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Connectivity as an emergent property of geomorphic systems

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ABSTRACT: Connectivity describes the efficiency of material transfer between geomorphic system components such as hillslopes and rivers or longitudinal segments within a river network. Representations of geomorphic systems as networks should recognize that the compartments, links, and nodes exhibit connectivity at differing scales. The historical underpinnings of connectivity in geomorphology involve management of geomorphic systems and observations linking surface processes to landform dynamics. Current work in geomorphic connectivity emphasizes hydrological, sediment, or landscape connectivity. Signatures of connectivity can be detected using diverse indicators that vary from contemporary processes to stratigraphic records or a spatial metric such as sediment yield that encompasses geomorphic processes operating over diverse time and space scales. One approach to measuring connectivity is to determine the fundamental temporal and spatial scales for the phenomenon of interest and to make measurements at a sufficiently large multiple of the fundamental scales to capture reliably a representative sample. Another approach seeks to characterize how connectivity varies with scale, by applying the same metric over a wide range of scales or using statistical measures that characterize the frequency distributions of connectivity across scales. Identifying and measuring connectivity is useful in basic and applied geomorphic research and we explore the implications of connectivity for river management. Common themes and ideas that merit further research include; increased understanding of the importance of capturing landscape heterogeneity and connectivity patterns; the potential to use graph and network theory metrics in analyzing connectivity; the need to understand which metrics best represent the physical system and its connectivity pathways, and to apply these metrics to the validation of numerical models; and the need to recognize the importance of low levels of connectivity in some situations. We emphasize the value in evaluating boundaries between components of geomorphic systems as transition zones and examining the fluxes across them to understand landscape functioning. © 2018 John Wiley & Sons, Ltd.

Introduction

Connectivity has become a widely used conceptual framework within geomorphology. Our primary objectives in this paper are to: (i) facilitate careful consideration of how to define and measure connectivity and disconnectivity across diverse spatial and temporal scales; (ii) explore the implications of connectivity, including the situations in which connectivity provides a useful framework or new insight, potential signatures of connectivity in geomorphic systems, and how connectivity can be used in resource management; and (iii) highlight gaps in current understanding of connectivity and potential pathways for future research. We first introduce some basic characteristics of connectivity as viewed in a geomorphic context, then review both the historical underpinnings of and recent work on connectivity in geomorphology. We then discuss the challenges of identifying and measuring connectivity, use river basins to illustrate the management implications of connectivity, and conclude with a summary of key questions and challenges to understanding and using connectivity in a geomorphic context.

Connectivity in a geomorphic context

As the scientific study of surface processes and landforms, and as a discipline that has largely developed from geology and physical geography, geomorphology has come to focus upon the fluxes of fluids (air, water) and sediment and the landforms resulting from, and influencing, those fluxes. The term geomorphic systems recognizes couplings among seemingly discrete components of Earth's surface and near-surface environments, such as water and sediment fluxes from hillslopes that govern the configuration of river channels or fluxes of eolian dust that influence rates of soil formation in geographically distant locations (Martignier *et al.*, 2013). Attention to fluxes of material through landscapes dates to the founding of geomorphology as a discipline (Gilbert, 1880). The term connectivity has become widely used to describe these fluxes within the past two decades.

Several definitions of connectivity have been proposed (Table I). We define connectivity as the efficiency of transfer of materials between system components. Definition of system components varies between disciplines, such as between geomorphology and ecology, and in relation to the material under consideration (e.g. water versus sediment). Geomorphic systems can be represented as networks with compartments, links, and nodes. Using a drainage basin as an example, hillslopes and valley bottoms are compartments, channel segments are links, and channel junctions are nodes.

Connectivity has value as a conceptual framing for investigating the spatial and temporal variability of fluxes because it directs attention to: (i) interactions among geomorphic system components that may appear to be isolated in time and space, such as how relative base level fall triggers river incision and subsequent hillslope adjustments over timespans of 10^3–10^4 years (Burbank *et al.*, 1996); (ii) the response of diverse geomorphic systems to varying inputs, such as how water and sediment fluxes from individual drainage basins respond to extreme storms as a function of characteristics such as basin size, river network structure, and the temporal sequence of extreme storms (Cenderelli and Wohl, 2003); (iii) the specific features of geomorphic systems that govern connectivity, such as the landforms that limit sediment fluxes within a drainage basin (Fryirs *et al.*, 2007a); and (iv) how human alterations of geomorphic systems influence system behavior, such as how flow regulation and associated changes in water and sediment connectivity alter river geometry and biotic communities. Connectivity also has value as a common framing shared among disciplines (Tetzlaff *et al.*, 2007; Werner and McNamara, 2007; Larsen *et al.*, 2012; Puttock *et al.*, 2013; Hauer *et al.*, 2016).

Connectivity is not an either/or attribute, but rather a continuum. Consequently, representations of geomorphic systems as networks must recognize that the compartments, links, and nodes exhibit connectivity at differing spatial and temporal scales and include diffuse and concentrated fluxes, and variable rates of flux (Passalacqua, 2017).

Connectivity is typically limited to some degree through time and across space, so that understanding of one extreme of the continuum, disconnectivity, is equally important (Faulkner, 2008). Components or processes that are disconnected are those that either are too remote from each other in space or time, so that a change in one component or process does not lead to change in another, or those in which a threshold must be overcome to allow connectivity: a critical shear stress must be exceeded to allow sediment transport, for example, or a flow magnitude must be exceeded to overtop the channel banks and laterally connect the channel and floodplain. The end member of disconnectivity must be treated with caution because something that is disconnected at a short time scale may be connected at a longer time scale. In general, all measures of connectivity are dependent on time and space scales and are relational in the sense of describing transfers between components of a system (Grant *et al.*, 2017).

Figure 1 illustrates the temporal aspect of connectivity in a manner similar to Schumm and Lichty's (1965) conceptualization of variables changing between dependent and independent status over diverse time scales. In this figure, sediment transport is highly connected and continuous over longer time and larger space scales, but disconnected in time and space when considered over periods of years to decades that include substantial periods of lower flow without sediment transport. Analogously, the longitudinal profile may be continuously adjusting to fluctuations in relative base level and thus longitudinally connected over cyclic time scales, but segmented by the presence of knickpoints and thus less longitudinally connected over graded and steady time scales.

Investigations of connectivity and disconnectivity in geomorphic systems can focus on fluxes of different types of materials, such as water (Bracken *et al.*, 2013; Larsen *et al.*, 2017) or sediment (Fryirs *et al.*, 2007a; Bracken *et al.*, 2015; Li *et al.*, 2016). Investigations can emphasize features that enhance or limit connectivity, such as landforms that create physical thresholds which must be exceeded before material can move between compartments (Kondolf *et al.*, 2006; Fryirs *et al.*, 2007a). Alternatively, investigations can emphasize the magnitude, duration, frequency, strength, timing, or spatial extent of connectivity (Cote *et al.*, 2009; Cavalli *et al.*, 2013). Jaeger and Olden (2012), for example, used electrical resistance sensors to quantify the longitudinal extent and duration of stream flow in an ephemeral channel network in Arizona, USA.

Framing connectivity in a geomorphic context provides a basis for considering both structural and functional components of the landscape. What has been referred to as structural connectivity is dependent on the position and spacing of landscape units and the extent to which they are in contact or distant from one another (Wainwright *et al.*, 2011). Landscape units can vary from entire mountain ranges or drainage basins down to patches of land cover (e.g. forest versus grassland) or individual grass clumps on a hillslope with spatially discontinuous vegetation cover. Structural connectivity influences the thresholds of magnitude and duration necessary to create fluxes between individual landscape units. Floodplain wetlands adjacent to an active channel and at lower elevations may require a lower magnitude flood to achieve surface hydrologic connectivity with the channel than do floodplain wetlands farther from and/or higher than the channel (Galat *et al.*, 1997; Poole *et al.*, 2002). The occurrence of longitudinally continuous flow along intermittent or ephemeral channels in drylands depends partly on the magnitude and duration of precipitation inputs, but also on the structural connectivity governed by valley surface and subsurface geometry as this geometry creates alluvial reservoirs that must be saturated before surface flow occurs (Falke *et al.*, 2011; Jaeger and Olden, 2012).

Table I. Definitions and quantitative metrics of connectivity (after Wohl, 2017, Tables I and II)

A)

Definition	Reference
Connectivity in the context of landscape dynamics describes the transmission of matter and energy among system components	(Harvey, 1987, 1997, 2001, 2002; Godfrey *et al.*, 2008)
Hydrological connectivity as the exchange of matter, energy, and biota between different elements of the riverine landscape via the aqueous medium	Amoros and Roux, 1988
Hydrological connectivity can be defined as the physical linkage of water and sediment through the fluvial system.	Hooke, 2003; Lesschen *et al.*, 2009
Hydrologic connectivity refers to the water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle	Pringle, 2003
River hydrologic connectivity refers to the water-mediated fluxes of material, energy, and organisms within and among components, e.g. the channel, floodplain, alluvial aquifer, etc. of the ecosystem	Kondolf *et al.*, 2006
Static/structural connectivity: static elements of hydrological connectivity are spatial patterns, such as hydrological runoff units, that can be categorized, classified, and estimated; spatial patterns in the landscape (Turnbull *et al.*, 2008)	Bracken and Croke, 2007
Dynamic/functional connectivity: describes both the longer term landscape developments, such as changes following abandonment of agriculture, and short-term variation in antecedent conditions and rainfall inputs to systems that result in nonlinearities in hillslope and catchment response to rainfall; how spatial patterns interact with catchment processes to produce water transfer in catchments (Turnbull *et al.*, 2008)	Bracken and Croke, 2007
Process connectivity: the evolutionary dynamics of how systems operate; also defined as flow of information among a system's drivers, where information is a reduction of the uncertainty in a variable's state	Bracken and Croke, 2007; Passalacqua, 2017; Ruddell and Kumar, 2009
Three stages of landscape connectivity: coupled linkage when there is free transmission between landscape units; partial coupling when a discontinuity between units results in pulses of sediment movement; partly connected stage when there is a decrease of transmission due to impediments, but some material can pass the impediment during an effective event; buffers hinder lateral connectivity, barriers hinder longitudinal connectivity, and blankets hinder vertical connectivity	Fryirs *et al.*, 2007a; Jain and Tandon, 2010
Initiation of a shallow groundwater table across hillslope, riparian, and stream zones	Jencso and McGlynn, 2011
Hydrologic connectivity describes connection, via the subsurface flow system, between the riparian zone and the upland zone, which occurs when the water table at the upland–riparian zone interface is above the confining layer (Also presents 10 other definitions from the literature, categorized with respect to water cycle or landscape features at the watershed scale, and landscape features, spatial patterns, and flow processes at the hillslope scale)	Bracken *et al.*, 2013
Sediment connectivity: the degree of linkage that controls sediment fluxes throughout landscapes and in particular between sediment sources and downstream areas	Cavalli *et al.*, 2013
Sediment connectivity is the water-mediated transfer of sediment between two different compartments of the catchment sediment cascade; catchment disconnectivity can be expressed as the degree to which any limiting factor constrains the efficiency of sediment transfer relationships	Fryirs, 2013
Connectivity defined as the transfer of matter between two different landscape compartments	Wester *et al.*, 2014
Connectivity describes the integrated transfer of sediment across all possible sources to all potential sinks in a system over the continuum of detachment, transport, and deposition, which is controlled by how the sediment moves between all geomorphic zones; on hillslopes, between hillslopes and channels, and within channels.	Bracken *et al.*, 2015
Describe two fluxes as connected if they are in close spatial proximity along the river network; refer to connectivity as the state of two or more fluxes being connected; dynamic connectivity refers to how the connectivity of fluxes changes in time	Czuba and Foufoula-Georgiou, 2015
Defines five layers of hydrologic connectivity as hillslope, hyporheic, stream-groundwater, riparian/floodplain, and longitudinal within channels	Covino, 2017

