, Laguerre C, Lucas C, Planchon O. 2014. FullSWOF: A Software for Overland Flow Simulation. In Advances in Hydroinformatics, Gourbesville P, Cunge J, Caignaert G (eds). Springer Singapore: Singapore; 221–231.

Dietterich, H.R., Cashman, K.V., 2014. Channel networks within lava flows: Formation, evolution, and implications for flow behavior. J. Geophys. Res. Earth Surf. 119, 1704–1724. 10.1002/2014JF003103.

Dupas R, Delmas M, Dorioz J-M, Garnier J, Moatar F, Gascuel-Odoux C. 2015. Assessing the impact of agricultural pressures on N and P loads and eutrophication risk. Ecological Indicators 48: 396–407.

Duvert, C., Gratiot, N., Anguiano-Valencia, R., Némery, J., Mendoza, M.E., Carlón-Allende, T., Prat, C., Esteves, M., 2011. Baseflow control on sediment flux connectivity: Insights from a nested catchment study in Central Mexico. Catena 87, 129–140. 10.1016/j.catena.2011.05.021.

Emanuel RE, Hazen AG, McGlynn BL, Jencso KG. 2014. Vegetation and topographic influences on the connectivity of shallow groundwater between hillslopes and streams. Ecohydrology 7(2): 887–895.

Favis-Mortlock, D., 2013. Systems and Complexity in Geomorphology, in: Shroder, J.F., Switzer, A.D., Kennedy, D.M. (Eds.), Treatise on Geomorphology. Elsevier, pp. 257–270.

Flügel W-A. 1995. Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. Hydrological Processes 9: 423–436.

Foerster S, Wilczok C, Brosinsky A, Segl K. 2014. Assessment of sediment connectivity from vegetation cover and topography using remotely sensed data in a dryland catchment in the Spanish Pyrenees. Journal of Soils and Sediments 14(12): 1982–2000.

Fryirs KA. 2013. (Dis)Connectivity in catchment sediment cascades: A fresh look at the sediment delivery problem. Earth Surface Processes and Landforms 38(1): 30–46.

Fryirs KA. 2017. River sensitivity: A lost foundation concept in fluvial geomorphology. Earth Surface Processes and Landforms 42(1): 55–70.

Fryirs KA, Brierley GJ, Preston NJ, Kasai M. 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. Catena 70(1): 49–67.

Fryirs KA, Brierley GJ, Preston NJ, Spencer J. 2007. Catchment-scale (dis)connectivity in sediment flux in the upper Hunter catchment, New South Wales, Australia. Geomorphology 84(3-4): 297–316.

Fryirs KA, Wheaton JM, Brierley GJ (2016) An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. Earth Surf. Process. Landforms 41:701–710. doi: 10.1002/esp.3893

Galpern P, Manseau M, Fall A. 2011. Patch-based graphs of landscape connectivity: A guide to construction, analysis and application for conservation. Biological Conservation 144(1): 44–55.

Gascuel-Odoux C, Bruneau P. 1990. A morphological assessment of soil microtopography using a digital elevation model on one square metre plots. Catena 17(4-5): 315–325.

Gascuel-Odoux C, Aurousseau P, Doray T, Squividant H, Macary F, Uny D, Grimaldi C. 2011. Incorporating landscape features to obtain an object-oriented landscape drainage network representing the connectivity of surface flow pathways over rural catchments. Hydrological Processes 25(23): 3625–3636.

Gay A, Cerdan O, Mardhel V, Desmet M. 2016. Application of an index of sediment connectivity in a lowland area. Journal of Soils and Sediments 16(1): 280–293.

Ghafari, H., Gorji, M., Arabkhedri, M., Roshani, G.A., Heidari, A., Akhavan, S., 2017. Identification and prioritization of critical erosion areas based on onsite and offsite effects. CATENA 156, 1–9. 10.1016/j.catena.2017.03.014.

Goldin B, Rudaz B, Bardou E. 2016. Application of a sediment connectivity GIS-based index in a basin undergoing glacier retreat: The case study of the Navizence catchment. Rendiconti Online della Società Geologica Italiana 39: 35–38.

Gomez C, Wassmer P, Starheim C, Hadmoko DS, Lavigne F. 2013. Graph theory: the Ford and Fuklerson, and the Edmonds-Karp Algorithms to Model Dynamic Sedimentary Systems. In Proceedings, IAG (ed).

Götz J, Heckmann T, Schrott L. 2013. Network analysis of sediment cascades derived from a digital geomorphological map - an example from the Gradenbach catchment (Schober Mountains, Austrian Alps). In Geophysical Research Abstracts, EGU (ed).

Gran KB, Czuba JA. 2017. Sediment pulse evolution and the role of network structure. Geomorphology 277: 17–30.

Grant GE, O'Connor J, Safran E. 2017. Excursions in fluvial (dis)continuity. Geomorphology 277: 145–153.

Grauso, S., Pasanisi, F., Tebano, C., 2018. Assessment of a Simplified Connectivity Index and Specific Sediment Potential in River Basins by Means of Geomorphometric Tools. Geosciences 8, 48-62. 10.3390/geosciences8020048.

