Introduction to the Special Issue: Connectivity in Geomorphology

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Abstract

With the increased recent attention on understanding the complex pathways and fluxes of material, energy, and organisms and the multidimensional coupling between various geomorphic process domains, the 47th Binghamton Geomorphology Symposium was organized around the theme of *Connectivity in Geomorphology*. Six key subthemes emerged: sediment connectivity, hydrologic connectivity, geochemical connectivity, riverine connectivity, landscape connectivity, and modeling of connectivity. Papers presented at the symposium and collected in this special issue elucidate the theoretical and conceptual underpinnings of connectivity but also provide field-based and analytical approaches to document the fundamental role of connectivity in geomorphic and ecological functioning. Among the consistent themes that emerged from the papers and from discussion during the symposium were (1) the interconnectedness of diverse forms of connectivity, (2) the appropriateness (or not) of conceptualizing connectivity as a gradient or continuum, and (3) the importance of an explicit recognition of disconnectivity as a mechanism to retain ecologically important materials and organisms within landscapes. Knowledge gaps identified in discussions during the symposium include: identifying questions that can be usefully addressed within a framework emphasizing connectivity; identifying feedbacks that enhance and limit connectivity; and quantification – of diverse aspects of

connectivity, of thresholds of connectivity, and of interactions among different types of connectivity.

Keywords: connectivity; sediment; landscape; rivers; modeling

1. Introduction

Connectivity – the transfer of matter, energy, or organisms between two different landscape compartments (Pringle, 2001, 2003; Jain and Tandon, 2010; Wainwright et al., 2011; Fryirs, 2013) – has been an important conceptual framework within geomorphology for decades. Its initial articulation focused perhaps more on sediment coupling between hillslopes and channels (Harvey, 1991, 2002); but with the greater contemporary focus in geomorphology on watershed-scale processes and geomorphology’s associated linkage with cognate fields such as ecology, hydrology, and geochemistry, connectivity has become an all-embracing term to represent the multidimensional fluxes of energy and matter at all scales and through multiple processes. With the protracted impacts of anthropogenic disturbance commonly associated with dams and other infrastructure such as levees and retaining walls, connectivity has taken on greater saliency through its counterpart – disconnectivity – which further serves to quantify the magnitude of the cessation or attenuation of watershed, reach scale, and local connectivity (Ward and Stanford, 1995; Magilligan et al., 2003; Kondolf et al., 2006; Fryirs, 2013; Wohl and Beckman, 2014). Moreover, as river restoration has become an important scientific, social, and policy initiative, a significant management thrust has reestablished connectivity through, for example, dam removal, large wood additions, and levee relocation; yet fear/hesitation exists within the geomorphic community that the science of river restoration may lag behind its application (Wohl et al., 2015).

In addition, with the recent initiation of the Critical Zone Observatories (CZO) in the U.S. (<http://criticalzone.org/national/>), there has been a greater recognition of, and focus on, the important atmospheric-terrestrial-ecological linkages, especially the quantification of how rocks, soil, water, air, and living organisms interact. The emergence of this research agenda has further necessitated a greater need to document material fluxes across spatial and temporal scales and to better establish the governing conditions that control the rate and pathways of these exchanges.

2. Rationale for symposium on connectivity

Although the concepts underlying connectivity are implicit in the earliest geomorphic thinking, ecologists have largely been responsible for reintroducing and popularizing the concept of connectivity during the past decade (cf. Pringle, 2001, 2003). However, the geomorphic community is increasingly explicitly emphasizing connectivity as a conceptual framework to understand fluxes, transfers, and transient and long-term storage of material and energy within landscapes. Nevertheless, the contours and specific attributes of a geomorphic framing of connectivity have been woefully lacking; hence the need for a symposium to better articulate a geomorphic vision of connectivity.

Most geomorphic attention has focused on riverine connectivity, which conceptually can be envisioned in a multidimensional space (Kondolf et al., 2006) that represents the exchange of material longitudinally, laterally, and vertically within and across watersheds and stream channels. Most recent geomorphic attention has focused on longitudinal connectivity, especially with the NSF Margins initiative and its associated source-to-sink research rubric (Aalto et al., 2008), although the exchange of sediment between channels and floodplains (lateral connectivity) during overbank flows has long been a research theme in geomorphology (Knox,

1972; Magilligan, 1985; Walling and Owens, 2003). Less attention has been paid to vertical connectivity, but with the recognition of the ecological dimensions of hyporheic flows (Stanford and Ward, 1988), there has been a sustained interest in quantifying the critical sediment and geochemical exchanges between the channel bed and subsurface (Cui et al., 2008; Wooster et al., 2008; Gartner et al., 2012; Covino, 2016; Stewardson et al., 2016).