B

Description	Metric	Reference
Primarily hydrologic metrics		
Integral connectivity scale lengths (ICSL)	Average distance over which wet locations are connected using either Euclidean distances or topographically defined hydrologic distances; 1 of 15 indices of hillslope hydrologic connectivity in Bracken *et al.* (2013: Table IV)	Western *et al.*, 2001
Attenuated imperviousness (I) $I = \left(\frac{\sum_j (A_j W_j)}{A_c}\right)$	Weighted impervious area as a percentage of catchment area; A_j is the area of the *j*th impervious surface; W_j is the weighting applied to A_j; A_c is catchment area	Walsh and Kunapo, 2009
River Connectivity Index (RCI) $DCI_P = \sum_{i=1}^{n} \frac{v_i^2}{V^2} * 100$	The size of disconnected river fragments between dams in relation to the total size of the original river network, based on Cote *et al.* (2009) DCI; size can be described in terms of volume (example at left), length, or other variables	Grill *et al.*, 2014

(*Continues*)

Table 1. (Continued)

B		
Description	Metric	Reference
Primarily sediment metrics		
Sediment delivery ratio (SDR) $SDR = \frac{\text{net erosion}}{\text{total erosion}}$	Measure of sediment connectivity	Brierley *et al.*, 2006
Connectivity Index (IC) $IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right)$ $D_{up} = \overline{W}\overline{S}\sqrt{A}$ $D_{dn} = \sum_i \frac{d_i}{W_i S_i}$ $W = 1 - \left(\frac{RI}{RI_{MAX}}\right)$ Roughness Index (RI) $RI = \sqrt{\frac{\sum_{i=1}^{25}(x_i - x_m)^2}{25}}$	D_{up} and D_{dn} are the upslope and downslope components of connectivity, respectively, with connectivity increasing as IC increases; $\overline{W}$ is the average weighting factor of the upslope contributing area, $\overline{S}$ is the average slope gradient of the upslope contributing area, and A is the upslope contributing area; d_i is the length of the flow path along the *i*th cell according to the steepest downslope direction, W_i and S_i are the weighting factor and the slope gradient of the ith cell, respectively; RI_{MAX} is the maximum value of *RI* in the study area; 25 is the number of processing cells within a 5 X 5 moving window, x_i is the value of one specific cell of the residual topography within the moving window, and x_m is the mean of the 25 cell values	Cavalli *et al.*, 2013
Complexity index based on overall relief Dh_{max} $Dh_{max} = E_{max} - E_{min}$ and slope variability *SV* $SV = S_{max} - S_{min}$	Where E_{max} and E_{min} are the maximum and minimum elevations, respectively, in the catchment; S_{max} and S_{min} are the maximum and minimum, respectively, % slope within the area of analysis (moving window)	Baartman *et al.*, 2013
Cluster Persistence Index (CPI) $CPI_i = \int_{\text{over all times } t} M_j^{(i)}(t)dt$	Defines clusters within a river network where mass (sediment) coalesces into a connected extent of the network; the superscript (i) denotes all clusters $M_j^{(i)}$ that occupy link *i* at time *t*	Czuba and Foufoula- Georgiou, 2015
Metrics for diverse fluxes		
$C(t) = \sum_{i=1}^{m(t)} \sum_{j=1}^{n_i(t)} p_{ij}(t)S_{ij}(t)$	Patch connectivity, along with line, vertex, and network connectivity, can be used to characterize landscape connectivity; patch connectivity is the average movement efficiency between patches; *C* is patch connectivity, $p_{ij}(t)$ is the area proportion of the jth patch in the ith land cover type to the total area under investigation at time *t*; *S* is movement efficiency; $0 \leq C(t) \leq 1.1$.	Yue *et al.*, 2004
$DCI = \frac{\sum_{i=1}^{v}\sum_{j=r+1}^{R} w_{ij}\frac{dx(j-r)}{d_{ij}}}{\sum_{i=1}^{v}\sum_{j=r+1}^{R} w_{ij}}$	Directional connectivity index (DCI); *i* is a node index, *j* is a row index, *r* is the row containing the node *i*, *R* is the total number of rows in the direction of interest, *dx* is the relative pixel length along that direction, d_{ij} is the shortest connected structural or functional distance between node *i* and any node in row *j*, w_{ij} is a weighting function	Larsen *et al.*, 2012
Adjacency matrix	Applies a connectivity analysis to a delta by identifying a set of objects (e.g. locations or variables) arranged in a network such that objects are nodes and connections or physical dependencies are links; evaluate connections between nodes using the mathematical technique of an adjacency matrix, which captures whether two nodes are connected, as well as link directionality and the strength of the connection	Newman *et al.*, 2006; Heckmann *et al.*, 2015; Passalacqua, 2017

The assemblage and spatial pattern of landforms (i.e. type, size, and adjacency) produces the structural, physical template from which to examine the extent to which interactions between landforms at different spatial and temporal scales occur. For example, Jain and Tandon (2010) and Hooke (2003) describe connectivity patterns in terms of whether landforms are connected, partially connected or discrete. Fryirs *et al.* (2007a) describe the position of landforms that act as blockages within the landscape. As water flows over landforms, elements that influence structural connectivity may be modified as the landscape evolves by weathering and erosion processes. The time scale of this evolution can be rapid, such as during large mass wasting events (Korup *et al.*, 2004), progressive over seasons and decades (Lane *et al.*, 2017), or acting over long-term time scales $>10^3$ years (Prasicek *et al.*, 2015).

Because we define connectivity as the efficiency of material transfer, we suggest that the structural configuration of geomorphic systems, although strongly influencing connectivity, be described as system configuration rather than structural connectivity. This leaves connectivity as referring specifically to what has been called functional connectivity.

Functional connectivity operates within this structural template. In geomorphic terms functional connectivity refers to the processes associated with the sources and fluxes of water, sediment, and solutes through a landscape and the transfer of those materials between multiple, contiguous structural components or between components of a system that are physically isolated except for relatively brief periods of connectivity (Jain and Tandon, 2010; Wainwright *et al.*, 2011). In analyses of functional connectivity, the strength of connectivity or linkage between

Geomorphic Process	Cyclic	Graded	Steady
Sediment transport	↑ connected	↓ connected	↓ connected
bedload	↑ connected	↓ connected	↓ connected
suspended load	↑ connected	↓ connected	↑ connected
Knickpoint retreat	↑ connected	↑ connected	± connected
Planform adjustments	↑ connected	↓ connected	± connected
Longitudinal profile evolution	↑ connected	↓ connected	± connected
Drainage network development	± connected	↑ connected	↑ connected

decreasing length of time →

Figure 1. Variations in connectivity of example geomorphic processes as a function of the time scale under consideration. Cyclic, graded, and steady time scales indicated as orders of magnitude in years. Upward and downward arrows indicate greater and lesser degrees of connectivity, respectively, and ± indicates either option. (After Schumm and Lichty, 1965, Table I.)

different parts of landscapes is considered. These linkages may be strong, weak, or non-existent (i.e. disconnected). Functional connectivity emphasizes the need to think about how the landscape limits the connectivity of the material under consideration, whether water, sediment, or nutrients. Frameworks for assessing hydrological connectivity and sediment connectivity and how these fluxes function in geomorphic terms have been developed and applied in many different landscape settings in order to understand landscape change through time and to develop strategies for managing landscape processes (Fryirs *et al.*, 2007b; Lane *et al.*, 2009). Lane and Milledge (2013), for example, used a catchment-scale model to evaluate the effect of shallow upland drains on flow hydrographs. Lisenby and Fryirs (2017a) compare the spatial distributions of landforms expected to influence coarse-sediment transport to downstream patterns of bed-sediment fining and evaluate the effects of landform-induced disconnectivity on sediment size distributions.

The configuration and state of the system under consideration strongly influence the expression of connectivity (Gran and Czuba, 2017; Rice, 2017). Increasing landscape morphological complexity can correspond to decreasing connectivity (Baartman *et al.*, 2013), for example, and segments of a river network with wider valley bottoms can produce longitudinal and lateral disconnectivity in fluxes (Fryirs, 2013; Wohl *et al.*, 2017b). The state of the system includes the capacity for adjustment and proximity to thresholds, as well as location within an evolutionary trajectory or spatially within a larger system (Brierley and Fryirs, 2016). Configuration and state are interrelated. Places in a river network with local sediment disconnectivity, for example, can accumulate sediment through time and become sites with higher potential for geomorphic change, or they can be areas that absorb change and limit manifestation of disturbance at off-site locations (Czuba and Foufoula-Georgiou, 2015; Lisenby and Fryirs, 2017a, 2017b).

Structural and functional connectivity are tightly interwoven. Many studies focus on how the spatial template created by structural configuration interacts with variations in available energy to drive spatial and temporal fluctuations in functional connectivity (Jencso *et al.*, 2009, 2010; Jensco and McGlynn, 2011; Souza *et al.*, 2016; Wohl *et al.*, 2017b). Croke *et al.* (2013) and Thompson *et al.* (2016), for example, use longitudinal variations in valley-bottom configuration and the measured and modeled extent of floodplain inundation during an extreme flood to infer connectivity between channel and floodplain. Other investigations examine how changes in structural configuration alter functional connectivity (Puttock *et al.*, 2013; Segurado *et al.*, 2015) or how changes in available energy or material inputs to a geomorphic system create simultaneous changes in structural configuration and functional connectivity (Wester *et al.*, 2014; Micheletti *et al.*, 2015). Vanacker *et al.* (2005) provides an example of how changes in structural configuration can alter functional connectivity by relating changes in the spatial distribution of agriculture and forested lands within a catchment in the Ecuadorian Andes to river channel response. Although the overall land use did not change, the changed spatial distribution of land use altered water and sediment connectivity within the catchment, resulting in channel narrowing, incision, and streambed fining. Wester *et al.* (2014) provides an example of how changes in energy and material inputs can alter structural configuration and connectivity by quantifying changes in morphodynamics and sediment transport on hillslopes following wildfire and rainstorms.

A reliable connectivity framework should allow for analysis of both the static and the dynamic aspects of landscapes, and therefore be flexible enough to consider structural configuration and functional connectivity over varying timeframes. Static frameworks provide a snapshot of how the landscape is structured and functioning at any particular point in time. Dynamic frameworks recognize three key factors. First, the structure of the landscape can change and therefore the type, position, and pattern of landforms in a landscape can change, producing alterations in connectivity. Second, the strength of functional connectivity is likely to change in association with changes to structural configuration. Third, structural configuration and functional connectivity may change depending on the magnitude of the disturbances that drive fluxes of water and sediment through landscapes (e.g. rainfall, floods, or mass wasting).

A common theme among investigations of connectivity is the response of a system to some change or lack of change in boundary conditions that may be external to the system (e.g. climate or tectonic inputs) or internal within the system (e.g. fluxes of water and sediment). Boundary conditions can vary depending on the time and space scales of the investigation. How such conditions, and their changes, are transferred to an output depends on the system configuration, which may also vary with time and space scales in response to the changes in flux caused by those boundary conditions (Romans *et al.*, 2016). Thus, changes in boundary conditions can be modified – either dampened or amplified – by linked sets of processes operating within the system. Resulting outputs may always converge or, more likely, be unique but similar in magnitude and frequency. For example, a mountainous drainage basin considered over the timespan of a century has relatively fixed boundary conditions such as the river network configuration and geometry of individual valley segments. Varying boundary conditions include inputs of water and sediment from adjacent uplands. Outputs fluctuate across space and through time in a manner that reflects river network configuration and valley geometry, but also water and sediment inputs at any point in time, as well as the history of water and sediment inputs and associated changes in the alluvial configuration of the channel and floodplain within valley segments (Figure 2). This conceptualization of connectivity focuses on how efficiently change is communicated to an output and therefore which processes and links need to be studied to effectively understand a geomorphic system.

Fluxes can also be conceptualized as information propagation, which Ruddell and Kumar (2009) define as the contribution of uncertainty-reducing or predictive information provided by the time lag history of one variable to the future value of another (Figure 3). In this conceptualization, the key questions become whether information can be propagated and how information propagation can be discontinuous in space and time (degree of connectivity), how it is propagated (processes of connectivity), and what is the transfer entropy of information propagation (defined as the asymmetric information flow between two variables, or directionality of connectivity; Schreiber, 2000).