Grauso, S., Pasanisi, F., Tebano, C., Grillini, M., Peloso, A., 2018. Investigating the Sediment Yield Predictability in Some Italian Rivers by Means of Hydro-Geomorphometric Variables. Geosciences 8, 249–268. 10.3390/geosciences8070249.

Gu, R., Deutschman, M., 2001. Hydrologic assessment of water losses in river. J. Water Resour. Plan. Manage. 127 (1): 6–12.

Gumiere SJ, Le Bissonnais Y, Raclot D, Cheviron B. 2011. Vegetated filter effects on sedimentological connectivity of agricultural catchments in erosion modelling: a review. Earth Surface Processes and Landforms 36(1): 3–19.

Guzmán, G., Quinton, J.N., Nearing, M.A., Mabit, L., Gómez, J.A., 2013. Sediment tracers in water erosion studies: Current approaches and challenges. Journal of Soils and Sediments 13 (4), 816–833. 10.1007/s11368-013-0659-5.

Guzzetti, F., Carrara, A., Cardinali, M., P.Reichenbach, 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31, 181–216.

Guzzetti F, Galli M, Reichenbach P, Ardizzone F, Cardinali M. 2006. Landslide hazard assessment in the Collazzone area, Umbria, Central Italy. Natural Hazards and Earth System Science 6: 115–131.

Haas F, Heckmann T, Wichmann V, Becht M. 2011. Quantification and Modeling of Fluvial Bedload Discharge from Hillslope Channels in two Alpine Catchments (Bavarian Alps, Germany). Zeitschrift für Geomorphologie N.F. Suppl. 55(3): 147–168.

Hamel P, Chaplin-Kramer R, Sim S, Mueller C. 2015. A new approach to modeling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. Science of The Total Environment 524-525: 166–177.

Harvey AM. 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. Catena 42(2–4): 225–250.

Harvey AM (2002) Effective timescales of coupling within fluvial systems: Geomorphology on Large Rivers. Geomorphology 44:175–201. doi: 10.1016/S0169-555X(01)00174-X

Hassan, M.A., Hogan, D.L., Bird, S.A., May, C.L., Gomi, T., Campbell, D., 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. J. Am. Water Res. Assoc. 41, 899–919.

Heckmann T, Hilger L, Meßenzehl K, Hoffmann T, Schwanghart W, Götz J, Buckel J. 2014. Network analysis of sediment cascades derived from digital geomorphological maps – a comparative study of three catchments in the Austrian and Swiss Alps. In Geophysical Research Abstracts, EGU (ed).

Heckmann T, Hilger L, Vehling L, Becht M. 2016. Integrating field measurements, a geomorphological map and stochastic modelling to estimate the spatially distributed rockfall sediment budget of the Upper Kaunertal, Austrian Central Alps. Geomorphology 260: 16–31.

Heckmann T, Schwanghart W. 2013. Geomorphic coupling and sediment connectivity in an alpine catchment — Exploring sediment cascades using graph theory. Geomorphology 182: 89–103.

Heckmann T, Schwanghart W, Phillips JD. 2015. Graph theory—Recent developments of its application in geomorphology. Geomorphology 243: 130–146.

Heckmann, T., Vericat, D., 2018. Computing spatially distributed sediment delivery ratios: Inferring functional sediment connectivity from repeat high-resolution digital elevation models. Earth Surf. Process. Landforms 218, 88. 10.1002/esp.4334.

Heinimann HR, Hollenstein K, Kienholz H, Krummenacher B, Mani P. 1998. Methoden zur Analyse und Bewertung von Naturgefahren: Eine risikoorientierte Betrachtungsweise: Bern.

Heiser, M., Scheidl, C., Eisl, J., Spangl, B., Hübl, J., 2015. Process type identification in torrential catchments in the eastern Alps. Geomorphology 232, 239–247. 10.1016/j.geomorph.2015.01.007.

Hoffmann T. 2015. Sediment residence time and connectivity in non-equilibrium and transient geomorphic systems. Earth-Science Reviews 150: 609–627.

Hogan, D.L., Bird, S.A., Hassan, M., 1998. Spatial and temporal evolution of small coastal gravel-bed streams: the influence of

forest management on channel morphology and fish habitats. In: Klingeman, P.C., Beschta, R.L., Komar, P.D., Bradley, J.B.

(Eds.), Gravel-Bed Rivers in the Environment. Water Resources Publications, Highland Ranch, CO, pp. 365– 392.

Hooke J. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. Geomorphology 56(1–2): 79–94.

Hooke JM, Sandercock P, Cammeraat LH, Lesschen JP, Borselli L, Torri D, Meerkerk A, van Wesemael B, Marchamalo M, Gonzalo B, Boix-Fayos C, Castillo V, Navarro-Cano JA. 2017. Mechanisms of Degradation and Identification of Connectivity and Erosion Hotspots. In Combating Desertification and Land Degradation, Hooke J, Sandercock P (eds). Springer International Publishing: Cham; 13–37.