In response to the increasing explicit recognition of the different dimensions and fluxes that can be conceptualized within a framework of connectivity, the 47th Binghamton Geomorphology Symposium (BGS) was organized around six distinct subthemes of hydrologic connectivity, sediment connectivity, geochemical connectivity, riverine connectivity, landscape connectivity, and modeling of connectivity (Fig. 1). Participants in the symposium explored issues of how to conceptualize and quantify diverse aspects of connectivity and also identified gaps in geomorphic understanding and application of connectivity.

Why a BGS? The BGS is one of the most recognizable annual geoscience meetings worldwide. For nearly 50 years, the symposium series has addressed a wide range of scientific and socially relevant topics in geomorphology, engaging a multitude of international geoscientists (Table 1). Paying close attention to the previous BGS's goal of producing scientifically relevant topics, the 47th BGS was organized around subthemes of connectivity in geomorphology (Table 2).

Among the existing gaps in developing a connectivity framework are (i) determining what research and management questions can be most effectively addressed within a conceptual framework that emphasizes connectivity; (ii) quantifying the different facets of connectivity (e.g., magnitude of fluxes, duration, frequency, timing, spatial extent) that occur within a natural system such as a river; (iii) quantifying thresholds of connectivity that, if crossed, can

significantly alter system function (e.g., reduced river longitudinal connectivity associated with reduced peak flows and resulting loss of fish migration); (iv) quantifying how different facets of connectivity interact; and (v) identifying feedbacks that enhance and limit connectivity. A simple but pertinent example of how different facets of connectivity interact comes from canyon rivers with dams. In these rivers, lateral sediment connectivity typically persists between uplands and the river corridor; but longitudinal hydrologic connectivity is lost as peak flows are stored behind the dam, causing an accumulation of sediment within the river corridor and associated changes in river form and habitat.

3. Outcomes of symposium and special issue

The two-day BGS and resulting special issue reveal that connectivity offers an important framework for understanding geomorphic processes at multiple scales. In particular, the papers on sediment connectivity stressed the fundamental importance of landscape scale and watershed structure in explaining the fate of sediment. Rice et al. (2016) examine the role of network structure and the resulting distribution of tributary confluences to help explain the pattern of channel aggradation. They test an automated method for predicting the likelihood of tributary-driven aggradation in three large drainage networks and show that their model can correctly identify ~ 75% of significant tributary confluences and 97% of insignificant confluences. Continuing on this theme of watershed structure, Gran and Czuba (2016) address the role of network structure in maintaining, dispersing, or transforming sediment pulses in fluvial systems. Their results indicate that the network structure, in terms of network geometry and the spatial pattern of transport capacity, can control sediment connectivity, especially where significant geologically controlled *bottlenecks* occur and should be considered when predicting sediment pulse behavior at the watershed scale. Looking more at channel-hillslope coupling and the

relative efficacy of the supply and delivery of coarse material to the channel, Sklar et al. (2016) illustrate how the spatial variation in weathering regime can lead to bimodal size distributions and downstream fining of channel sediment by downvalley fining of hillslope sediment supply using two examples of hillslope control on river sediment size.

The papers on hydrologic connectivity also stress the importance of scale and structure in understanding connectivity. Passalacqua (2016) explores network representations of deltas as links and nodes and develops the Delta Connectome. The Connectome conceptualizes a delta as a leaky network with continual exchanges of matter and energy between the network and the surroundings. The leakiness, or connectivity, of the network can be quantified by measuring selected fluxes and changes in delta form through time. Gooseff et al. (2016) use the relatively simple structure and seasonal changes that occur in the McMurdo Dry Valleys of Antarctica to characterize hydrologic connectivity within the valley bottoms. They find that even in this relatively simple setting, the magnitude, spatial extent, and duration of hydrologic connectivity is dynamic, with variations over multiple orders of magnitude. They propose simple hydrologic metrics for characterizing this connectivity, with a focus on flow volume (including lack of flow) and frequency. Macfarlane et al. (2016) explore changes in hydrologic connectivity associated with beaver dams, which change not only surface stream flow but also surface-hyporheic exchanges and evapotranspiration and water balance in valley bottoms. They present a capacity model that can be used to predict the limits of riverscapes to support beaver dams and test the model in watersheds of several states in the western United States, finding good agreement between model predictions and actual dam locations. The model provides an example of how existing databases can be used to predict alterations of diverse forms of hydrologic connectivity within river networks as a result of a specific type of alteration – in this case, beaver dams. Each