Although structural configuration and functional connectivity are tightly interrelated, functional connectivity is the focus of most studies of connectivity in geomorphic systems. Consequently, connectivity refers primarily to functional connectivity in the rest of this paper unless stated otherwise.

Connectivity research in geomorphology: origins and current focus

Historical underpinnings of connectivity in geomorphology

The historical underpinnings of connectivity in geomorphic systems emerged from two fundamental perspectives. One involves the cultural or societal management of geomorphic systems, such as river basin management for flood control, irrigation, and water supply (Kondolf *et al.*, 2006). The other perspective involves basic and applied observations linking Earth surface processes to landform dynamics, such as source to sink connections linking erosion, transport, and deposition to processes of hillslope and valley formation (Harvey, 1987; Anthony and Julian, 1999; Warrick *et al.*, 2015). These origins can be traced back thousands of years and are still relevant in a contemporary context for why connectivity in geomorphic systems merits our attention (Table II).

The earliest known societal actions seeking to understand and to measure connectivity in geomorphic systems can be traced back to at least 5000 BC when the Sumerians and the Egyptians engineered elaborate projects to manipulate the movement and storage of river water for flood control and irrigation (Newson, 1997). These and subsequent manipulations of geomorphic systems and associated changes in connectivity were sometimes undertaken in ignorance of basic aspects of the hydrologic cycle. Perhaps the most fundamental question faced by early naturalists confronted with a river was the source of continued flow in the absence of precipitation (Tuan, 1968; Duffy, 2017). Although notions regarding the hydrological cycle can be traced back to much earlier (Duffy, 2017), it was not until Bernard Palissy formally elucidated the hydrological cycle in the late 16th century that a comprehensive account of the connectivity between the ocean, atmosphere, precipitation, and river systems was developed (Karterakis *et al.*, 2007).

Italian and French Renaissance scholars, *c.* 1400–1800, examined landscape-scale processes of erosion, transport, and deposition, and their role in creating channel networks on the landscape and major river valleys (Hugget, 2007). In the 18th and 19th centuries, Scottish geologists James Hutton and John Playfair made many of the same observations regarding the role of erosion as a dominant force on the landscape, noting that rivers are systematically ordered from smaller headwater streams to progressively larger rivers. The underlying concept that a river is connected to, and is responsible for forming the landscape – particularly the valley – through which it flows, is usually attributed to Playfair (1802). During the 19th century,

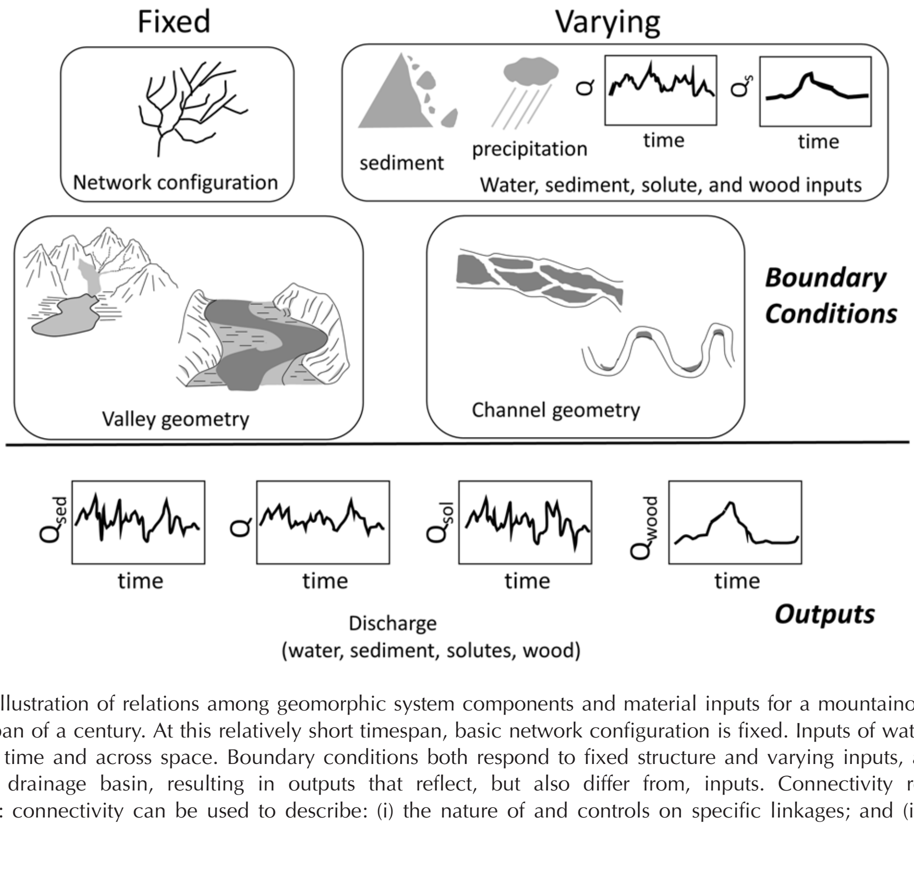

Figure 2. Schematic illustration of relations among geomorphic system components and material inputs for a mountainous drainage basin considered over the timespan of a century. At this relatively short timespan, basic network configuration is fixed. Inputs of water, sediment, and other materials vary through time and across space. Boundary conditions both respond to fixed structure and varying inputs, and influence fluxes of materials through the drainage basin, resulting in outputs that reflect, but also differ from, inputs. Connectivity represents one way to express these relations: connectivity can be used to describe: (i) the nature of and controls on specific linkages; and (ii) the evolving state of the drainage basin.

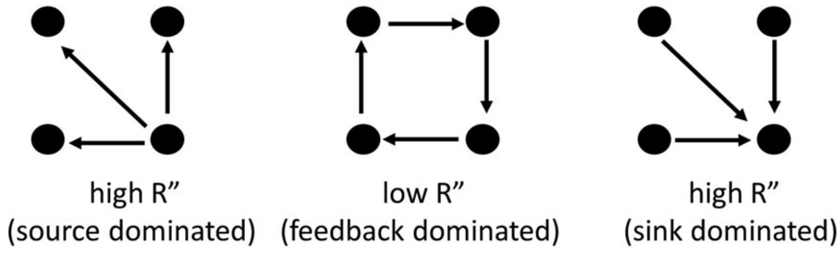

Figure 3. Schematic illustration of connectivity as information propagation. This figure illustrates network feedback statistics for three example cases on a four-node network. R″ is the surrogate source–sink redundancy, a measure of the topology of the network's couplings. Flows from a single source dominate the network on the left, resulting in a higher value of R″. Circular flows dominate the network in the middle, resulting in minimum R″ and feedback dominance. Flows into a single sink dominate the network on the right, resulting in a higher value of R″. (From Ruddell and Kumar, 2009, Figure 1.)

Table II. Historical (5000 BC–early 1900s) contributions to connectivity in geomorphic systems from a fluvial perspective. Selections from Hugget (2007), Newson (1997), Gregory and Lewin (2014) and authors' discretion

Mesopotamia, Sumerians (5000–3000 BC): Hydraulic-based irrigation and flood control projects of the Tigris and Euphrates via canals and drainage of floodplains and marshlands.

Egypt, Egyptians (5000–2000 BC): River and society connections involving water supply, irrigation, and flood storage projects. Collection of river levels using the Roda 'nilometer' for predicting lateral river–floodplain connections for irrigation and flood control.

Emporer Yu the Great, China (2200–2101 BC): River network and basin mapping, and engineering of flood control using dikes, dams, dredging, and irrigation canal systems.

Lucius Anneaus Seneca (4 BC–AD 65): Roman philosopher recognition that rivers erode and create their valleys.

Claudius Ptolemy (100 AD–168 AD): Greek–Egyptian scientists depicted the first river basin map of the Nile connecting the 'Mountains of the Moon' headwaters to the 'Upper, Middle, and Lower Lands' and eventually with the Mediterranean Sea.

Leonardo DaVinci (1452–1519): Italian renaissance scholar illustrated how rivers carved valleys and moved materials from one place and deposited them in another, and painted the first slope-contoured, shaded relief drainage map of the Arno River in Italy (1502–1503), complete with head-waters, tributaries, and main stem river connections.

Giovanni Targioni-Tozzetti (1712–1784): Italian scholar observed that river patterns and the courses they took in their valleys were a function of the lithology and processes of differential erosion.

Jean-Étienne Guettard (1715–1786): French naturalist recognized mountain to sea connections, i.e. sediment eroded from mountains was deposited as floodplains or carried to the sea.

James Hutton (172–1797): Scottish geologist who recognized erosion was the dominant forces carving large river valleys. Hutton also engineered hydrologic connections on the landscape by building canals for navigation and water supply.

John Playfair (1748–1819): Scottish professor who expanded on Hutton's ideas, and showed that channels form in systematic order, whereby small rivers drain into larger rivers and so forth, until you have a mainstem river and valley complex, and that these river networks are organized into drainage basins.

Captain Henry M. Shreve (1785–1851): American soldier, artificially cut a neck through 'Turnbull's Bend' on the Mississippi River disconnecting the river from its preferred path down the Atchafalaya in 1831. This led to the construction of the Old River Control Structure in 1963, which has permanently controlled the course of the river ever since.

George Perkins Marsh (1801–1882): American environmentalists pioneered early understanding of human-induced land cover and land use changes and their connections to impacts to land and water processes.

Charles Darwin (1809–1882): English explorer observed rivers as agents of erosion, attributed anthropomorphic terms youth, middle age, old age, and rejuvenation to cycles of landscape evolution.

John Newberry (1822–1892): American geologist recognized that rivers carved tremendous canyons, i.e. Grand Canyon, through the terrain of the American West.

John Wesley Powell (1834–1902): American soldier, professor, and head of USGS (1870–1892), first scientists to descend the Colorado River system from its headwaters. Established hydrologic surveys for commissioning of western US dams.

Grove Karl Gilbert (1843–1918): American geologists contributed substantially to our understanding of geomorphology as an open system of inputs, outputs, and fluxes of energy and material exchanges from his work in the western US and most notable his regional geologic-geomorphic descriptions of the Henry Mountains, Utah. Described landscape evolution through processes of erosion, incision, transport, and deposition.

Robert Horton (1875–1945): Textbook father of network-based stream order patterns from topographic analysis, and applications of stream order to quantifying drainage basin sizes, accumulation through a network, hill-slope erosion, and runoff processes.

John T. Hack (1913–1991): Established early theories of dynamic equilibrium and steady state models that described geomorphic processes and forms changing relative to a balanced steady state of inputs and outputs.

Luna B. Leopold (1915–2006): Established field methods for quantifying fluvial forms and processes, by understanding connections among sediment sources, transport, and deposition.

Arthur N. Strahler (1918–2002): Advanced Horton's stream order concepts into the format commonly used today, and contributed to quantitative methods for measuring other morphometric indices and hillslope erosion processes.

M. Gordan 'Reds' Wolman (1924–2010): Established field methods for quantifying fluvial forms and processes, with a focus on floodplain depositional styles and the importance of drainage basin and local scale controls.

Richard Chorley (1927–2002): Introduced complex system theory to geomorphology through sub-system classification of morphological, cascading, process-response, and control systems.

Stanley Schumm (1927–2011): Developed concept of sediment budgets as a method for quantifying sediment sources, transport, and sinks through a drainage basin and for measuring sediment yield.

James C. Knox (1941– 2012): Provided significant evidence that human-induced changes have substantially more sedimentation impacts to rivers and floodplains than natural, climate-driven changes. Knox's work underscores the importance of why understanding river–landscape connectivity dynamics is critical to how we interpret geomorphic form, process, and management practices.

this perceived connectivity between the river and the landscape that it drains prompted the recognition that geomorphic effects could propagate through the landscape, linking, for example, deforestation on slopes and floods in channels (Marsh, 1864). Indigenous peoples and Asian civilizations may have recognized these forms of connectivity earlier, but the contemporary geomorphic tradition largely derives from western Europe and North America.