Huber A, Heckmann T, Haas F, Becht M. 2015. DEM-based scaling of bedload sediment yield in low-order torrents of the Isar catchment. In Guidelines for assessing sediment dynamics in alpine basins and channel reaches: Final Report of the SedAlp Project, Work Package 4: Vienna; Annex 39-46.

Jain V, Tandon SK. 2010. Conceptual assessment of (dis)connectivity and its application to the Ganga River dispersal system. Geomorphology 118(3-4): 349–358.

Jamshidi, R., Dragovich, D., Webb, A.A., 2014. Distributed empirical algorithms to estimate catchment scale sediment connectivity and yield in a subtropical region. Hydrol. Process. 28 (4), 2671–2684.

Jencso KG, McGlynn BL, Gooseff MN, Wondzell SM, Bencala KE, Marshall LA. 2009. Hydrologic connectivity between landscapes and streams: Transferring reach- and plot-scale understanding to the catchment scale. Water Resources Research 45(4)

Kalantari, Z., Cavalli, M., Cantone, C., Crema, S., Destouni, G., 2017. Flood probability quantification for road infrastructure: Data-driven spatial-statistical approach and case study applications. Science of The Total Environment 581-582, 386–398. 10.1016/j.scitotenv.2016.12.147.

Kleinhans MG, Bierkens MFP, van der Perk M. 2010. On the use of laboratory experimentation: “Hydrologists, bring out shovels and garden hoses and hit the dirt”. Hydrology and Earth System Sciences 14: 369–382.

Kondolf GM, Boulton AJ, O'Daniel S, Poole GC, Rahel FJ, Stanley EH, Wohl E, Bång A, Carlstrom J, Cristoni C, Huber H, Koljonen S, Louhi P, Nakamura K. 2006. Process-Based Ecological River Restoration: Visualizing Three-Dimensional Connectivity and Dynamic Vectors to Recover Lost Linkages. Ecology and Society 11(2).

Korup O. 2005. Geomorphic imprint of landslides on alpine river systems, southwest New Zealand. Earth Surface Processes and Landforms 30(7): 783–800. http://dx.doi.org/10.1002/esp.1171.

Kumar R, Jain V, Prasad Babu G, Sinha R. 2014. Connectivity structure of the Kosi Megafan and role of rail-road transport network. Geomorphology 227: 73–86.

Laita A, Kotiaho JS, Mönkkönen M. 2011. Graph-theoretic connectivity measures: what do they tell us about connectivity? Landscape Ecology 26(7): 951–967.

Lane SN, Brookes CJ, Kirkby MJ, Holden J. 2004. A network-index-based version of TOPMODEL for use with high-resolution digital topographic data. Hydrological Processes 18(1): 191–201.

Lane SN, Reaney SM, Heathwaite AL. 2009. Representation of landscape hydrological connectivity using a topographically driven surface flow index. Water Resources Research 45(8): n/a. http://dx.doi.org/10.1029/2008WR007336.

Lane SN. 2005. Roughness - time for a re-evaluation? Earth Surface Processes and Landforms 30(2): 251–253.

Lane SN, Bakker M, Gabbud C, Micheletti N, Saugy J-N. 2017. Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. Geomorphology 277: 210–227.

Lange, J., 2005. Dynamics of transmission losses in a large arid stream channel. Journal of Hydrology 306: 112–126.

Le Bissonnais, Y., Cerdan, O., Lecomte, V., Benkhadra, H., Souchère, V., Martin, P., 2005. Variability of soil surface characteristics influencing runoff and interrill erosion. Catena 62 (2-3), 111–124.

Lehotský, M., Rusnák, M., Kidová, A., Dudžák, J., 2018. Multitemporal assessment of coarse sediment connectivity along a braided-wandering river. Land Degrad Dev 9, 289. 10.1002/ldr.2870.

Leopold, L.B., Maddock Jr., T., 1953. The hydraulic geometry of stream channels and some physiographic implications. Professional Paper 252, Washington, D.C., 64 pp.

Leopold, L.B., Wolman, M.G., 1957. River channel patterns: Braided, meandering, and straight. Professional Paper 282B, Washington, D.C., 50 pp.

Li, G., West, A.J., Densmore, A.L., Hammond, D.E., Jin, Z., Zhang, F., Wang, J., Hilton, R.G., 2016. Connectivity of earthquake-triggered landslides with the fluvial network: Implications for landslide sediment transport after the 2008 Wenchuan earthquake. J. Geophys. Res. Earth Surf. 121, 703–724. 10.1002/2015JF003718.

Lisenby PE, Fryirs KA. 2017a. Sedimentologically significant tributaries: Catchment-scale controls on sediment (dis)connectivity in the Lockyer Valley, SEQ, Australia. Earth Surface Processes and Landforms 42(10): 1493–1504.

Lisenby, P.E., Fryirs, K.A., 2017b. 'Out with the Old?' Why coarse spatial datasets are still useful for catchment-scale investigations of sediment (dis)connectivity. Earth Surf. Process. Landforms 42, 1588–1596. 10.1002/esp.4131.

