Earth Surface Processes and Landforms

(Dis)connectivity in hydro-geomorphic systems - emerging concepts and their applications

Journal:	*Earth Surface Processes and Landforms*
Manuscript ID	Draft
Wiley - Manuscript type:	ESEX commentary
Keywords:	fluvial, catchment, water, sediment, complexity
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ESEX Commentary

(Dis)connectivity in hydro-geomorphic systems - emerging concepts and their applications

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Abstract

In geomorphology, connectivity has emerged as a framework for understanding the transfer of water and sediment through landscapes. Over the past decade, sessions on (dis)connectivity at the General Assembly of the European Geosciences Union (EGU), and more recently, three mini-conferences in 2020 and 2021 called "Connectivity Conversations", organized by the International Association of Geomorphologists (IAG) working group on "Connectivity in Geomorphology", have created a space for the exchange of ideas relating to (dis)connectivity in geomorphology and related disciplines. The result of these initiatives has been a collection of research articles related to a special issue (SI) entitled "(Dis)connectivity in hydro-geomorphic systems - emerging concepts and their applications". In this paper we provide a synthesis that embraces the SI contributions related to the application of the connectivity concept in different environments and geomorphic process domains, spatial and temporal scales, types and spatial dimensions of connectivity and the role of human impacts and associated river and catchment management aspects.

Keywords

Fluvial, catchment, water, sediment, complexity

Introduction

In the past two decades, connectivity has emerged as a useful conceptual framework for understanding the transfer of water and sediment through landscapes. Connectivity thinking in (hydro-)geomorphic research entails a range of benefits for investigating the spatial and temporal variability of material fluxes and (complex) system behaviour (Wohl et al., 2019; Poeppl et al., in press), by focussing on the interactions among system components, geomorphic response to varying inputs, and the role of humans in influencing the behaviour of geomorphic systems. The effects of widespread disruptions in connectivity in hydro-geomorphic systems have been recognised, especially with research on natural, leaky dams (e.g., beaver dams and log jams). We use the term (dis)connectivity to refer to the different levels of connectivity, from the highly disconnected, to the highly connected, combining the study of fluxes between geomorphic features with that of the role of disruptions in the transfer of mass in hydro-geomorphic systems. Over the past decade, sessions on (dis)connectivity at the General Assembly of the European Geosciences Union (EGU), and more recently, three mini-conferences in 2020 and 2021 called “Connectivity Conversations“ (CC), organized by the IAG “Connectivity in Geomorphology” working group, have created a space for the exchange of ideas relating to (dis)connectivity, surrounding methodological approaches, spatial and temporal scales, process domains, spatial dimensions of connectivity, structural and functional connectivity (SC/FC), drivers of change in connectivity, and the different processes/materials for which connectivity is a useful concept.

Applications of the connectivity concept in geomorphology are incredibly diverse in terms of their goals, the approaches used, whether or not (and how) they differentiate between structural and functional connectivity or the type of material (e.g. water, sediment, biota) they are concerned with. The special issue (SI) “(Dis)connectivity in hydro-geomorphic systems - emerging concepts and their applications” brings together 10 papers that were presented at EGU (dis)connectivity sessions and the CC in 2020 and 2021, that explore various aspects of these key themes (see overview in Table 1).

Table 1: Overview of the SI papers

	Methodical approach	Scale (spatial/ temporal)	Environment/ process domain(s)	Spatial dimension	Type of material	FC/SC	Anthropogenic influence
Bizzi et al. (2021)	Modelling	Network/years	Mountain, coastal/fluvial	Longitudinal	Sediment	FC	Dams
González-Romero et al. (2021)	Index, field measurements, field mapping	Small catchment/years	Forests/ hillslope	Longitudinal, lateral	Sediment	SC (incl. FC aspects)	Log barriers, check dams
Hiatt et al. (2022)	Network analysis	Network/years	Deltas/fluvial	Longitudinal	Water	Both	Not mentioned
Hinshaw et al. (2022)	Field mapping/ monitoring, conceptual	Reach/years	Mountain/fluvial	Longitudinal, lateral	Water, sediment, organic	SC/FC	Channel engineering/ restoration
Kemper et al. (2022)	Mapping, field measurements	Network/ decades-centuries	Mountain/fluvial	Longitudinal	Water, sediment	SC/FC	Dam
Khan et al. (2021)	Modelling	Network/years	Mountain/fluvial	Longitudinal	Sediment	FC	Not mentioned
Martini et al. (2022)	Index, field mapping	Catchment/-	Mountain/hillslope	Lateral	Sediment	SC	Not mentioned
Singh et al. (2022)	Remote sensing, indices	Reach/ years to decades	Wetland/fluvial	Longitudinal	Water	Both	Agriculture
Sonke et al. (2022)	Network analysis	Network/ decades	Estuary/ fluvial-coastal	Longitudinal	Water, sediment	SC	Channel engineering
Turley et al. (2021)	Indices	Catchment/ years	Mountain/ fluvial-hillslope	Longitudinal, lateral	Sediment	Both	Not mentioned