Early human modifications of river connectivity in the United States occurred during 19th century artificial river cutoffs and wood removal (Table II). Human manipulations of connectivity in US rivers continued with hydrologic surveys conducted by John Wesley Powell that led to the commissioning of numerous large dams on western rivers. After the pace of dam building increased to a peak in the mid-20th century in the US and western Europe, subsequent recognition of the detrimental effects of altered connectivity within river corridors drove efforts to remove dams or modify their operating regime (Bednarek, 2001). Another widespread form of river engineering, the channelization of large meandering or anastomosing rivers such as the Danube (Pisut, 2002) and the Rhine (Diaz-Redondo *et al.*, 2017) in Europe during the latter half of the 19th century also resulted in increased longitudinal connectivity and reduced lateral connectivity for water and sediment.

During this 19th century period of intensified river engineering, geomorphology was being established as a scientific discipline and with that grew a conceptual framework that described landforms relative to systems theories and linkages between process and response dynamics. GK Gilbert, a prominent founder of geomorphology in the United States, was the first to discuss feedbacks among inputs, outputs, and exchanges of material and energy through geomorphic processes (Gilbert, 1877).

In their modern incarnations, the principles of geomorphic connectivity draw heavily on historical antecedent ideas of the watershed as a fundamental unit, the linkages between process and form, and the importance of understanding how materials and disturbances propagate through watersheds. A century after Gilbert's seminal 1877 publication on the geology of the Henry Mountains, for example, Chorley and Kennedy (1971) defined the geomorphic system as a process–response complex consisting of two interacting sub-systems – the morphological system and the cascading system. The morphological system includes the physical, geomorphic landforms on Earth's surface and the cascading system includes the energy and mass/material fluxes interacting with the morphology of the landforms. One sub-system cannot function independently of the other and collectively they function relative to process–response dynamics that vary in space and time, and at varied scales of space (spatial area considerations) and time (temporal period or rate consideration). Within the connectivity framework, the morphological system defines the structural connectivity and the cascading system represents the functional connectivity.

Chorley and Kennedy's (1971) coupled process–response complex, and the transfer of energy and matter between landforms and within the system, represents the first mention of connectivity in geomorphology. This work built on the classic equilibrium theory of cyclic, graded, and steady time (Schumm and Lichty, 1965) and threshold-lag-reaction-recovery equilibriums of dynamic, dynamic meta-stable, and steady time (Chorley and Kennedy 1971; Schumm, 1979; Chorley and Beckinsale, 1980; Graf, 1988).

Brunsden and Thornes (1979) advanced the concepts of process–response coupling by contending that the process of landscape change is driven by the capacity of the landscape to transmit an impulse between system components, and that the capacity is controlled by the landscape connection between components (described as path density) and the strength of the coupling (how (in) directly the impulse is transmitted). The sensitivity of landscape change is then determined by the rate of response. Highly connected and strongly coupled systems respond quickly and are commonly more morphologically complex, whereas less-connected and weakly coupled systems respond slowly and are less complex (Brunsden and Thornes, 1979). These ideas are direct predecessors of the concepts of information propagation (Ruddell and Kumar, 2009) and network-based graph theory (Heckmann *et al.*, 2015).

Other major historical contributions linking landscape connectivity to geomorphic systems involved the development of methods and techniques for quantitatively measuring drainage basin morphometry and surface runoff (Horton, 1945; Strahler, 1952, 1954). The classic Horton (1945) and Strahler (1954) stream ordering methods also represent one of the few spatial connectivity metrics shared across biological and physical disciplines for communicating structural and functional properties of riverine ecosystems (Stanford and Ward, 1992). The foundations for quantifying stream morphometry using network- and areal-based measurements (Gardiner, 1975) provided a spatial and conceptual framework for organizing river basins relative to dominant processes, such as the production, transport, and, deposition zones described by Schumm (1977). These spatial frameworks led to advances in analyzing source-to-sink sediment budget and sediment yield dynamics (Trimble, 1977, 1983; Walling, 1983) and later to disturbance-driven geomorphic process-domains organized along a river continuum (Montgomery, 1999).

Geomorphic understandings of process–response coupling and its role in landscape sensitivity to change (Brunsden, 1993, 2001; Harvey, 1997, 2002; Nakamura *et al.*, 2000) and sediment budget fluxes (Dietrich and Dunne, 1978; Walling, 1983; Reid and Dunne, 2003, 2016) are increasingly incorporated within broader inter- and multi-disciplinary programs that integrate perspectives from hydrology, biology, ecology, and biogeochemistry with a focus on connectivity relationships (Wohl *et al.*, 2017a). Human manipulations of land cover, topography, and river corridors have strongly altered connectivity across diverse landscapes (Pringle, 2003; Hooke, 2006; Fryirs, 2013). River restoration is now the most widely practiced management action explicitly designed to mitigate some of the negative aspects of past human-induced alterations of connectivity (Buijse *et al.*, 2002; Kondolf *et al.*, 2006; Magilligan *et al.*, 2016a). Consequently, it is important to highlight that although recognition of the importance of geomorphic connectivity may seem like a relatively recent development, its roots are deep.

Current work on connectivity

In the last two decades, research using connectivity as a conceptual framework has experienced a boom in geomorphology, developing new or adapting already existing concepts of connectivity to better understand system complexity and response to change (Bracken *et al.*, 2013, 2015; Poeppl *et al.*, 2017). In this context, geomorphologists have also begun to assimilate notions of connectivity from other disciplines, especially ecology (Merriam, 1984; Amoros and Roux, 1988; Ward and Stanford, 1989; Ward, 1997) and hydrology (Pringle, 2001, 2003) (cf. Bracken and Croke, 2007; Poeppl *et al.*, 2017), seeking to better describe water and sediment dynamics in catchment systems (Croke *et al.*, 2005; Brierley *et al.*, 2006; Fryirs *et al.*, 2007a, 2007b; Turnbull *et al.*, 2008; Wainwright *et al.*, 2011; Fryirs, 2013; Gomez-Velez and Harvey, 2014; Bracken *et al.*, 2015; Lisenby and Fryirs, 2017a, 2017b). Depending on the respective disciplinary basis, three types of connectivity have commonly been differentiated in geomorphic contexts, although all of the types are interdependent: (1) sediment connectivity, which is the potential for sediment to move through geomorphic systems (Hooke, 2003) as governed by the physical coupling of landforms; (2) landscape connectivity, which is the physical coupling of landforms; and (3) hydrological connectivity, which describes the passage of the transporting medium from one part of the landscape to another. Structural configuration and functional connectivity are inherent in each of these types of connectivity.

Considerations of sediment connectivity in geomorphology are generally rooted in: (i) sediment budget approaches, emphasizing how the distribution of sediment stores and sinks reflect and influence the travel distances and pathways of sediment movement in geomorphic systems; or (ii) hillslope–channel connectivity (Harvey, 2012; Li *et al.*, 2016), catchment-scale sediment tracing (Fryirs and Gore, 2013), or continuum-based approaches using the concept of hydrological connectivity (Lexartza-Artza and Wainwright, 2009, 2011; cf. Bracken *et al.*, 2015). In an ecological context, hydrological connectivity was defined by Pringle (2001) as being the water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle. Prior to that, stream ecology conceptual models including the river continuum concept (Vannote *et al.*, 1980), the flood-pulse model (Junk *et al.*, 1989), and the serial discontinuity concept (Ward and Stanford, 1983) emphasized the ecological implications of diverse forms of connectivity. Ecological approaches to connectivity have been assimilated by hydrologists, resulting in a novel framework for understanding runoff and run on in catchment systems (Bracken and Croke, 2007; Ali and Roy, 2009).

Landscape connectivity has been defined in landscape ecology as being the degree to which a landscape facilitates or impedes the movement of individuals (Taylor *et al.*, 1993). Similar notions regarding the role of structural landscape characteristics in a geomorphic context can be found in the coupling concept of Brunsden and Thornes (1979) and, later, in conceptualizations of the four-dimensional nature of lotic ecosystems (Ward, 1989). Brierley *et al.* (2006) elaborated these ideas and developed a connectivity framework in which they characterized different forms of landscape connectivity based on the position of geomorphic processes in a catchment (i.e. longitudinal, lateral, and vertical connectivity), explaining the efficiency of sediment transfer relationships within catchment systems (see also Fryirs et al., 2007a, Fryirs et al., 2007b). In bio-geomorphic floodplain systems, the four dimensions of connectivity provide a framework to examine hydrologic-mediated exchanges of organisms, nutrients, carbon, and energy (Zeug *et al.*, 2005; Opperman *et al.*, 2010; Kupfer *et al.*, 2014; Matella and Merenlender, 2015).

Also following ecological literature (Turner, 1989), geomorphologists drew a distinction between structural connectivity as the extent to which landscape units are physically linked to one another (With *et al.*, 1997; Tischendorf and Fahrig, 2000; Turnbull *et al.*, 2008; Wainwright *et al.*, 2011) and functional connectivity as accounting for the way in which interactions between multiple structural characteristics affect geomorphic processes (Kimberley *et al.*, 1997; With *et al.*, 1997; Turnbull *et al.*, 2008; Wainwright *et al.*, 2011; Bracken *et al.*, 2015). Recent studies have suggested that geomorphic system response to change can be governed by feedback relationships between structural configuration and functional connectivity (Turnbull *et al.*, 2008; Wainwright *et al.*, 2011; Bracken *et al.* 2015; Poeppl *et al.*, 2017). These structural–functional feedback relationships further drive a variety of bio-geomorphic interactions in river systems (e.g. exchanges of water, sediment, and propagules) that influence coupled landforms and development of biotic communities (Hupp and Bornette, 2003; Osterkamp and Hupp, 2010; Meitzen and Kupfer, 2015).

Identifying signatures of connectivity in the geomorphic record

One of the challenges of a conceptual framework designed around connectivity is to identify signatures of differing degrees of connectivity in contemporary geomorphic processes and in sedimentary or other records of past processes. The first instinct when looking for a signature of connectivity is to detect changes in a measurement that corresponds to, for example, an input to the system. From a hydrological perspective, this may be looking for a peak in a hydrograph in response to a storm. From a sediment perspective, this could be identifying a pulse of increased eolian dust inputs that affects rate of soil formation. From a geomorphic perspective this may not be quite so straightforward, however, for at least two reasons. First, a peak in, for instance, water or sediment output at a point in space partly reflects what is happening in the basin above that point, but several different combinations of events or circumstances may give rise to this response (equifinality) (Chorley, 1962). Second, the geomorphic response is governed by the availability of transporting mechanisms such as water but also the supply of sediment and the landscape configuration as shaped by the history of sediment-transporting flows (Harvey, 1997; Cenderelli and Wohl, 2003). This implies that the geomorphic system has a more effective memory of past events than the hydrological system, in which memory can (literally) evaporate. Therefore, the connectivity signature may be better represented with a spatial metric that encompasses how geomorphic processes operate over time and space. Examples of this include DEMs of difference (DoD) in which topographies from different time periods can be compared to indicate where there have been elevation changes and thus erosion and deposition (Lane *et al.*, 1994; Wheaton *et al.*, 2010). The use of this method has been greatly aided by the recent widespread availability of high-resolution lidar topographic data (Jones *et al.*, 2007; Passalacqua *et al.*, 2015; Clubb *et al.*, 2017).

Geomorphic responses that represent changes in connectivity are highly nonlinear. Commonly controlled by erosional thresholds such as slope failure angles or entrainment thresholds in bedload transport, the response of a landscape or drainage basin to different magnitude forcings can thus be complex. Evidence of this is widespread throughout geomorphic studies, dating to Schumm's work on complex response (Schumm, 1973) as well as more recent modeling work (Coulthard and Van De Wiel, 2007). Modeling the geomorphic response of basins to climate change, Coulthard *et al.* (2012) show how increases in rainfall magnitude lead to linear increases in water outputs but exponential increases in sediment delivery. This is driven partly by thresholds in sediment transport but also by spatial and temporal changes in availability of sediment, which in turn are contingent upon the basin's past history of events.

When viewing river bedload transport, Jerolmack and Paola (2010) argue that sediment transport processes can act as a nonlinear filter which can completely erase (or 'shred') the original characteristics of an environmental signal (i.e. its relative magnitude and duration). The degree of this shredding is thought to depend on the ratio between the signal frequency and the time scale of 'morphodynamic turbulence' in the system (Jerolmack and Paola, 2010). When signal frequency is shorter than the turnover induced by turbulence, the signal is lost.