Lizaga I, Quijano L, Palazón L, Gaspar L, Navas A. 2016. Enhancing Connectivity Index To Assess The Effects Of Land Use Changes In A Mediterranean Catchment. Land Degradation and Development.

López-Vicente M, Poesen J, Navas A, Gaspar L. 2013. Predicting runoff and sediment connectivity and soil erosion by water for different land use scenarios in the Spanish Pre-Pyrenees. Catena 102: 62–73.

López-Vicente M, Quijano L, Palazón L, Gaspar L, Navas A. 2015. Assessment of soil redistribution at catchment scale by coupling a soil erosion model and a sediment connectivity index (central spanish pre-pyrenees). Cuadernos de Investigación Geográfica 41(1): 127.

López-Vicente M, Nadal-Romero E, Cammeraat ELH. 2017a. Hydrological Connectivity Does Change Over 70 Years of Abandonment and Afforestation in the Spanish Pyrenees. Land Degradation and Development 28(4): 1298–1310.

López-Vicente M, Sun X, Onda Y, Kato H, Gomi T, Hiraoka M. 2017b. Effect of tree thinning and skidding trails on hydrological connectivity in two Japanese forest catchments. Geomorphology.

López-Vicente, M., Álvarez, S., 2018. Influence of DEM resolution on modelling hydrological connectivity in a complex agricultural catchment with woody crops. Earth Surf. Process. Landforms 43, 1403–1415. 10.1002/esp.4321.

Lu, H., Moran, C.J., Sivapalan, M., 2005. A theoretical exploration of catchment-scale sediment delivery. Water Resour. Res. 41, 225. 10.1029/2005WR004018.

Magilligan FJ, Graber BE, Nislow KH, Chipman JW, Sneddon CS, Fox CA. 2016. River restoration by dam removal: Enhancing connectivity at watershed scales. Elementa: Science of the Anthropocene 4: 108.

Mahoney, D.T., Fox, J.F., Al Aamery, N., 2018. Watershed erosion modeling using the probability of sediment connectivity in a gently rolling system. Journal of Hydrology 561, 862–883. 10.1016/j.jhydrol.2018.04.034.

Mao L, Dell'Agnese A, Comiti F. 2017a. Sediment motion and velocity in a glacier-fed stream. Geomorphology 291: 69–79.

Mao L, Picco L, Lenzi MA, Surian N. 2017b. Bed material transport estimate in large gravel-bed rivers using the virtual velocity approach. Earth Surface Processes and Landforms 42(4): 595–611.

Marchi L, Dalla Fontana G. 2005. GIS morphometric indicators for the analysis of sediment dynamics in mountain basins. Environmental Geology 48(2): 218–228.

Mardhel V, Frantar P, Uhan J, Mio A (eds). 2004. Index of development and persistence of the river networks as a component of regional groundwater vulnerability assessment in Slovenia.

Marra WA, Kleinhans MG, Addink EA. 2014. Network concepts to describe channel importance and change in multichannel systems: Test results for the Jamuna River, Bangladesh. Earth Surface Processes and Landforms 39(6): 766–778.

Martínez-Murillo, J.F., López-Vicente, M., 2018. Effect of Salvage Logging and Check Dams on Simulated Hydrological Connectivity in a Burned Area. Land Degrad. Develop. 29, 701–712. 10.1002/ldr.2735.

Mayor ÁG, Bautista S, Small EE, Dixon M, Bellot J. 2008. Measurement of the connectivity of runoff source areas as determined by vegetation pattern and topography: A tool for assessing potential water and soil losses in drylands. Water Resources Research 44(10): n/a.

McHugh, M., Wood, G., Walling, D.E., Morgan, R., Zhang, Y., Anthony, S., Hutchins, M., 2002. Prediction of sediment delivery to watercourses from land: Phase II. Environment Agency, Bristol, vii, 99.

Meßenzehl K, Hoffmann T, Dikau R. 2014. Sediment connectivity in the high-alpine valley of Val Müschauns, Swiss National Park – linking geomorphic field mapping with geomorphometric modelling. Geomorphology 221: 215–229.

Michaelides K, Wainwright J. 2002. Modelling the effects of hillslope-channel coupling on catchment hydrological response. Earth Surface Processes and Landforms 27(13): 1441–1457.

Micheletti N, Lane SN. 2016. Water yield and sediment export in small, partially glaciated Alpine watersheds in a warming climate. Water Resources Research 52(6): 4924–4943.

Minor ES, Urban DL. 2008. A Graph-Theory Framework for Evaluating Landscape Connectivity and Conservation Planning. Conservation Biology 22(2): 297–307. http://dx.doi.org/10.1111/j.1523-1739.2007.00871.x.

Mitasova, H.L. , Hofierka, J. , Zlocha, M. and Iverson, L.R. 1996: Modelling topographic potential for erosion and deposition using GIS . International Journal of Geographical Information Systems 10: 629 —41 .

Montgomery, D.R., Dietrich, W.E., 1988. Where do channels begin? Nature 336, 232–234.