of the three papers examining hydrologic connectivity emphasizes the implications of this form of connectivity for biogeochemistry and biotic communities.

Geochemical connectivity under eroding hills is the focus of the BGS contribution by Brantley et al. (2016). Vertical movement of uplifted rock on geologic timescales is subjected to weathering as lateral movement through erosion. On shorter timescales, water fluxes move vertically downward then laterally either as interflow, when permeability contrasts occur in the weathering zone, or as deep groundwater. Such fluid flows set up shallow and deep weathering fronts where active biogeochemical reactions occur. The rate of rock advection upward relative to downward-acting weathering reactions governs rates at which minerals dissolve and erosion removes rock particles. In some environments, weathering approximates erosion, leading to steady-state conditions. The paper by Hilton (2016) relates climatic influences on export of particulate organic carbon from the terrestrial biosphere ($\text{POC}_{\text{biosphere}}$) to geochemical measurements, flow and suspended sediment quantities, and catchment slope in a sample of global forested watersheds. Results indicate that catchments with steep slopes may contribute nearly half of the global $\text{POC}_{\text{biosphere}}$ erosion flux and that a significant relationship exists between annual runoff and annual $\text{POC}_{\text{biosphere}}$, supporting strong connectivity between forested hillslopes and rivers. Furthermore, a model of climate influences on rates of runoff and hence erosion and discharge of $\text{POC}_{\text{biosphere}}$ indicates that small increases in annual runoff result in an approximately four-fold increase in $\text{POC}_{\text{biosphere}}$ discharge, underscoring the sensitivity of carbon fluxes to predicted changes in runoff. A final paper on geochemical connectivity by Covino (2016) documents how hydrological connections span numerous spatial dimensions and spatiotemporal scales, creating a mosaic of nested processes. Understanding hydrologic flow paths is essential to geochemical connectivity because water moves through heterogeneous

subsurface environments that have the potential to increase or decrease nutrient and carbon loading to the channel network. To advance our understanding of hydrologic connectivity and how it influences carbon and nutrient dynamics, a concerted effort in field-based investigations across broad spatial and temporal scales and modeling efforts that explicitly address process heterogeneity and feedbacks is essential.

The papers addressing riverine connectivity examine the multidimensional physical and social aspects of connectivity and the fundamental ecological and geomorphic importance of disconnectivity. Although acknowledging the importance of considering and conceptualizing connectivity, Grant et al. (2016) elucidate the critical role of disconnectivity and discontinuities in watershed processes. As they assert, a discontinuous view provides an important spatial and temporal framing as it incorporates nonuniform, nonprogressive, and nonequilibrium thinking into understanding geomorphic processes and landscapes. Echoing Renwick (1992) and Phillips (1992), they assert that not all landscapes tend toward a presumed equilibrium state and that, depending on the spatial and temporal lens, it is the disruptions in the system that provide an important element of geomorphic and ecological complexity. Cadol and Wine (2016) focus on the directionality of connectivity and show that geomorphology can be a first-order control on riparian ecohydrology by conditioning the magnitude and rate of geochemical and hydrologic exchanges in semiarid settings. Using detailed field, climatic, and geospatial data, they quantify the association between vegetation greenness (using EVI) and valley metrics (width, slope, and concavity) and the interannual variability in flow and rainfall characteristics. Their detailed statistical analysis reveals great statistical and ecological value in including geomorphic parameters along with climatic and hydrologic information to quantify vegetation greenness. The geomorphic parameters, especially valley curvature, may not just create statistical