Environments and geomorphic process domains

Hydro-geomorphic connectivity emerges from a complex interplay between different environmental factors such as geology, relief, landscape position, climate, soils, biota, and human activity (e.g. Bracken and Croke, 2007; Poeppl et al., 2017; Keesstra et al., 2018). These factors further govern water and sediment dynamics in different environmental settings and geomorphic process domains (i.e. fluvial, hillslope, coasts/deltas, periglacial, glacial, aeolian; cf. Poeppl et al., in press). In this SI, five contributions have dealt with connectivity in mountain environments, with a specific focus on fluvial processes by Hinshaw et al. (2022; South Fork McKenzie River basin, Cascade Mountains, Oregon, USA), Kemper et al. (2022; Yampa River basin, Rocky Mountains, Colorado, USA), and Khan et al. (2021; Richmond River catchment, Great Dividing Range, Australia), on hillslope processes by Martini et al. (2022; Rio Cordon catchment, Italian Alps), or on both environments as shown by Turley et al. (2021; Tahoma Creek catchment, Cascade Mountains, Washington, USA). Two papers investigated connectivity relationships in river and catchment systems (Bizzi et al., 2021: Vjosa River, Albania; González-Romero et al., 2021: Segura River catchment, Spain), while two contributions had a specific focus on delta, estuary and wetland environments (Hiatt et al., 2022; Sonke et al., 2022; Singh et al., 2022).

Type of material

A common definition of connectivity in geomorphology is ”the degree to which matter and organisms can move among patches in a landscape or ecosystem” (Wohl, 2017), and the ’matter’ studied can be water, sediment, solutes or organic material. Focusing solely on longitudinal connectivity of water through a catchment often lends itself to pure hydrological studies, whereas the role of various types of disconnectivity on water fluxes has been a recent theme in hydro-geomorphic research. Sediment (dis)connectivity controls rates of landscape erosion and types of channel features and thus habitat in rivers. Ecological questions can be answered using a hydro-geomorphic framework of (dis)connectivity for studies on hydrochory (seed/plant propagule dispersal by water) and other passive dispersal of organisms (e.g., macroinvertebrates and pelagic-spawning fish), or nutrient and carbon storage.

In this SI, two studies focus on connectivity of only water (Hiatt et al., 2022; Sinha et al., 2022). Sonke et al. (2022) examine connectivity of both water and sediment. Most studies focus on sediment connectivity (González-Romero et al. 2021; Bizzi et al., 2021; Martini et al., 2022), including Kemper et al. (2022) who concentrate on catchment-scale connectivity using vegetation establishment as a proxy for when sediment was eroded or deposited in particular locations in the catchment. Only one study focuses on other types of matter than sediment and water: Hinshaw et al. (2022) examine changes in connectivity of water, sediment and organic matter through time after a restoration method that aims to increase lateral connectivity.

Spatial dimensions

Within hydro-geomorphic systems, connectivity and the lack thereof can be studied in several spatial dimensions, but it has traditionally been tied to longitudinal transport and continuity of material. In fact, the very reason that rivers are able to act as conduits for water and sediment and thus erode landscapes is based on downstream connectivity (Ferguson, 1981).

Fundamental fluvial geomorphic theories, such as downstream hydraulic geometry (Leopold and Maddock, 1953), rely on downstream connectivity of water flows. The effects of disconnectivity on longitudinal fluxes originally received most attention in terms of anthropogenic effects of building dams (e.g. Graf, 1999; 2006; Nilsson et al. 2005); however, natural forms of longitudinal disconnectivity, in terms of e.g., beaver dams, wood jams, and lakes, can play a pivotal role in steering fluxes of water (Puttock et al., 2021), sediment (Wohl and Scott, 2016) and plant propagules (Su et al., 2019). Hydro-geomorphic connectivity occurs in two other directional dimensions: lateral (channel-floodplain/hillslope) and vertical (hyporheic) connectivity. In contrast to longitudinal connectivity, bidirectional connectivity of material is an important trait in the lateral and vertical dimensions, where sediment, water and plant propagules can move laterally from the floodplain or hillslope to the channel or be stored on the floodplain or vertically to and from the hyporheic zone. The potential for lateral and vertical connectivity is intricately tied to the degree of longitudinal connectivity. For example, naturally confined or anthropogenically channelized/incised systems have high levels of longitudinal connectivity, but may only allow lateral connectivity in one direction (hillslope to channel) but do not allow for attenuation of flows or retention of sediment and propagules that may be stored on the floodplain.