Montgomery, D.R., Dietrich, W.E., 1989. Source areas, drainage density, and channel initiation. Water Resour. Res. 25 (8), 1907–1918.

Montgomery DR, Buffington JM. 1997. Channel-reach morphology in mountain drainage basins. GSA Bulletin 109(5): 596–611.

Montgomery DR, Dietrich WE. 1994. A physically based model for the topographic control on shallow landsliding. Water Resources Research 30(4): 1153–1171.

Montgomery DR, Foufoula-Georgiou E. 1993. Channel network source representation using digital elevation models. Water Resources Research 29(12): 3925–3934.

Montgomery DR, Buffington JM. 1998. Channel processes, classification, and response. In River ecology and management: Lessons from the Pacific coastal ecoregion, Naiman RJ, Bilby RE, Kantor S (eds). Springer: New York.

Moore, I. D., and G. J. Burch. 1986. Modeling erosion and deposition: Topographic effects. Trans. ASAE 29(6): 1624-1630.

Moore ID, Grayson RB, Ladson AR. 1991. Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. Hydrological Processes 5: 3–30.

Morche D, Schmidt K-H, Heckmann T, Haas F. 2007. Hydrology and Geomorphic Effects of a High-Magnitude Flood in an Alpine River. Geografiska Annaler. Series A, Physical Geography 89(1): 5–19.

Mulder VL, Bruin S de, Schaepman ME, Mayr TR. 2011. The use of remote sensing in soil and terrain mapping — A review. Geoderma 162(1-2): 1–19.

Neugirg F, Kaiser A, Huber A, Heckmann T, Schindewolf M, Schmidt J, Becht M, Haas F. 2016. Using terrestrial LiDAR data to analyse morphodynamics on steep unvegetated slopes driven by different geomorphic processes. Catena 142: 269–280.

Neugirg P. 2016. Modellbasierte Analyse der Sediment-Konnektivität und ihres Verhältnisses zur Sedimentbilanz: (model-based assessment of sediment connectivity as a factor of sediment delivery, in German). MSc Thesis: Eichstaett.

Nicoll T, Brierley G. 2016. Within-catchment variability in landscape connectivity measures in the Garang catchment, upper Yellow River. Geomorphology.

Nippgen F, McGlynn BL, Emanuel RE. 2015. The spatial and temporal evolution of contributing areas. Water Resources Research 51(6): 4550–4573.

Nippgen F, McGlynn BL, Marshall LA, Emanuel RE. 2011. Landscape structure and climate influences on hydrologic response. Water Resources Research 47(12): n/a-n/a.

Nunes, J.P., Wainwright, J., Bielders, C.L., Darboux, F., Fiener, P., Finger, D., Turnbull, L., 2018. Better models are more effectively connected models. Earth Surf. Process. Landforms 32, 1297. 10.1002/esp.4323.

Ortíz-Rodríguez AJ, Borselli L, Sarocchi D. 2017. Flow connectivity in active volcanic areas: Use of index of connectivity in the assessment of lateral flow contribution to main streams. Catena 157: 90–111.

Otto J-C. 2006. Paraglacial sediment storage quantification in the Turtmann Valley, Swiss Alps. Doctoral Dissertation: Bonn.

Otto J-C, Löwner M-O. 2008. Towards an automatic identification of sediment cascades from geomorphological maps using graph theory. In Proceedings, ICCE (ed).

Parsons AJ, Bracken L, Poeppl RE, Wainwright J, Keesstra SD. 2015. Introduction to special issue on connectivity in water and sediment dynamics. Earth Surface Processes and Landforms: n/a.

Pascual-Hortal L, Saura S. 2006. Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation. Landscape Ecology 21(7): 959–967.

Passalacqua P. 2017. The Delta Connectome: A network-based framework for studying connectivity in river deltas. Geomorphology 277: 50–62.

Patton, P.C., Schumm, S.A., 1975. Gully Erosion, Northwestern Colorado: A Threshold Phenomenon. Geol 3 (2), 88.

Pearson, E., Smith, M.W., Klaar, M.J., Brown, L.E., 2017. Can high resolution 3D topographic surveys provide reliable grain size estimates in gravel bed rivers? Geomorphology 293, 143–155.

Peñuela A, Darboux F, Javaux M, Bielders CL. 2016. Evolution of overland flow connectivity in bare agricultural plots. Earth Surface Processes and Landforms 41(11): 1595–1613.

Peñuela A, Javaux M, Bielders CL. 2015. How do slope and surface roughness affect plot-scale overland flow connectivity? Journal of Hydrology 528: 192–205.

Persichillo, M.G., Bordoni, M., Cavalli, M., Crema, S., Meisina, C., 2018. The role of human activities on sediment connectivity of shallow landslides. CATENA 160, 261–274. 10.1016/j.catena.2017.09.025.

Peters DPC, Havstad KM. 2006. Nonlinear dynamics in arid and semi-arid systems: Interactions among drivers and processes across scales. Journal of Arid Environments 65(2): 196–206.

Poeppl RE, Keesstra SD, Maroulis J. 2017. A conceptual connectivity framework for understanding geomorphic change in human-impacted fluvial systems. Geomorphology 277: 237–250.