relationships but may indicate physical causal processes, such as increased soil moisture availability on concave surfaces, which generates convergent subsurface flow paths. In an attempt to characterize the role of anthropogenic, geologic, and geomorphic boundary conditions on the rate and magnitude of longitudinal connectivity, Wohl et al. (2016) parameterize connectivity along North St. Vrain Creek watershed in Colorado with the specific focus of identifying the role of reach-scale channel gradient as a first-order control on geomorphic and geochemical exchanges. Using readily available topographic, lithologic, climatic, infrastructural (e.g., dams and roads), and vegetation data, they rank these landscape scale controls that, in concert with reach-scale gradient, dictate the rate of geochemical and sedimentological fluxes (and direction). They show that steep channel reaches engender the highest longitudinal connectivity for all materials considered, whereas lower gradient reaches attenuate longitudinal connectivity and generate longer residence time of water, sediment, and organic matter. However, despite limiting longitudinal connectivity, these lower gradient reaches generate greater lateral (channel-floodplain) and vertical (channel-hyporheic) connectivity. Disconnectivity in the fluvial system can extend into the social engagement with rivers and riverscapes. As geomorphologists we tend to focus on fluxes of sediment and nutrients, but as Kondolf and Pinto (2016) remind us, connectivity can also refer to the communication and movement of people, goods, ideas, and culture along and across river and may exhibit the same dimensions of longitudinal, lateral, and vertical connectivity. Moreover, as they show in their expansive international coverage, the social fabric of rivers has been significantly affected by human alterations of the channel and the broader riparian zone, further suggesting that reconnecting rivers geomorphically may have important social implications.

To address landscape connectivity, Nicholl and Brierly (2016) investigate process linkages related to sediment flux in two basins of the upper Yellow River using a GIS-based connectivity index compared to satellite image interpretation and field mapping. They find that landscape connectivity governs sediment availability, transport frequency, and sediment storage sites in the basin. Although the two methods generally confirm patterns of landscape connectivity, some areas of disconnectivity were misidentified, leading the authors to conclude that within-basin variability in connectivity may be missed without field appraisals of the landscape dynamics that control erosion and deposition. The paper by Lane et al. (2016) examines the response of glaciated regions to climatic warming. Using nearly 40 years of sediment flushing records from hydropower operations, the authors quantify coarse sediment export from a basin undergoing rapid glacial recession in the Swiss Alps. These data, combined with sediment transport capacities, DEM of differencing, and hydrologic routing, indicate that increased sediment yields from glacial recession may be offset by increased resistance to transport, challenging the hypothesis that an increase in paraglacial areas as glaciers retreat increases sediment export through connectivity. Results suggest that negative feedbacks may limit coarse sediment transport in upper portions of the basin. In the paper by May et al. (2016), waterfalls are shown to create conditions of landscape disconnectivity. In streams within the Oregon Coast Range, USA, bedrock knickpoints forming waterfalls isolate salmonid populations compared to catchments without knickpoints. The authors conclude that knickpoints control base level and hence channel incision such that lower channel slopes, wider valley bottoms, and increased resilience to landslide disturbances support greater habitat quantity and quality. A conceptual connectivity framework is presented by Poepl et al. (2016) to describe geomorphic change in human-impacted fluvial systems. The authors contend that no systematic data are

available on how different types of human activity affect connectivity relationships. Application of the framework brings increased understanding of connectivity and complexity in fluvial geomorphology, especially in coupled human-geomorphic systems.

The final subtheme of the BGS focused on modeling connectivity, although all of the papers included some discussion of qualitative or quantitative modeling. Houssais and Jerolmack (2016) note the tendency to differentiate landscapes into process domains and develop sediment transport laws for each domain. Noting the consistency of basic components of grain entrainment, they return to a perspective originally advocated by Bagnold (1954, 1956) and conceptualize the longitudinal profile of a hillslope-river-shelf system as equating to a gradient of decreasing dominance by granular friction and increasing dominance by fluid drag on transport capacity. One outcome of this is recognition of the importance of creep by sediment particles in both hillslope and river systems, which implies the possibility of unifying sediment transport across diverse environments. Coulthard and Van de Wiel (2016) use the CAESAR landscape evolution model to explore connectivity in the River Swale basin of England. They focus on how changes in vegetation cover alter erosion, deposition, and sediment yield and how sediment dynamics reflect basin-scale connectivity expressed through linkages from upstream to downstream areas, but also from downstream to upstream areas.