The spatial dimensions of (dis)connectivity focused on in this SI are likely representative of the distribution of studies in general, where most focus is on the role of longitudinal connectivity of water, sediment and plant propagules. There is a clear focus on longitudinal connectivity of sediment (Bizzi et al., 2021; Kemper et al., 2022; Turley et al., 2021; Khan et al., 2021), followed by that of water fluxes in estuarine channels and wetlands (Hiatt et al., 2022; Sinha et al., 2022). Three studies combined aspects of longitudinal and lateral connectivity, either in the channel-floodplain (Hinshaw et al. 2022) or the catchment perspective (González-Romero et al., 2021; Turley et al., 2021). We deemed only one article to explicitly solely focus on lateral connectivity (Martini et al., 2022).

Functional connectivity (FC) and structural connectivity (SC)

Within geomorphology a distinction is often made between SC (network architecture) and FC (dynamical processes; e.g. Wainwright et al., 2011; Bracken et al., 2015, Wohl et al., 2019). This distinction between structural and functional connectivity is an artificial one, that tries to separate the influence of system structure on dynamical processes (Turnbull et al., 2018), yet is nevertheless useful as it allows simplification of the characterisation/quantification of connectivity. As seen from the collection of studies within this SI, there is a general tendency to focus within geomorphology on either structural connectivity (e.g. Martini et al 2022) or functional connectivity (e.g. Bizzi et al 2021 and Khan et al 2021), and rarely do studies focus on both (but see Hiatt et al 2021), often because the approaches used make it challenging to make such a distinction.

What is still less common in geomorphology is the quantification of functional connectivity. It is this combined analysis of structural and functional connectivity that has the potential to allow for greater insights into key locations within the landscape where feedbacks between form and function are particularly pronounced, which cannot be obtained without a connectivity-oriented approach (as demonstrated in Turnbull et al., 2019). In order for useful comparisons between structural and functional connectivity to be made, the template over which structural and functional connectivity are compared also needs to be the same. Graph theory approaches are very powerful in this regard, as network topology enables structural connectivity metrics to be determined, whilst also allowing for functional connectivity to be quantified. An example of this application is given in Hiatt et al. (2021) where they explore how FC metrics vary with different network characteristics.

Anthropogenic influence on connectivity

Different types of human activity can alter the connectivity in hydro-geomorphic systems and thus their sensitivity to change (Fryirs 2017; Poeppl et al., 2017). Human impacts on water and sediment connectivity in river systems, for example, can be either direct (e.g. due to dam construction/river engineering) or indirect (e.g. due to land cover/land use changes; cf. Gregory, 2006; Poeppl et al., 2017). Human disturbance of connectivity in geomorphic systems can further be differentiated between ramped (i.e. sustained; e.g. due to dam construction) and pulsed (i.e. event; e.g. a flash flood after dam breach) types of inputs (Brundsen and Thornes, 1979; Poeppl et al., 2017). Moreover, the recognition of (past) human disturbances and how these have modified natural connectivity relationships, and in how far they can or should be managed, is of major importance, especially in river and catchment management contexts (Fryirs and Brierley, 2009; Poeppl et al., 2017; Keesstra et al., 2018; Wohl et al., 2019; Poeppl et al., 2020).

In this SI, different types of human disturbance of connectivity have been addressed in different contexts. Bizzi et al. (2021) observed that a dam-induced decrease of longitudinal sediment connectivity of ca. 50 % would likely cause existing braided reaches to shift toward single-thread morphology. Similarly, Kemper et al. (2022) reported on the effects of dam closure on water and sediment connectivity and associated changes in channel dynamics, while Sonke et al. (2021) discussed the specific relevance of the propagation of human disturbances (e.g. due to dredging and dumping) through channel networks. Singh et al. (2022) focussed their work on the role of land-use changes on wetland-catchment (dis)connectivity and drainage re-organisation on wetland-river (dis)connectivity. González-Romero et al. (2021) included the disconnecting effects of check dams and log barriers in their analyses, further discussing their role in managing suspended sediment yields in post-fire catchments. Hinshaw et al. (2022) surveyed the consequences of levee bank removal, channel re-grading and large wood addition for hydro-geomorphic connectivity and channel evolution in a river restoration context.