This framework can also help explain why some events and/or systems can faithfully record responses to large signals

(Romans *et al.*, 2016). One example appears to be the response of suspended sediment in mountain rivers to large-scale landslide sediment inputs triggered by earthquakes (Hovius *et al.*, 2011; Wang *et al.*, 2015). Recent work following the 2008 Mw7.9 Wenchuan earthquake shows immediate (hourly time scale) and multi-annual increases in river suspended sediment concentration and sediment flux following the event (Wang *et al.*, 2015). These observations mirror river suspended sediment data following the 1999 Chi-Chi earthquake in Taiwan (Hovius *et al.*, 2011) and records of sand, silt, and mud accumulation in lakes fed by catchments draining the Alpine Fault in New Zealand over the last ~1000 years (Howarth *et al.*, 2012). These steep mountain catchments have elements of structural connectivity that can greatly enhance the transfer of landslide sediment to river channels (Li *et al.*, 2016). In addition, the erosion and transfer of suspended sediment viewed from the framework of Jerolmack and Paola (2010) may be considered as the morphodynamic equivalent of laminar flows; i.e. the nonlinear responses may be less important. Clearly, the internal operation of sediment transport systems needs to be considered when examining records in the context of understanding connectivity.

Choice of metric will also heavily influence the signature. Above, we used the example of sediment output at a point, but other metrics commonly used include slope–area products and hypsometric curves (Sternai *et al.*, 2011; Hancock *et al.*, 2016). Although these provide useful overall indicators of different landscape shapes or form, such metrics can be relatively insensitive to alterations and changes in the landscape that are highly apparent in a visual comparison. For example, Hancock *et al.* (2016) show how simulated landscapes with very different drainage networks and forms have very similar landscape statistics. Furthermore, landscapes and sedimentary records are palimpsest in that they can be erased and re-written. Therefore, a record of past changes, and indeed a whole landscape, may be incomplete as an indicator of what has driven its final form.

All the above issues are likely to be affected by the scale of study. For example, simple first-order streams, with limited degrees of freedom to store sediment and then allow this sediment to be re-mobilized, may respond more linearly to forcing than larger second-, third- or higher-order streams (Trimble, 2013). Here, larger expanses of, for example, floodplain may absorb any stratigraphic change that represents a signature of connectivity or generate false signals through autogenic processes. Temporally, this also affects what type of signature we are looking for. A tectonic signal operating over a long time scale may override the autogenic processes and other factors, muddying or masking the signal. But these processes and factors may be very important when looking for the connectivity signature from a large event (Goodbred, 2003; Jain and Tandon, 2010).

Continual deposition has the potential to serve as an indicator of connectivity, but only at the temporal and spatial scale of the deposit. The depositional record of a limited area does not indicate how far up channel or gradient the connectivity may have extended into the transport and erosional zones, although sediment fingerprinting (Walling *et al.*, 1999) can be used to infer the extent of longitudinal connectivity. Because of thresholds and complex response, however, a lack of uniformity does not necessarily indicate disconnectivity except at the smallest time scales of depositional processes. Examples include autogenic rhythmites at time scales of 1 to 100 s; slipface bedding planes at hourly to weekly time scales; and repeating sequences resulting from complex basin response at annual to centennial time scales (Schumm, 1981). In all these cases, the flux driving the deposition could be described as disconnected at time scales smaller than the signal frequency, but connected at greater time scales.

Uniformity and cyclicity can thus be considered indicators of connectivity within the lateral extent of a deposit over the relevant time scale, but their absence does not preclude connectivity. A reach in steady-state equilibrium, which is passing the exact amount of sediment received, is certainly well connected, but it will leave no trace of its role as a connecting part of the landscape. A basin may receive a particular sequence of sediments from its connected source areas, but the lack of repeating cycles does not necessarily negate its connectivity.

Thus, a depositional approach to identifying connectivity is limited to the spatial extent of the deposit or to the linkages that can be inferred from sediment characteristics via techniques such as sediment fingerprinting. Similarly, nothing can be said with certainty about connectivity below the temporal resolution of the stratigraphy. If a daily pulse of sediment slowly builds a delta, then the system would be disconnected at some time scale shorter than a day, but connected at any scales longer than a day. The bedding resolution is the temporal dividing line. Viewed in the opposite sense, if connectivity is a critical filter in the interpretation of upstream forcing (e.g. climate), inferring changes in that forcing without considering connectivity may be incorrect (Lane *et al.*, 2017).

In summary, issues around spatial and temporal scale of measurements or depositional records, as well as the existence of equifinality and nonlinearity in geomorphic systems, pose fundamental challenges to identifying connectivity. Consequently, the methods used to identify connectivity vary substantially among studies in relation to the specific aspects of connectivity under consideration (Table III). This is unlikely to change in the future. Most of the methods listed in Table III are based on inferred connectivity as reflected in landscape changes through time or as simulated using numerical models calibrated against datasets that span limited time and space scales. Although the list in Table III is not exhaustive, the relative proportions of methods relying on direct measurements of fluxes versus inferred fluxes represent the proportions of these approaches in the geomorphic literature.

Measuring connectivity

Another basic challenge of a conceptual framework designed around connectivity is to quantify fluxes that reflect connectivity. Although connectivity provides a powerful conceptual framework for understanding geomorphic systems, there is currently a lack of consensus on how to measure and to compare connectivity quantitatively across temporal and spatial scales and between geomorphic systems (Bracken *et al.*, 2013; Wohl, 2017; Table I). This may be unavoidable given the issues discussed above that arise from the interest in diverse aspects of connectivity. At some level, however, the lack of consensus on connectivity metrics gives rise to many challenging questions we are currently unable to answer quantitatively. Examples include questions of broad scope: is there a spatial scale at which landscape connectivity is most sensitive to human influences (Vanacker *et al.*, 2005)?; where and when is restoring connectivity an appropriate strategy (Kondolf *et al.*, 2006)? or, under what conditions are Eulerian versus Lagrangian frameworks more appropriate to developing insights into a particular geomorphic system (Doyle and Ensign, 2009)? Examples of more specific questions include: are deltas inherently more connected than dendritic drainage networks (Passalacqua, 2017)?; or can factors that determine thresholds governing longitudinal connectivity of mobile large wood in a river network be quantitatively predicted (Kramer and Wohl, 2017)? Although many studies have quantified connectivity, most have used approaches developed for the specific question at hand

Table III. Examples of methods used to identify signatures of geomorphic connectivity

Description	Sample references
Measured fluxes	
Used 40 years of erosion-pin data, along with sediment trap data and sequential aerial photos and floodplain surveys to measure and infer sediment fluxes from hillslopes to pediments, floodplains, and channels	Godfrey *et al.*, 2008
Measured precipitation, riparian water table, and stream flow and used these data as input to model hydrological connectivity	Jencso *et al.*, 2009
Used arrays of electrical resistance sensors to quantify longitudinal connectivity of flow through time in drylands rivers	Jaeger and Olden, 2012
Used piezometers and subsurface samplers to measure vertical hydraulic gradients and specific discharge as indices of vertical hydrological connectivity between a channel and hyporheic zone	Wainwright *et al.*, 2011
Inferred fluxes	
Catchment-scale sediment flow diagrams that identify spatial variability in patterns of sediment inputs, outputs, and storage based on direct measurements or, more commonly, spatial configuration of landscape units and relative volumes of stored sediment	Trimble, 1983; Fryirs *et al.*, 2007
Visual or morphologic assessments of characteristics (size, spatial distribution, function) of landscape units in relation to facilitating or retarding sediment connectivity	Brierley *et al.*, 2006
Modeled the delivery of landslide-generated sediment to channel networks; sediment generation from hillslopes and channel banks and its delivery to the channel network modeled using a modified form of SHALSTAB coupled to a network index version of TOPMODEL	Reid *et al.*, 2007
Because alkalinity of stream waters reflects relative influence of groundwater and unsaturated zone runoff, used alkalinity as index of hydrologic connectivity at catchment scale	Tetzlaff *et al.*, 2007
Used 1D hydrological modeling to infer hydrological connectivity among lakes and channels in the Danube River delta	Coops *et al.*, 2008
Used *in situ* water level and MODIS satellite data to relate mainstem river level fluctuations to delta inundation on Canada's Peace-Athabasca delta; temporal covariance between the two datasets allows inference of hydrologic connectivity processes, as well as inundation extent	Pavelsky and Smith, 2008
Used diatom sedimentary assemblages to discriminate between three categories of delta lakes with differing types of hydrological connectivity to the Slave River of Canada	Sokal *et al.*, 2008
Simulated runoff and sediment dynamics at the catchment scale with a dynamic landscape evolution model that can simulate erosion and sedimentation based on a limited number of input parameters	Lesschen *et al.*, 2009
Assessed hydrologic connectivity of the Mackenzie River and lakes on its delta from duration of 'connection time' based on elevation of sill height for a lake and daily river water levels from stream gage records	Tank *et al.*, 2009
Visual evaluation of location of sediment sources, degree of coupling to stream network, channel morphology, and magnitude of erosion and deposition following a rainstorm	Cavalli *et al.*, 2013
Used 2D simulation and river corridor topography to numerically model flood inundation extent for varying discharges and from this inferred lateral connectivity between channel and floodplain	Croke *et al.*, 2013
Field observations of surface-flow connectivity combined with topography of river corridor to infer relative degrees of hydrological connectivity among active channel and abandoned channel water bodies on the floodplain	Phillips, 2013
Numerically simulated coarse sediment transport via diverse geomorphic processes (rockfall, debris flows, slope wash, fluvial transport) and used these data in graph-based network analysis	Heckmann and Schwanghart, 2013
Data from ground surveys used with digital terrain model differencing techniques and morphological sediment budgets to infer sediment connectivity	Wester *et al.*, 2014
Measured rates of channel migration from sequential aerial photos used to identify locations of enhanced geomorphic change, which is inferred to reflect spatial variation in sand transport	Czuba and Foufoula-Georgiou, 2015
Used archival digital photogrammetry to reconstruct history of topographic change and inferred sediment fluxes in a catchment	Micheletti *et al.*, 2015
Represented sediment transport from each source in a watershed as a suite of individual cascading processes that are incorporated into an integrated modeling framework of sediment cascades that is used to infer patterns of connectivity and locations of disconnectivity	Schmitt *et al.*, 2016

(Bracken *et al.*, 2013, 2015; Wohl, 2017). Few studies have sought to develop connectivity metrics that are intended to be general and widely applicable. In this section, we review the wide variety of published methods for quantifying connectivity in geomorphic systems, and explore the opportunities and challenges for developing a general approach to measuring this elusive but vital attribute of landscapes.

Many questions arise in considering how best to measure connectivity, starting with whether connectivity is the state of a geomorphic system (structural connectivity) or a measurable flux (process connectivity)? Is it possible to quantify the essential aspects of connectivity in a single general metric, or are the dominant controls and manifestations of connectivity so varied that site-specific or process-specific metrics will always be needed (Blue and Brierley, 2016)? Are structural connectivity and functional connectivity more or less amenable to a standardized measurement approach? How sensitive are connectivity metrics to the methods and tools of data collection and the temporal and spatial scales of analysis? Should connectivity be measured directly or is it sufficient to quantify it indirectly, by measuring the factors that influence connectivity or its effects on landforms and material fluxes? Do we need a suite of metrics that can capture the cause and effect relationships among the drivers, attributes, and effects of connectivity? Can we as geomorphologists effectively forecast how connectivity relationships will alter geomorphic forms, processes, and fluxes brought about by climate and land use change? To address these questions, we begin by considering previously published connectivity metrics within a cause and effect framework, according to whether they provide a direct measure of connectivity or indirectly quantify the effects or the causes of connectivity.