Poeppl RE, Keiler M, von Elverfeldt K, Zweimüller I, Glade T. 2012. The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment, Austria. Geografiska Annaler: Series A, Physical Geography 94(4): 511–529.

Poeppl, R.E., Parsons, A.J., 2018. The geomorphic cell: A basis for studying connectivity. Earth Surf. Process. Landforms 43, 1155–1159. 10.1002/esp.4300.

Quiñoñero-Rubio JM, Boix-Fayos C, de Vente J. 2013. Desarollo y aplicacion de un indice multifactorial de conectividad de sedimentos a escala de cuenca: Development and application of a multifactorial sediment connectivity index on the catchment scale (in Spanish). Cuadernos de Investigación Geográfica 39(2): 203–223.

Rainato R, Picco L, Cavalli M, Mao L, Neverman AJ, Tarolli P. 2017. Coupling Climate Conditions, Sediment Sources and Sediment Transport in an Alpine Basin. Land Degradation and Development.

Reid SC, Lane SN, Montgomery DR, Brookes CJ. 2007. Does hydrological connectivity improve modelling of coarse sediment delivery in upland environments? Geomorphology 90(3-4): 263–282.

Rodet, J., Lautridou, J.P., 2003. Contrôle du karst quaternaire sur la genèse et l'évolution du trait de côte d'une région crayeuse de la Manche (pays de Caux, Normandie, France). In: Le Quaternaire de Normandie: nouvelles données biochronologiques et géochronologiques. Quaternaire, 14 (1): 31–42.

Rubinov, M., Sporns, O., 2010. Complex network measures of brain connectivity: Uses and interpretations. NeuroImage 52, 1059–1069. 10.1016/j.neuroimage.2009.10.003.

Sass O, Haas F, Schimmer C, Heel M, Bremer M, Stöger F, Wetzel K-F. 2012. Impact Of Forest Fires On Geomorphic Processes In The Tyrolean Limestone Alps. Geografiska Annaler: Series A, Physical Geography 94(1): 117–133.

Schaepman ME, Ustin SL, Plaza AJ, Painter TH, Verrelst J, Liang S. 2009. Earth system science related imaging spectroscopy—An assessment. Remote Sensing of Environment 113: S123-S137

Schilling, K.E., Helmers, M., 2008. Tile drainage as karst: conduit flow and diffuse flow in a tile-drained watershed. Journal of Hydrology 349: 291–301.

Schmitt RJP, Bizzi S, Castelletti A. 2016. Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity. Water Resources Research: n/a-n/a.

Schmitt RJP, Bizzi S, Castelletti A. Kondolf G.M. 2017. Stochastic modeling of sediment connectivity for reconstructing sand fluxes and origins in the unmonitored Se Kong, Se San, and Sre Pok tributaries of the Mekong River. Journal of Geophysical Research – Earth Surface 10.1002/2016JF004105.

Schrott L, Niederheide A, Hankammer M, Hufschmidt G, Dikau R. 2002. Sediment Storage in a Mountain Catchment: Geomorphic Coupling and Temporal Variability (Reintal, Bavarian Alps, Germany). Zeitschrift für Geomorphologie N.F. Suppl. 127: 175–196.

Schumm, S.A., Lichty, R.W., 1965. Time, Space and Causality in Geomorphology. American Journal of Science 263, 110–119.

Segurado P, Branco P, Ferreira MT. 2013. Prioritizing restoration of structural connectivity in rivers: a graph based approach. Landscape Ecology 28(7): 1231–1238.

Shore M, Murphy PNC, Jordan P, Mellander P-E, Kelly-Quinn M, Cushen M, Mechan S, Shine O, Melland AR. 2013. Evaluation of a surface hydrological connectivity index in agricultural catchments. Environmental Modelling and Software 47: 7–15.

Sidle RC, Sasaki S, Otsuki M, Noguchi S, Rahim Nik A. 2004. Sediment pathways in a tropical forest: effects of logging roads and skid trails. Hydrological Processes 18(4): 703–720.

Singh M, Tandon SK, Sinha R. 2017. Assessment of connectivity in a water-stressed wetland (Kaabar Tal) of Kosi-Gandak interfan, north Bihar Plains, India. Earth Surface Processes and Landforms.

Skolaut C, Liébault F, Habersack H, Lenzi MA, Rusjan S, Sodnik J, Pichler A. 2015. Synthesis Report: Sediment Management in Alpine Basins (SedAlp): Integrating sediment continuum, risk mitigation and hydropower.

Slaymaker O. 2006. Towards the identification of scaling relations in drainage basin sediment budgets. Geomorphology 80(1–2): 8–19.

Smetanová, A., Paton, E.N., Maynard, C., Tindale, S., Fernández-Getino, A.P., Marqéus Pérez, M.J., Bracken, L., Le Bissonnais, Y., Keesstra, S.D., 2018. Stakeholders' perception of the relevance of water and sediment connectivity in water and land management. Land Degrad Dev 29, 1833–1844. 10.1002/ldr.2934.