4. Toward a synthesis of connectivity

Among the points that emerged consistently from the very different treatments of connectivity in the papers included in the special issue are (i) the arbitrariness of commonly employed scientific divisions of connectivity, (ii) leakiness, and (iii) disconnectivity. Although many papers focus on a distinct form of connectivity, such as the movement of sediment or water, the papers in this special issue clearly indicate that such distinctions are arbitrary and

limited, as is the organization of the papers into subthemes. Most of the papers overlap in the forms of connectivity that they address because the fluxes of diverse materials and organisms throughout the critical zone are inextricably intermingled. A second point that emerged repeatedly in the papers and in discussions during the symposium is that connectivity is not most appropriately conceptualized as an *on-off switch*, but rather a *dimmer switch* because fluxes occur along a continuum across space and through time. Distinguishing channelized flow within a river corridor may be convenient, for example, but an extensive literature clearly documents that river flow is leaky, with hyporheic exchanges, groundwater exchanges, atmospheric inputs and losses, and channel-floodplain exchanges. Similarly, papers such as Passalacqua (2016) explicitly recognize the leakiness of a delta network. Finally, connectivity implies the corollary of disconnectivity. Disconnectivity is an equally important concept but is less emphasized in many contexts than connectivity (although important exceptions exist: e.g., Burchsted et al., 2010, 2014; Fryirs, 2013; Grant et al., 2016). Disconnectivity becomes especially important in understanding how ecosystems retain matter, energy, and organisms over timescales relevant to living organisms (e.g., watersheds retaining excess sediment and nutrients resulting from land use, or nearshore environments retaining nutrients from fluvial inputs). Future work will build upon the papers in this special issue to synthesize geomorphic approaches to connectivity and fill in the knowledge gaps identified here.

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Table 1
List of past Binghamton Geomorphology Symposia

<i>Title</i>	<i>Editor(s)</i>	<i>ISBN</i>
1. Environmental Geomorphology (1970)	D.R. Coates	Oct. 1970 ^a
2. Quantitative Geomorphology (1971)	M. Morisawa	Oct. 1971 ^a
3. Coastal Geomorphology (1972)	D.R. Coates	0-045-51038-5
4. Fluvial Geomorphology (1973)	M. Morisawa	0-045-51046-6
5. Glacial Geomorphology (1974)	D.R. Coates	0-045-51045-8
6. Theories of Landform Development (1975)	W.N. Melhorn and R.C. Flemal	0-686-10458-7
7. Geomorphology and Engineering (1976)	D.R. Coates	0-045-51040-7
8. Geomorphology in Arid Regions (1977)	D.O. Doehring	0-045-51041-5
9. Thresholds in Geomorphology (1978)	D.R. Coates and J.D. Vitek	0-045-51033-4
10. Adjustments of the Fluvial System (1979)	D.D. Rhodes and E.J. Williams	0-840-32108-2
11. Applied Geomorphology (1980)	R.G. Craig and J.L. Craft	0-045-51050-4
12. Space and Time in Geomorphology (1981)	C.E. Thorn	0-045-51056-3
13. Groundwater as a Geomorphic Agent (1982)	R.G. LeFleur	0-045-51069-5
14. Models in Geomorphology (1983)	M.J. Woldenberg	0-045-51075-X
15. Tectonic Geomorphology (1984)	M. Morisawa and J.T. Hack	0-045-51098-9
16. Hillslope Processes (1985)	A.D. Abrahams	0-045-51102-0
17. Aeolian Geomorphology (1986)	W.G. Nickling	0-045-51133-0
18. Catastrophic Flooding (1987)	L. Mayer and D. Nash	0-045-51142-X
19. History of Geomorphology (1988)	K.J. Tinkler	0-045-51138-1
20. Appalachian Geomorphology (1989)	T.W. Gardner and W.D. Sevon	0-444-88326-6
21. Soils and Landscape Evolution (1990)	P.L.K. Knuepfer and L.D. McFadden	0-444-88692-3
22. Periglacial Geomorphology (1991)	J. Dixon and A. Abrahams	0-471-93342-2
23. Geomorphic Systems (1992)	J.D. Phillips and W.H. Renwick	0-444-89809-3
24. Geomorphology: The Research Frontier and Beyond (1993)	J.D. Vitek and J.R. Giardino	0-444-89971-5
25. Geomorphology and Natural Hazards (1994)	M. Morisawa	0-444-82012-4
26. Biogeomorphology, Terrestrial and Freshwater Systems (1995)	C.R. Hupp, W.R. Osterkamp, A.D. Howard	0-444-81867-7
27. The Scientific Nature of Geomorphology (1996)	B.L. Rhoads and C.E. Thorn	0-471-96811-0
28. Engineering Geomorphology (1997)	J.R. Giardino, R.A. Marston, M. Morisawa	0-444-50301-3
29. Coastal Geomorphology (1998)	P.A. Gares and D.J. Sherman	Nov. 2002 ^b
30. Geomorphology in the Public Eye: Policy Issues and Education (1999)	P.L.K. Knuepfer and J.F. Petersen	Oct. 2002 ^b
31. Integration of Computer Modeling and Field Work in Geomorphology (2000)	J.F. Shroder, Jr. and M.P. Bishop	0-444-51532-1
32. Mountain Geomorphology (2001)	D.R. Butler, S.J. Walsh, G.P. Malanson	0-444-51531-3
33. Dams and Geomorphology (2002)	P. Beyer	0-444-52231-X
34. Ice Sheet Geomorphology (2003)	P.L.K. Knuepfer, J. Fleisher, D.R. Butler	April 2006 ^b
35. Weathering and Landscape Evolution (2004)	A. Turkington, J. Phillips, S. Campbell	0-444-52031-7
36. Geomorphology and Ecosystems (2005)	M. Doyle, M. Thoms, C. Renschler	Sept. 2007 ^c
37. The Human Role in Changing Fluvial Systems (2006)	L.A. James and W.A. Marcus	Sept. 2006 ^c