Advances and remaining challenges in understanding geomorphic systems using connectivity as a framework

One of the main benefits of studying a system from a connectivity perspective is that it allows the influence of local-scale processes on large-scale system form and function to be disentangled. Within geomorphology, studies of connectivity range across spatial and temporal scales, from plot-based experiments to large river basin assessments and network-based approaches as well as from static representations of connectivity (also referred to as structural connectivity derived from network topology) to dynamical representations of connectivity (also referred to as process-based, or functional connectivity), ranging from seconds to millennia.

Within the geomorphological community, there has been a multitude of connectivity overview papers that have helped to bring together ways to operationalise this framework and bring quantitative meaning to discussions surrounding connectivity in geomorphology. Nevertheless, these frameworks continue to evolve – for instance, in this special issue, Kemper et al. (2021) present a sediment-ecological framework for large river networks that links geomorphic and ecologic processes across space and time at catchment scales. The importance of the coupling between geomorphological and ecological processes is a recurrent theme (for example Hinshaw et al., 2022; Singh et al., 2022; Kemper et al, 2022) and speaks to the importance of multi-disciplinary perspectives (Turnbull et al., 2018).

Both the scope of a study (i.e. in terms of network topology or dynamical processes and their interactions, and the system boundary) along with its scale determine the methodical approach to assess connectivity (e.g. Keesstra et al., 2018; Turnbull et al., 2018; Singh et al., 2020). One of the main challenges in quantifying connectivity from a geomorphological perspective is the definition of fundamental units of study as well as the availability and generation of suitable datasets that allow for detailed characterisations of landscape form and function over relevant space and time scales (Poeppl and Parsons, 2018; Turnbull et al., 2018). These datasets are essential in order for the geomorphic community to move beyond conceptual frameworks for the study of connectivity, to operationalise these frameworks, and to allow for an improved understanding of emergent patterns and characterisation of connectivity. However, it still remains common within geomorphology to allude to the concept of connectivity, rather than operationalise (and thus quantify) the concept. A common approach to attempt to surmount this challenge in geomorphology is the use of indices that are focused on the structure of the landscape (SC) and use a relatively narrow set of parameters (e.g. topography, vegetation cover). A key example of this is the Index of Connectivity (Borselli et al., 2008) which has been widely applied (see for example Martini et al., 2022). There have been attempts to expand this index further, e.g. to capture the potential influence of dynamical processes by the addition of further parameters (see Gonzalez-Romero et al., 2021).

Characterising FC within geomorphology is still challenging. Given the inherent challenge of collecting data suitable for characterising FC, one approach is to model the processes for which we are interested in quantifying FC. Modelling is particularly powerful as it allows us to fill in the spatial and temporal gaps in observed records, and capture dynamical processes at relevant spatial and temporal scales for the system in question, thus enabling the quantification of FC over time. Modelling approaches used to quantify FC are particularly important in systems where patterns of structural connectivity are not pronounced (e.g. in agricultural regions) (Baartman et al., 2020). An important caveat concerning the use of models to better understand connectivity is that not all models represent the landscape in sufficient detail to allow the connectivity of key processes to emerge (Nunes et al., 2017). Within this SI, two contributions are particularly notable in their use of modelling approaches to better understand the functional dynamics of geomorphic systems. Bizzi et al. (2021) use the CASCADE river network-scale model to undertake a network-scale assessment of sediment flux through the Vjosa River channel network in Italy. Khan et al. (2021), also using the CASCADE model, explore how the pattern and configuration of sediment cascades facilitate or restrict geomorphic adjustment in different parts of the catchment. Both Bizzi et al. (2021) and Khan et al. (2021) interpret their results within a connectivity framework.

Empirical approaches to the study of FC within geomorphology are less common, because of the challenges in data collection at relevant space and time scales. The increasing availability of multi-temporal high-resolution digital terrain models and aerial imagery over recent years presents opportunities for the characterisation of FC over longer timescales, where differences in elevation over time are indicative of long-term erosional and depositional processes can be discerned from high-resolution digital elevation models (DEM), or where patterns of erosion can be derived from aerial imagery. Turley et al. (2021) explore the application of a range of different approaches to the quantification of SC and FC. They find that the approaches that utilise high-resolution input data, tend to generate the best characterisation of connectivity when compared with field observations, and conclude that characterisations of FC that account for dynamical processes nevertheless remain important, which is clearly an area where progress still needs to be made within geomorphology.