Smith MJ, Pain CF. 2009. Applications of remote sensing in geomorphology. Progress in Physical Geography 33(4): 568–582.

Smith MW. 2014. Roughness in the Earth Sciences. Earth-Science Reviews 136: 202–225.

Sougnez N, van Wesemael B, Vanacker V. 2011. Low erosion rates measured for steep, sparsely vegetated catchments in southeast Spain. Catena 84(1-2): 1–11.

Souza, J.O.P., Correa, A.C.B., Brierley, G.J., 2016. An approach to assess the impact of landscape connectivity and effective catchment area upon bedload sediment flux in Saco Creek Watershed, Semiarid Brazil. Catena 138, 13–29. 10.1016/j.catena.2015.11.006.

Stangl, J., Rascher, E., Sass, O., 2016. Comparative analysis of sediment routing in two different alpine catchments, in: Beylich, A.A., Dixon, J.C., Zwoliński, Z. (Eds.), Source-to-sink-fluxes in undisturbed cold environments. Cambridge Univ Press, 364-377.

Stock, J., Dietrich, W.E., 2003. Valley incision by debris flows: Evidence of a topographic signature. Water Resour. Res. 39 (4)

Surian N, Righini M, Lucía A, Nardi L, Amponsah W, Benvenuti M, Borga M, Cavalli M, Comiti F, Marchi L, Rinaldi M, Viero A. 2016. Channel response to extreme floods: Insights on controlling factors from six mountain rivers in northern Apennines, Italy. Geomorphology.

Tarboton DG. 1997. A New Method for the Determination of Flow Directions and Upslope Areas in Grid Digital Elevation Models. Water Resources Research 33(2): 309–319.

Tarolli P, Sofia G. 2016. Human topographic signatures and derived geomorphic processes across landscapes. Geomorphology 255: 140–161.

Taylor PD, Fahrig L, Henein K, Merriam G. 1993. Connectivity Is a Vital Element of Landscape Structure. Oikos 68(3): 571–573.

Tejedor A, Longjas A, Zaliapin I, Foufoula-Georgiou E. 2015. Delta channel networks: 2. Metrics of topologic and dynamic complexity for delta comparison, physical inference, and vulnerability assessment. Water Resources Research 51(6): 4019–4045.

Tejedor A, Longjas A, Zaliapin I, Foufoula-Georgiou E. 2015. Delta channel networks: 1. A graph-theoretic approach for studying connectivity and steady state transport on deltaic surfaces. Water Resources Research 51(6): 3998–4018.

Theler, D., Reynard, E., Lambiel, C., Bardou, E., 2010. The contribution of geomorphological mapping to sediment transfer evaluation in small alpine catchments: Recent advances in landslide investigation. Geomorphology 124 (3–4), 113–123.

Tiranti D, Cavalli M, Crema S, Zerbato M, Graziadei M, Barbero S, Cremonini R, Silvestro C, Bodrato G, Tresso F. 2016. Semi-quantitative method for the assessment of debris supply from slopes to river in ungauged catchments. The Science of the total environment 554-555: 337–348.

Tiranti, D., Crema, S., Cavalli, M., Deangeli, C., 2018. An Integrated Study to Evaluate Debris Flow Hazard in Alpine Environment. Front. Earth Sci. 6, 4. 10.3389/feart.2018.00060.

Tischendorf L, Fahrig L. 2000. How should we measure landscape connectivity? Landscape Ecology 15: 633–641.

Toth C, Jóźków G. 2016. Remote sensing platforms and sensors: A survey. ISPRS Journal of Photogrammetry and Remote Sensing 115: 22–36.

Trevisani S, Cavalli M. 2016. Topography-based flow-directional roughness: Potential and challenges. Earth Surface Dynamics 4(2): 343–358.

Trimble, S.W., 1999. Decreased Rates of Alluvial Sediment Storage in the Coon Creek Basin, Wisconsin, 1975-93. Science 285 (5431), 1244–1246. 10.1126/science.285.5431.1244.

Turnbull L, Wainwright J, Brazier RE. 2008. A conceptual framework for understanding semi-arid land degradation: ecohydrological interactions across multiple-space and time scales. Ecohydrology 1(1): 23–34.

Turnbull, L., Hütt, M.-T., Ioannides, A.A., Kininmonth, S., Poeppl, R., Tockner, K., Bracken, L.J., Keesstra, S., Liu, L., Masselink, R., Parsons, A.J., 2018. Connectivity and complex systems: Learning from a multi-disciplinary perspective. Appl Netw Sci 3, 47. 10.1007/s41109-018-0067-2.

Urban D, Keitt T. 2001. Landscape connectivity: A graph-theoretic perspective. Ecology 82(5): 1205–1218.

van den Eeckhaut M, Reichenbach P, Guzzetti F, Rossi M, Poesen J. 2009. Combined landslide inventory and susceptibility assessment based on different mapping units: an example from the Flemish Ardennes, Belgium. Natural Hazards and Earth System Science 9: 507–521.