Most studies of connectivity are motivated primarily by understanding how connectivity affects specific aspects of landscape dynamics, such as the movement of sediment between hillslopes and channels or through a stream network (Fryirs and Brierley, 2001; Fryirs, 2013; Bracken *et al.*, 2015; Gran and Czuba, 2017; Lane *et al.*, 2017). Hence, a straightforward approach is to quantify fluxes directly and to use those measurements to infer the degree of connectivity in the transport system, which represents a Eulerian approach. This can be done at a single point such as a catchment outlet or at many locations distributed through the system. Sediment transport processes, for example, are measured using erosion plots for small-scale measurements of sediment flux (Cerdà and García-Fayos, 1997; Wainwright *et al.*, 2000; Boix-Fayos *et al.*, 2006) or suspended sediment sampling methods and/or bedload traps in streams and rivers for larger-scale measurements (Garcia *et al.*, 2000; Bunte and Abt, 2005). In geomorphic connectivity research, functional connectivity is commonly inferred from measured water and sediment fluxes, either on the plot scale (Turnbull *et al.*, 2010; Wainwright *et al.*, 2011; Puttock *et al.*, 2013) or on the catchment scale (Duvert *et al.*, 2011; Lane *et al.*, 2017). Sediment tracers have been increasingly utilized to quantify erosion and deposition of sediments and to derive structural and functional connectivity of geomorphic systems (D'Haen *et al.*, 2013; Fryirs and Gore, 2013; Koiter *et al.*, 2013), which represents more of a Lagrangian approach.

The sediment delivery ratio (SDR) is one of the most widely-used indirect metrics of the effects of connectivity measured at a point along the boundary of the system (Walling, 1983; Brierley *et al.*, 2006; Fryirs, 2013; Baartman *et al.*, 2013). The SDR quantifies the fraction of mass eroded within an upstream catchment that is transported past the catchment outlet. The SDR varies between 0 and 1, thus providing an integrated, non-dimensional measure of the degree of connectivity of sediment sources and transport pathways within the catchment. Other studies that use output fluxes to infer upstream connectivity include Ali and Roy (2010), which measures stream discharge and infers connectivity of zones of high soil moisture, and recent work on deltaic systems which quantifies the hydrological connectivity of channels and interdistributary islands (Larsen *et al.*, 2012; Hiatt and Passalacqua, 2015, 2017), and relates sediment output from delta distributary channels to upstream connectivity between geomorphic elements of the delta system (Liang *et al.*, 2016c; Passalacqua, 2017).

In contrast to quantifying the bulk system output at a single point in space, metrics for the local effects of connectivity at many locations across the landscape are inherently more complex. This approach relies on a conceptual model of the internal dynamics of the system that facilitates identifying which sub-systems to measure and the scale and density of measurements. Numerical models can overcome this challenge by predicting outcomes for every point in the landscape. Modeling approaches include cellular automata (Baartman *et al.*, 2013; Masselink *et al.*, 2016a; Coulthard and Van De Wiel, 2017), process-based modeling (Mueller *et al.*, 2007), statistical models (Poeppl *et al.*, 2012), and GIS approaches based on network theory (Lane *et al.*, 2009; Heckmann and Schwanghart, 2013; Masselink *et al.*, 2016b). For example, Coulthard and Van de Wiel (2017) model changes in sediment fluxes due to the cascading impacts of land use change, and infer landscape connectivity across large distances and in both upstream and downstream directions. Czuba and Foufoula-Georgiou (2015) and Gran and Czuba (2017) use a model of sand transport through a natural channel network to indirectly quantify local connectivity by defining a cluster persistence index (CPI). The CPI is calculated from the time integral of sand mass passing a point in the network and identifies locations where discrete packets of sand coalesce and disperse due to longitudinal variations in transport connectivity. Examples of field-based studies that measure the local outcomes of connectivity include: Vanacker *et al.* (2005), which infers changes in water and sediment connectivity from measured changes in channel geometry and grain size; Croke *et al.* (2013) and Thompson *et al.* (2016), which use the measured and modeled extent of floodplain inundation during an extreme flood to infer connectivity between channel and floodplain; and Wester *et al.* (2014), which measures topographic elevation changes over time in gullies following wildfire to document spatial variation in sediment transport and deposition and infer patterns of local transport connectivity.

Connectivity in geomorphic systems has also been indirectly quantified through measurements of the key drivers that promote or inhibit connections in natural and human-disturbed landscapes (Bracken and Croke, 2007; Poeppl *et al.*, 2017). For example, Borselli *et al.* (2008) develop a connectivity index (IC) that expresses the relative sediment transport efficiency upstream and downstream of any point in the landscape, using topographic attributes such as drainage area, mean slope, and travel distance between elements. Cavalli *et al.* (2013) adapt the IC for use in mountainous catchments by including the effect of topographic roughness in reducing connectivity. This spatial index has been able to reconcile temporal variability in sediment export from partly glaciated basins (Micheletti and Lane, 2016). Measures of land surface roughness extracted from DEMs have been used in other studies of landscape disconnectivity, including Baartman *et al.* (2013), which defines a topographic Complexity Index based on local relief and slope variation, and Lane *et al.* (2017), which uses pit-filling and flow-routing algorithms to assess the impact of roughness on sediment throughput. In geomorphic terms, this latter study seeks to avoid the limitations of the common hydrological approach to noise in topographic data that leads to artificial pits, or sites of disconnection. Many hydrological analyses of routing begin by filling pits such that flow continuity can be achieved. In hydrology, but particularly in geomorphology, problems can arise with doing this when real pits, sites of reduced connectivity or disconnection, are eliminated by such algorithms. Other studies that quantify geomorphic drivers of connectivity include: Rice (2017), which uses drainage area, Strahler order and other catchment attributes to predict the relative disconnectivity of tributary junctions; Cadol and Wine (2017), which infers differential connectivity between streams and riparian vegetation in various geomorphic settings defined by measurements of valley width, topographic curvature and slope; and May *et al.* (2017), which describes reduced coupling between hillslopes and channels due to wider valley bottoms and gentler hillslope gradients in catchments upstream of bedrock-controlled waterfalls. IC are static representations of connectivity that can be very useful for determining areas of high and low structural connectivity within a geomorphic system under study (Nicoll and Brierley, 2017).

The connectivity of a geomorphic system can also be explicitly quantified using analytical techniques originally developed in other fields, such as network theory (Newman, 2006) and studies of percolation (Grimmett, 1989). The system must first be represented as a network composed of source or storage elements (nodes) that are connected by pathways of potential transport (links). Nodes can be pixels or other polygons in a continuous representation of a landscape, or one- to three-dimensional elements in a graphical representation of the network structure. Links can be formed uniformly with adjacent elements or specified in terms of network structure and other factors representing distance, direction, transport thresholds and transport efficiency. Once the system is defined spatially and dynamically, connectivity can be quantified using a variety of statistics that measure the central tendency or variability of connections between network elements. For example, Western *et al.* (2001) characterize the degree of hillslope hydrologic connectivity by defining the integral connectivity scale length (ICSL), which represents the average distance separating hillslope elements that are connected by a continuous downslope path of elements with soil moisture above a threshold value.

As networks grow in size and complexity, matrices are needed for network connectivity and flow computation. David *et al.* (2011) provides an example, using a matrix-based version of the traditional Muskingum method of flow routing, to develop a river network model in which lateral inflow to a river network is calculated by a land-surface model and flow in all reaches of a river network is calculated using the routing equation.

The mathematical model of a network is the graph. Graph theory, which is the study of graphs, has been applied to geomorphic systems (Haggett and Chorley, 1969; Phillips, 2012; Heckmann and Schwanghart, 2013; Marra *et al.*, 2013; Tejedor *et al.*, 2015) as a means of characterizing network structure and fluxes within networks, as well as simulating propagation of system changes through networks (Heckmann and Schwanghart, 2013). A graph can be formally described as $G = (N, E)$, in which N indicates nodes and E indicates edges. A graph is represented using an adjacency matrix, which is a square matrix with as many rows and columns as there are nodes in G. Such a matrix can provide a mathematic framework for exploring functional connectivity by analyzing nodes, edges, and paths (Heckmann and Schwanghart, 2013). Kupfer *et al.* (2014) apply network-based graph theory to model spatial and temporal changes in lateral connectivity of a large floodplain under different flood recurrence scenarios. Meitzen and Kupfer (2015) apply this same model to examine how connectivity influences abandoned channel infilling and vegetation development patterns. Tejedor *et al.* (2015) use spectral graph theory to develop a quantitative framework for channel network connectivity on deltas. Building on studies of neural networks in the human brain, Passalacqua (2017) uses an adjacency matrix to quantify the interactions between channel, levee, and island components of a delta. This approach permits an integrated evaluation of structural configuration and functional connectivity.

Cote *et al.* (2009) develops another direct metric of network connectivity to quantify the impact of barriers to fish migration at the catchment scale. Cote *et al.* (2009) defines the Dendritic Connectivity Index (DCI) based on summing the length of stream reaches linked by passable potential barriers, normalized by the total length of the stream network, which represents the probability that an organism is able to move between any two points within the network. Grill *et al.* (2014) builds on this work by defining a River Connectivity Index (RCI) that considers other reach attributes such as volume, habitat classification, and usability by a given species.

The preceding review illustrates the wide variety of metrics developed to quantify connectivity, both directly using techniques from network analysis and indirectly through measurements of fluxes and other outcomes of connectivity, and the topographic and other factors that drive variations in connectivity. Structural connectivity/configuration is captured most explicitly in the direct quantification of network properties, but is also implicit in many of the metrics that quantify the drivers of connectivity. On the other hand, metrics based on measuring the outcomes of connectivity primarily quantify functional connectivity. Studies that compare metrics representing different types of connectivity have the potential to quantify the cause and effect relationships at the heart of geomorphic connectivity. For example, Baartman *et al.* (2013) shows that Sediment Delivery Ratio, in natural and modeled catchments, declines systematically with increasing Complexity Index, thus linking structural drivers of connectivity with functional outcomes. Similarly, Beckman and Wohl (2014) show that variations in carbon content in fine sediment deposits, a proxy for sediment residence time and functional disconnectivity, correlate with boundary conditions including valley morphology, log jam spacing, and forest stand age. They also show that increased connectivity, through destruction of wood jams, leads to reductions in sediment deposition and channel roughness, which in turn inhibits the trapping of mobile wood that might otherwise anchor new wood jams. Thus, by linking the causes and effects of (dis) connectivity, Beckman and Wohl (2014) illustrate how feedback loops, with the potential to form multiple alternative states, can arise in connectivity dynamics.

A key question that arises when quantifying connectivity is: compared with what? In any given geomorphic system, is there a maximum or optimum level of connectivity to compare with? Non-dimensional connectivity metrics have the potential to quantify connectivity relative to a reference value. A simple example is the Sediment Delivery Ratio (Walling, 1983), which at its maximum value of 1.0 implies complete connectivity, albeit without directly quantifying any of the upstream connections or considering the time scale over which connectivity is operating. A more spatially explicit non-dimensional metric is the hydrologic connectivity parameter Tau (h) of Western *et al.* (2001), which is integrated to calculate the integral connectivity scale length (ICSL) described above. Tau (h) represents the probability that any two pixels separated by a distance h are connected by a continuous path of pixels with soil moisture above a threshold value, and thus varies between 0 and 1. Several other connectivity metrics are composed of dimensionless ratios that vary between 0 and 1, including the Dendritic and River Connectivity Indices (Cote *et al.*, 2009; Grill *et al.*, 2014) and the Complexity Index (Baartman *et al.*, 2013). These dimensionless metrics are normalized by the maximum values for the local catchment, making them useful for quantifying the effect of changes within the catchment, such as dam construction, but less useful for comparisons between catchments or other geomorphic systems.

Perhaps the most significant challenge in quantifying connectivity is the issue of scale. The frequency and efficiency of connections within any geomorphic system vary systematically with the temporal and spatial scale of analysis. Hence the measures of connectivity produced by any robust metric should also vary with scale. Because most transport processes are intermittent, connectivity should increase when measured over longer characteristic time scales (McGuire and McDonnell, 2010; Bracken *et al.*, 2013, 2015). Conversely, because movement of material occurs over finite distances in any given transport event, measured values of connectivity should decrease as spatial scale increases (Western *et al.*, 2001; McGuire and McDonnell, 2010; Bracken *et al.*, 2013, 2015).