An important development within geomorphology has been the application of network analysis approaches derived from graph theory. The value of the implementation of graph theory, and the suite of connectivity-based measures of graph characteristics derived from network theory, is that it allows a more robust quantification of connectivity that enables the operationalisation of the concept of connectivity – something that is still often lacking within geomorphological studies. A detailed review of the recent developments in the application of graph theory in geomorphology is given by Heckmann et al (2015). In order to apply graph theory within geomorphology, one of the first tasks is to represent the system as a network. Approaches to network representation are well developed for relatively simple and directed networks, but less so for multi-channel networks, typical of e.g. estuaries. In this SI, Sonke et al. (2021) explore two approaches (one local, one global) to identifying channel networks from the terrain of a river bed, based on the volume of alluvium between them. The resulting channel networks (and thus quantification of structural connectivity) are very sensitive to the approach used, with the local approach yielding optimal results. The insight provided by this local approach is that it allows for a new understanding of topological (or structural) connectivity of the channel networks, whereby alluvial connectivity is the inverse of the volume of sediment that needs to be removed in order for two channels to be connected.

A clear definition of the network topology then allows for interrogation of how dynamical processes are related to it, i.e. SC-FC relations. Building on the work of Tejedor et al. (2015a, 2015b), Hiatt et al. (2022) present a useful summary of how estuarine channel structure is related to dynamical connectivity, by exploring schematic networks that represent end-member states of plausible estuarine network topologies and then further explore these relations with reference to a range of real-world estuarine networks. Notably, they find that FC in the flood direction differs from FC in the ebb direction. This finding is significant in as much as it highlights that the patterns and magnitude of dynamical connectivity cannot be inferred from SC alone.

There is great scope to drive forward our understanding of connectivity in geomorphology by linking modelling approaches more explicitly with the suite of connectivity measures derived from network science. Such linkages should be relatively straightforward in river network models such as CASCADE (as detailed in this SI in Khan et al. (2021) and Bizzo et al. (2021)) that already have an underlying node and edge network structure.

Several authors have highlighted that (dis)connectivity as a concept should form a basis for informed decision-making in river and catchment management incl. river restoration (Keesstra et al., 2018; Wohl et al., 2019; Poeppl et al., 2020). Still, in practice most management plans overlook the role of (dis)connectivity in driving natural and human-induced disturbance and treatment responses in river and catchment systems (Poeppl et al., 2020), often further lacking holistic approaches to manage these systems in a sustainable manner. However, especially in integrated catchment management and recent river restoration efforts, aspects of lateral connectivity are increasingly being incorporated (e.g. Cluer and Thorne, 2013). In this SI, Hinshaw et al. (2022) addressed the problem of how to examine structural and functional connectivity after a new restoration strategy of Stage-0 restoration and to accurately determine how the newly restored structural connectivity translates to functional connectivity.

Conclusions

The concept of connectivity has shown to be applied to different environments and geomorphic process domains, on different spatial and temporal scales, spatial dimensions of connectivity as well as in diverse contexts using different (methodical) approaches (e.g. measuring, indices, modelling). The SI contributions have dealt with connectivity in mountain environments, river and catchment systems, as well as delta, estuary and wetland environments focussing on fluvial and/or hillslope processes. Moreover, different types of human impact (e.g. dams, land use changes) have been addressed in different contexts (e.g. river process and form, river and catchment management). Most of the articles focus on water and/or sediment connectivity studying either FC or SC, but rarely both - a general tendency in geomorphological connectivity research often related to lacking data on processes, their dynamics as well as on process-form relationships. Furthermore, it can be observed that many (if not most) connectivity studies in geomorphology rather tend to infer connectivity from different types of (obtained) data and results instead of operationalising the concept of connectivity by actually quantifying connectivity. An important development within geomorphology has been the application of network analysis approaches derived from graph theory which allows for a more robust quantification of connectivity (e.g. see Sonke et al., 2021; Hiatt et al., 2022 in this SI). Network-based approaches are promising as they allow for a quantitative interrogation of how dynamical processes are related to system structure (i.e. SC-FC relations). Nevertheless, applications of network-based approaches require some rethinking of how to most appropriately represent geomorphic systems as networks, and critical evaluation of suitable network-based metrics to improve our understanding of these systems.

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