Vandromme, R., Gay, A., Cerdan, O., 2015. Cartographie de la connectivité - Projet VERSEAU. Rapport final: (BRGM/RP-65184-FR). BGRM, Orléans, 35 pp. http://infoterre.brgm.fr/rapports/RP-65184-FR.pdf.

Vente J de, Poesen J, Bazzoffi P, van Rompaey A, Verstraeten G. 2006. Predicting catchment sediment yield in Mediterranean environments: The importance of sediment sources and connectivity in Italian drainage basins. Earth Surface Processes and Landforms 31(8): 1017–1034.

Vente J de, Poesen J, Arabkhedri M, Verstraeten G. 2007. The sediment delivery problem revisited. Progress in Physical Geography 31(2): 155–178.Verdú JM, Batalla RJ, Martínez-Casasnovas JA. 2005. High-resolution grain-size characterisation of gravel bars using imagery analysis and geo-statistics. Geomorphology 72(1-4): 73–93.

Vigiak O, Borselli L, Newham LTH, McInnes J, Roberts AM. 2012. Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio. Geomorphology 138(1): 74–88.

Vrieling A. 2006. Satellite remote sensing for water erosion assessment: A review. Catena 65(1): 2–18.

Wainwright J. 2006. Degrees of separation: Hillslope-channel coupling and the limits of palaeohydrological reconstruction. Catena 66(1-2): 93–106.

Wainwright J, Turnbull L, Ibrahim TG, Lexartza-Artza I, Thornton SF, Brazier RE. 2011. Linking environmental régimes, space and time: Interpretations of structural and functional connectivity: Geomorphology on Multiscale Feedbacks in Ecogeomorphology. Geomorphology 126(3–4): 387–404.

Walling DE. 1983. The sediment delivery problem: Scale Problems in Hydrology. Journal of Hydrology 65(1–3): 209–237.

Walling DE, Zhang Y. 2004. Predicting slope-channel connectivity: a national-scale approach. IAHS Publication 288: 107–114.

Walque B de, Degré A, Maugnard A, Bielders CL. 2017. Artificial surfaces characteristics and sediment connectivity explain muddy flood hazard in Wallonia. CATENA 158: 89–101.

Weekes AA, Torgersen CE, Montgomery DR, Woodward A, Bolton SM. 2012. A Process-Based Hierarchical Framework for Monitoring Glaciated Alpine Headwaters. Environmental Management 50(6): 982–997.

Wemple BC, Swanson FJ, Jones JA. 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. Earth Surface Processes and Landforms 26(2): 191–204.

Whiting PJ, Bradley JB. 1993. A process-based classification system for headwater streams. Earth Surface Processes and Landforms 18: 603-612.

Wichmann V, Heckmann T, Haas F, Becht M. 2009. A new modelling approach to delineate the spatial extent of alpine sediment cascades: GIS and SDA applications in geomorphology. Geomorphology 111(1-2): 70–78.

Wilson JP, Gallant JC (eds). 2000. Terrain analysis: Principles and applications // Terrain analysis: Principles and applications. John Wiley and Sons: New York [etc.].

Wohl E. 2004. Limits to downstream hydraulic geometry. Geology 32 (10): 897-900.

Wohl E. 2006. Human impacts to mountain streams. Geomorphology 79(3-4): 217–248.

Wohl E. 2015. Rivers in the critical zone. In Principles and Dynamics of the Critical Zone, Giardino JR, Houser C (eds). Elsevier Science: Burlington; 267–294.

Wohl, E., 2017. Connectivity in rivers. Progress in Physical Geography 41 (3), 345–362.

Wohl E, Beckman ND. 2014. Leaky rivers: Implications of the loss of longitudinal fluvial disconnectivity in headwater streams. Geomorphology 205: 27–35.

Wohl E, Magilligan FJ, Rathburn SL. 2017. Introduction to the special issue: Connectivity in Geomorphology. Geomorphology 277: 1–5.

Wohl E, Rathburn S, Chignell S, Garrett K, Laurel D, Livers B, Patton A, Records R, Richards M, Schook DM, Sutfin NA, Wegener P. 2017. Mapping longitudinal stream connectivity in the North St. Vrain Creek watershed of Colorado. Geomorphology 277: 171–181.

Wohl, E., Brierley, G., Cadol, D., Coulthard, T.J., Covino, T., Fryirs, K.A., Grant, G., Hilton, R.G., Lane, S.N., Magilligan, F.J., Meitzen, K.M., Passalacqua, P., Poeppl, R.E., Rathburn, S.L., Sklar, L.S., 2018. Connectivity as an Emergent Property of Geomorphic Systems. Earth Surf. Process. Landforms. 10.1002/esp.4434.

Xu, X., Li, J., Tolson, B.A., 2014. Progress in integrating remote sensing data and hydrologic modeling. Progress in Physical Geography 38 (4), 464–498.

Zah R, Niederost M, Rinderspacher H, Uehlinger U, Ward JV. 2001. Long-Term Dynamics of the Channel Network in a Glacial Floodplain, Val Roseg, Switzerland. Arctic, Antarctic, and Alpine Research 33(4): 440.