One approach is to determine the fundamental temporal and spatial scales for the phenomenon of interest and to make measurements at a sufficiently large multiple of the fundamental scales to capture reliably a representative sample of transport events. If landslides are a key component of sediment connectivity within a drainage basin, for example, measuring sediment connectivity across a timespan that includes more than one landslide and intervening periods with other modes of sediment delivery is important (Reid *et al.*, 2007; Cavalli *et al.*, 2013; Dethier *et al.*, 2016). Similarly, measurements of longitudinal hydrologic connectivity within a river during floods should incorporate a time scale that includes multiple floods (Jaeger and Olden, 2012).

Another approach seeks to characterize how connectivity varies with scale, by applying the same metric over a wide range of temporal and spatial scales. Western *et al*. (2001) provides an example based on multiple soil moisture datasets. Alternatively, statistical measures that characterize the frequency distributions of connectivity across scales can be used, as Ali and Roy (2010) did for soil moisture and stormflow in a humid temperate forested catchment or Sendrowski and Passalacqua (2017) did for hydrological processes on a delta influenced by river discharge, tides, and wind.

Ultimately, the tools and methods available to collect the relevant data will constrain the scales at which connectivity can be analyzed. Technological advances such as terrestrial lidar, structure-from-motion photogrammetry, wireless sensor networks, and new techniques for tracing and tracking sediment fluxes create opportunities to expand the range of scales over which connectivity can be quantified (Cavalli *et al*., 2013; Fonstad *et al*., 2013; Smith and Vericat, 2015).

Several key ideas for future directions in measuring connectivity emerge from this discussion. First is the recognition that distinct metrics are probably needed to characterize structural configuration and functional connectivity and that no single overarching metric for connectivity is likely to emerge. Second, it will be fruitful to explore combinations of metrics that can represent the cause and effect relationships that link the drivers, structures, and outcomes of geomorphic connectivity and give rise to feedbacks and emergent system behavior. Third, nondimensional measures that characterize connectivity relative to meaningful reference values are needed to compare connectivity across scales and between systems. Finally, quantifying how connectivity varies with temporal and spatial scales of analysis will both inform future study designs and provide insight into the nature of connectivity in diverse geomorphic systems. A single metric that represents all aspects of connectivity is unlikely, but meaningful progress can be made in the absence of such a universal metric.

Using connectivity

Identifying and measuring connectivity provides a useful approach in basic and applied geomorphic research (Wohl, 2017). An explicit focus on connectivity can facilitate identification of spatial and temporal disparities in material fluxes within geomorphic systems, for example, as well as enhancing understanding of mechanisms of retention of materials within a particular system or component of a system. Characterizing connectivity can provide insight into the response of geomorphic systems to disturbance, the nonlinear behavior that may result from those disturbances, and the resistance or resilience of the system to disturbances. Explicit attention to connectivity can also promote transdisciplinary approaches to understanding and communicating geomorphic process and form.

Effective approaches to the management of landscape connectivity in river basins

In this section, we explore the implications of connectivity for management of rivers. The implications discussed here also apply to other geomorphic environments, but rivers are particularly the target of environmental management, including restoration and rehabilitation, and a more extensive literature addresses management of rivers relative to management of other geomorphic systems.

Effective river management programs seek to attain the best achievable state for a healthy and responsive river under prevailing and future conditions. Geomorphically informed river management practices incorporate flexibility and future variability in the design and implementation of management practices through articulation of open-ended and dynamic goals (Downs and Gregory, 2004; Brierley and Hooke, 2015; Brierley and Fryirs, 2016). Such planning and design exercises recognize that what has gone before influences our capacity to manage and modify rivers, but altered boundary conditions and evolutionary trajectories constrain the best achievable state and functionality that can be attained under prevailing and likely future conditions. This entails working with river morphodynamics at the reach scale, framed in relation to catchment-scale sediment and other fluxes. Landscape connectivity exerts a critical influence upon these relationships.

Understanding connectivity in relation to the morphodynamics of rivers is critical for making informed decisions in river management practice. Essentially, such understanding is concerned with the management of fluxes. In an era where forecasting river responses to a range of natural and human disturbances is critical to management and planning, understanding connectivity provides a core foundation from which to work. Forecasting where disturbance is likely to be manifest and the extent to which on-site and off-site impacts will result is critical to risk assessment and planning. Forecasting flood hazards requires an understanding of hydrological connectivity. Managing sediment hazards and legacy sediments requires an understanding of not only sediment sources, transport and deposition, but also the extent to which a catchment contains blockages or pathways of conveyance (James, 2010; Wohl, 2015). Managing contaminants or the spread of exotic flora and fauna requires that the dispersal pathways provided by rivers and floodplains are well understood (Haycock and Burt, 1993; Coulthard and Macklin, 2003). The connectivity among the component parts of the system and the manner in which these parts fit together set the template of the dynamic physical habitat mosaic in a river corridor.

Concerns for the sediment regime of a river take account of the nature and rate of sediment generation in a particular landscape setting, and controls upon the effectiveness of erosion and transport mechanisms that move materials through river systems (Benda *et al*., 2004; Czuba and Foufoula-Georgiou, 2014, 2015; Wohl *et al*., 2015a; Schmitt *et al*., 2016). In the development and implementation of catchment-scale river management plans (Sear *et al*., 1995; Gilvear, 1999; Brierley and Fryirs, 2009; Toone *et al*., 2014; Wohl *et al*., 2015a, 2015b), reach-scale sensitivity and catchment-scale connectivity are key considerations in determining river recovery potential and the range of potential trajectories of geomorphic river adjustment (Brierley and Fryirs, 2005; Fryirs, 2013, 2017). Connectivity relationships exert a primary control upon the efficiency with which disturbance responses are mediated through catchments, and associated lag times. This may present significant constraints upon what is achievable in managing sediment flux relationships in any given catchment. The (ir) reversibility of geomorphic adjustments to river type, and appraisals of sediment flux at the catchment scale, are important considerations in assessment of likely trajectories of adjustment (Wohl, 2011; Fryirs *et al*., 2012; Grabowski *et al*., 2014; Scorpio *et al*., 2015; Brierley and Fryirs, 2016; Ziliani and Surian, 2016). These insights support the derivation of moving targets for management programs (Brierley and Fryirs, 2016) and help to ensure that management actions are appropriate for a particular site (Brierley and Fryirs, 2009).

Analysis of geomorphic river recovery appraises how a river has adjusted in the past and what the river is adjusting toward. The potential for river recovery following disturbance reflects a river's inherent sensitivity to change and the severity of impacts to which the system is or has been subject (Hooke, 2015; Fryirs, 2017). Multiple potential trajectories can emerge, dependent on the condition of a reach, likely responses to disturbances, prevailing, system-specific driving factors and time lags, and how connectivity relationships mediate these processes and shape the evolutionary trajectories adopted (Phillips, 2007; Fryirs *et al.*, 2009; Standish *et al.*, 2014; Phillips and Van Dyke, 2016).

Assessing river recovery requires that the history, pathway, and rate of adjustment of each reach in the catchment of interest is known (Kondolf and Larsen, 1995; Surian *et al.*, 2009b; Wohl, 2011; Fryirs *et al.*, 2012; Fryirs and Brierley, 2012, 2016; Grabowski *et al.*, 2014; Rathburn *et al.*, 2013, 2018). Analysis of each reach in its catchment connectivity context provides a basis to evaluate the impact of pressures and limiting factors that may inhibit or enhance river recovery on the likely future trajectories of adjustment (Brierley and Fryirs, 2005, 2009; Ziliani and Surian, 2012, 2016; Standish *et al.*, 2014; Scorpio *et al.*, 2015; Fryirs and Brierley, 2016). When applied effectively, catalytic management activities in certain parts of catchments may trigger recovery processes that can accelerate recovery elsewhere. Appraisals of additional, off-site impacts require that the connectivity dynamics of the system are understood. Alternatively, analysis of connectivity relationship is required to identify where certain measures may have negative off-site impacts that will damage the recovery process. This helps in choosing passive versus active restoration measures; where in a catchment activities are likely to be most successful; and the scale and form of intervention that is required (Lane *et al.*, 2008; Fryirs and Brierley, 2016). In some instances, connectivity relationships can be used to guide management that maintains the fully functional portions of a catchment. As an example, Lane *et al.* (2008) show how in an upland river basin, native woodland planting focused on well-connected tributaries could reduce coarse sediment supply rates as an alternative to downstream sediment dredging and engineering. Understanding catchment-scale, spatial and temporal sediment and hydrological connectivity provides foundational knowledge with which to forecast river recovery potential and determine what is realistically achievable at the reach scale.

The availability of sediment for river recovery, and hence the timeframe of recovery, may vary markedly from catchment to catchment dependent on the connectivity dynamics of that catchment. Assessment of river recovery potential allows managers to assess in which reaches sediment should be retained and stored for river recovery, and where sediments can be released (Fryirs and Brierley, 2001). It is important to ensure that there is neither too much nor too little sediment to facilitate river recovery (Kondolf, 1998; Brooks and Brierley, 2004; Florsheim *et al.*, 2006; Jacobson *et al.*, 2009; Smith *et al.*, 2011; Fryirs and Brierley, 2016). Conceptual models can be used to communicate stages and timeframes of geomorphic adjustment (Simon, 1989; Brierley and Fryirs, 2005; Fryirs *et al.*, 2012; Stella *et al.*, 2013; Cluer and Thorne, 2014; Fryirs and Brierley, 2016; Phillips and Van Dyke, 2016). These insights can be used to assess whether geomorphic adjustments are likely to be reversible, considering how channel boundary conditions, flow and sediment inputs, and connectivity relationships have changed over time. Process-based modeling applications can be used to quantify timeframes of adjustment, using confidence limits to express potential uncertainties in future forecasts (Smith *et al.*, 2011; Small and Doyle, 2012; Ziliani and Surian, 2016).

Given differences in landscape connectivity relationships in differing environmental and landscape settings, there is profound variability in the ways and rates with which responses to disturbances that disrupt the sediment regime are mediated through a catchment (Fryirs *et al.*, 2007a, 2007b; Lane *et al.*, 2008; Surian *et al.*, 2009a, 2009b; Kuo and Brierley, 2013, 2014; Lisenby and Fryirs, 2017a, 2017b). Fryirs *et al.* (2009) refer to this as a response gradient. Highly connected systems rapidly convey disturbance responses through the system, whereas responses to disturbances in disconnected landscapes may be absorbed within certain parts of the system (Harvey, 2002; Hooke, 2003; Fryirs *et al.*, 2007a, 2007b, 2009; Jain and Tandon, 2010; Fryirs, 2013).

Catchment-scale conceptual models of process interactions, connectivity and evolutionary traits provide a basis to predict responses to management interventions (Mika *et al.*, 2010). Analysis of threatening processes helps to identify and prioritize what forms of management intervention are required in what parts of the system (Brierley and Fryirs, 2005, 2009, 2016; Czuba and Foufoula-Georgiou, 2014; Fryirs and Brierley, 2016; Ziliani and Surian, 2016). Such efforts seek to maximize cumulative benefits while minimizing off-site impacts of interventions (Schmidt *et al.*, 1998). Catchment-framed analysis of connectivity provides the basis for answering questions such as:

- Where should we prioritize our efforts to enhance the recovery of systems?
- Will a treatment reach experience degrading or positive influences from upstream (e.g. sediment slugs, headcuts)?
- From where will the sediment be sourced and dispersed to enhance river recovery in the study reach? Is enhancing sediment connectivity required?
- Where should sediment conveyance be suppressed to protect other reaches and minimize off-site impacts? Is enhancing sediment disconnectivity required?
- How will rehabilitation of the treatment reach affect downstream reaches?

These questions can be answered using conceptual models, qualitative evaluations, numerical simulations, and quantitative metrics: the key point is to characterize levels of connectivity, the processes and forms that promote or retard connectivity, and the response of the geomorphic system to changes in connectivity. Answers to these questions can be used in a range of management situations, including dam construction, removal, and modification of operating regime; incursions of exotic vegetation; mining activities; land use and land cover changes; post-fire treatment priorities (Figure 4); channelized reaches that flush sediments; and inferring whether sediment slugs enhance or inhibit downstream conveyance. Six general points that may assist efforts to manage landscape connectivity in relation to concerns for sediment regime are outlined in Table IV. The most effective technique (s) for addressing each point are likely to be site-specific. Ultimately, river basin management can focus on specific processes and fluxes without regard to connectivity, but measuring and conceptualizing process and flux in a connectivity framework facilitates an understanding of how basin configuration and fluxes of material respond to varying inputs through time and across space.

Connectivity, flow regulation and river–floodplain infrastructure

Connectivity is fundamental to management plans for river restoration/rehabilitation both as a goal and as a process. Because dams, water diversions, and other infrastructure such as weirs and check dams fragment waterways, their ubiquitous global presence has had a profound effect on hydrologic, sedimentological, and ecological connectivity (Junk *et al.*, 1989; Nilsson *et al.*, 2005), both within the channel and across the broader riparian zone longitudinally, laterally, and vertically

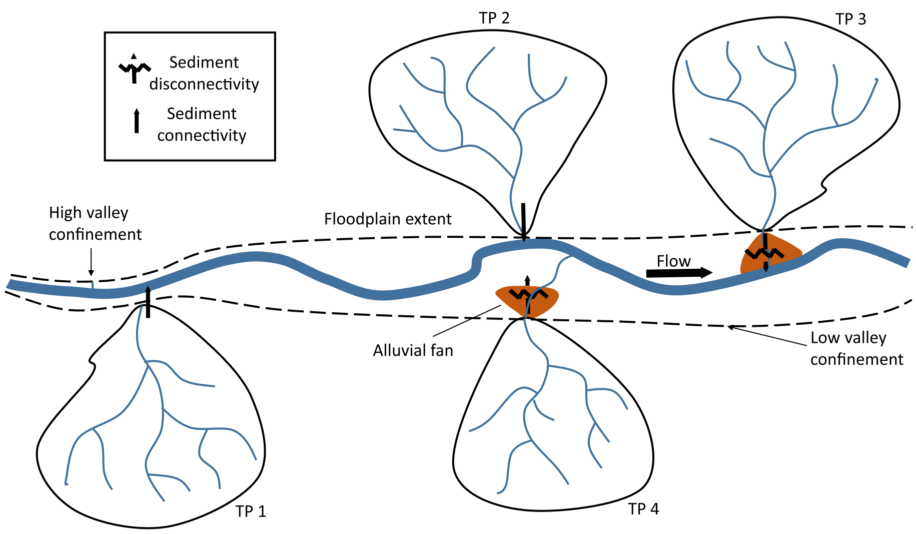

Figure 4. Schematic illustration of sediment connectivity and disconnectivity influences on post-fire treatment priorities based on observations from the South Fork Cache la Poudre watershed in northern Colorado, USA. TP1–TP4 indicate sub-basins with highest (TP1) to lowest (TP4) treatment priority based on sediment connectivity. Basins in which tributary alluvial fans limit sediment connectivity to the mainstem represent lower priorities for post-fire treatments designed to limit sediment yield, such as mulching. TP1 has the highest priority because the confined mainstem valley enhances transport of sediment delivered from the sub-basin, whereas the presence of a floodplain along the mainstem at the junction of TP2 may limit downstream sediment fluxes. (From Rathburn *et al.*, 2018, Figure 11.) [Colour figure can be viewed at wileyonlinelibrary.com]

(Kondolf *et al.*, 2006). To combat some of these effects, river managers, scientists, and non-governmental organizations have argued for management plans to ameliorate the effects of impoundment on watershed connectivity. In some instances, dam removal has been the preferred option as it provides the more robust opportunity for re-establishing sediment and hydrologic connectivity (Grant and Lewis, 2015; Foley *et al.*, 2017; Major *et al.*, 2017) while also having immediate impacts ecologically by permitting fish passage (Kornis *et al.*, 2014; Pess *et al.*, 2014; Magilligan *et al.*, 2016a) or by providing the necessary sedimentological conditions for enhancing spawning habitat (Magilligan *et al.*, 2016b). In instances where removal is not an option, watershed managers have advocated for environmental flows (Bunn and Arthington, 2002; Arthington *et al.*, 2006) to best mimic the natural flow regime (Poff *et al.*, 1997) with the goal of re-establishing greater hydrologic connectivity especially across the riparian zone to maintain floodplain forest communities (Rood *et al.*, 2005) or to generate longitudinal and lateral sediment connectivity and bar formation (Schmidt *et al.*, 2001; Topping *et al.*, 2005). However, the

Table IV. Aspects of landscape connectivity important in managing sediment regime

Identify expectations and realistic targets: The key issue in managing landscape connectivity is determination of ‘what are we measuring against’ (i.e. what is expected in any given system)? Recognizing explicitly that human disturbance has modified natural process linkages in a given catchment, what attributes of the prevailing sediment regime are manageable (i.e. what is realistically possible)? Inevitably, these are context- and catchment-specific situations.

Identify relevant components of sediment dynamics: Develop an understanding of forms and rates of sediment generation and patterns of sediment stores and their ease/frequency of reworking in a given system. How have human activities modified natural connectivity relationships in that system? How have these changes impacted upon the evolutionary trajectory of the system and over what timeframe? Is it possible, or desirable, for human activities to manage or reverse these traits?

Identify rates of sediment movement and geomorphic recovery: Quantify timeframes of sediment movement through a system as a basis to evaluate whether geomorphic river recovery is possible. This entails analysis of the extent to which human disturbance has modified natural patterns and trends of sediment sources, transfer and deposition (Fryirs and Brierley, 2009). In some cases, rates of movement have been accelerated (e.g. deforestation), elsewhere they have been suppressed (e.g. dams). In some instances, excess sediments are available to be reworked such that aggradation may ensue in downstream reaches (e.g. legacy effects of human impacts such as mining activities or abandoned water mills), elsewhere limited upstream availability of sediment (sediment exhaustion) may inhibit prospects for geomorphic recovery in downstream reaches where channel are over-enlarged (e.g. Fryirs and Brierley, 2001; Hooke, 2003; Brooks and Brierley, 2004).

Identify the catchment context: The sediment regime and associated process morphodynamics in any given reach must be viewed in their catchment context, assessing how upstream and downstream reaches influence the reach of interest. Any given reach is subjected to changes in boundary conditions. Most reaches are adjusting to legacy effects (Coulthard and Macklin, 2003; James, 2010; Evrard *et al.*, 2011; Wohl, 2015). Longitudinal connectivity relationships determine the nature, extent and rate with which changes to boundary conditions in one part of a system impact upon morphodynamic interactions elsewhere in that system. Pulses of sediment movement through river systems operate over different time scales and with variable impacts on a reach-by-reach basis. Resulting aggradational–degradational trends exert a key control upon channel adjustments over a range of time scales.

Identify the historical range of variability: Caution must be applied in the use of theoretical regime principles to predict rates of sediment movement and associated forms and rates of channel adjustment, as these framings assume continuity and uniformity in sediment inputs. However, sediment inputs vary and we need to know when and how they are likely to change if we are to make these assessments. In light of this issue, analysis of the historical range of variability of a river reach provides a critical basis to inform management applications pertaining to the range of channel sizes and configuration that are appropriate or expected for a given setting (Wohl, 2011; Rathburn *et al.*, 2013; Reid and Brierley, 2015).

Identify natural levels of connectivity: If working in a largely disconnected landscape, maintain disconnectivity of longitudinal process in interactions whenever possible. For example, if wetlands associated with discontinuous watercourses are present, these features exert important controls on downstream fluxes and create unique habitats and nutrient storage that are important to preserve (Brierley *et al.*, 1999).

reduction in connectivity associated with changes in water flow is commonly emphasized at the expense of the effects of such infrastructure and water management on sediment and sediment regime (Wohl *et al.*, 2015a; Gabbud and Lane, 2016), which runs the risk of introducing environmental remediation that has less than optimal effects.

What do we still need to know?

Throughout our discussions and literature review, we identify common themes and ideas that merit further research. First, there is increased understanding of the importance of capturing the heterogeneity of landscapes and their connectivity patterns in space and time (Fryirs and Brierley, 2009). With new technologies, such as high-resolution topographic data and ever-increasing model capabilities, we have the information needed to capture geomorphic features and thus connectivity pathways over a wide range of spatial and temporal scales (Passalacqua *et al.*, 2015). These mechanisms of mass and information transfer need to be quantified with appropriate metrics. Although bulk measures are helpful and easy to compute, they prevent us from capturing how connectivity patterns may vary spatially and temporally. Quantifying this heterogeneity is particularly important for restoration efforts that work with process and connectivity principles (Ward *et al.*, 2001; Kondolf *et al.*, 2006).

Several authors have suggested that graph and network theory metrics may be helpful tools to analyze connectivity in landscapes (Lane *et al.*, 2009, 2017; Heckmann *et al.*, 2015; Cheung *et al.*, 2016; Gran and Czuba, 2017; Passalacqua, 2017). These tools have proven useful in a variety of disciplines and for the analysis of many complex systems (Newman, 2010). There are obvious applications of these metrics in geomorphology. When dealing with river networks, for example, channels and tributary junctions are easily identified as links and nodes (Marra *et al.*, 2013; Heckmann *et al.*, 2015). In this case, the natural system essentially maps into the mathematical model, at least in terms of structure. Thinking about network dynamics, however, and thus the fluxes along the system, mapping into a network mathematical model may not be as obvious. For example, there may be leakages in the system (e.g. due to channel–floodplain connectivity) and these losses will have to be represented in the model, either as a distributed loss along the link or by characterizing the structural configuration (e.g. levee channels) through which this transport may occur and the nonlinearities of fluxes (e.g. stage-dependent lateral connectivity). In addition, the sediment and the nutrient networks – the collection of links and nodes along which solids and solutes are transported – may not be as continuous as the water transportation network, depending on the time scale of analysis. This may call for other approaches (e.g. the dynamic tree approach of Zaliapin *et al.*, 2010) able to represent mathematically the superposition of multiple interacting networks of different spatial structure and temporal dynamics.

We have to understand which metrics are most helpful and representative of the physical system and its connectivity pathways. These metrics are also needed 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. These validated models can then be used to simulate scenarios of disturbance and change and to predict landscape response in space and time (Liang *et al.*, 2016a, 2016b).

Another theme that emerged in our discussions is the general tendency to promote connectivity as a desirable landscape characteristic, thus labeling disconnectivity or low degrees of connectivity as a condition to avoid. However, disconnectivity or low levels of connectivity are present in landscapes as geomorphic features and boundaries between different process domains, not least because without them today's geomorphic processes would not be creating the long-term sedimentary record of the future. In many cases, low levels of connectivity create environmental and societal benefits, such as nutrient retention and biotic uptake that improve water quality (Haycock and Burt, 1993; Wegener *et al.*, 2017), sediment retention that increases habitat abundance and diversity (Jacobson *et al.*, 2009), and attenuation of hydrologic fluxes that reduces flood hazards (Lininger and Latrubesse, 2016). Geomorphologists have a critical role to play in communicating to resource managers and the public the benefits that can be derived from maintaining or restoring varying forms of connectivity and disconnectivity.

Finally, instead of imposing boundaries and studying landscapes and processes in compartments, there is value in evaluating boundaries as transition zones and examining the fluxes across them to understand landscape functioning. Our equations and numerical models are commonly built in the same compartmentalized fashion. This calls for the development of equations and models able to capture process transitions and for a critical understanding of where and when connectivity or disconnectivity may be preferable to favor the long-term sustainability of our planet.

To summarize: connectivity provides a useful conceptual framework for quantifying transfers of materials; examining factors that enhance or limit these transfers; understanding and predicting geomorphic responses to changed input and boundary conditions; and communicating understanding of geomorphic systems to resource managers and stakeholders. Landscapes and processes that promote and retard connectivity are heterogeneous in time and space. Geomorphic systems include transitions and leakiness rather than just simple compartments linked by fluxes. Connectivity within geomorphic systems occurs along a continuum in which levels of disconnectivity can be critical to landscape and ecosystem integrity. There is not likely to be any single connectivity metric that adequately characterizes all forms of connectivity, but the absence of a universal connectivity metric does not preclude meaningful progress in quantifying diverse forms of connectivity.

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