38. Complexity in Geomorphology (2007)	A.B. Murray and M.A. Fonstad	Nov. 2007 ^c
39. Fluvial Deposits and Environmental History (2008)	P. Hudson, K. Butzer, T. Beach	Sept. 2008 ^c
40. Geomorphology and Vegetation: Interactions, Dependencies, and Feedback Loops (2009)	W.C. Hession, T. Wynn, L. Resler, J. Curran	April 2010 ^c
41. Geospatial Technologies and Geomorphological Mapping (2010)	L.A. James, M.P. Bishop, S.J. Walsh	Jan. 2012 ^c
42. Zoogeomorphology and Ecosystem Engineering (2011)	D.R. Butler and C.F. Sawyer	July 2012 ^c
43. The Field Tradition in Geomorphology (2012)	C.J. Legleiter and R.A. Marston	Oct. 2013 ^c
44. Coastal Geomorphology & Restoration (2013)	N. Jackson, K. Nordstrom, R. Feagin, W. Smith	Oct. 2013 ^c
45. Planetary Geomorphology (2014)	D. Burr and A. Howard	July 2015 ^a
46. Experimental Geomorphology (2015)	S.J. Bennett, P. Ashmore, C. McKenna Neuman	Sept. 2015 ^a
47. Connectivity in Geomorphology (2016)	E. Wohl, F. Magilligan, S. Rathburn	

Notes

^a softcover copy published w/o ISBN

^b no hardbound volume published; published in *Geomorphology* (date listed)

^c hardbound copy published w/o ISBN

Table 2

Connectivity themes addressed by presentations during the 47th Binghamton Geomorphology Symposium

Connectivity theme	Topics (authors)
Sediment	Fluxes and storage of particulate mineral matter in any geomorphic environment – hillslope, glacial, eolian, coastal, or fluvial (Rice et al., 2016; Gran and Czuba, 2016; Sklar et al., 2016)
Hydrologic	Fluxes and storage of water between the atmosphere and surface and subsurface geomorphic components (Passalacqua, 2016; Gooseff et al., 2016; Macfarlane et al., 2016)
Geochemical	Fluxes and storage of dissolved or particulate individual elements or compounds, such as nitrogen and organic carbon, throughout the critical zone (Brantley et al., 2016; Hilton, 2016; Covino, 2016)
Riverine	Fluxes and storage of water, solutes, sediment, particulate organic matter, and organisms within channel and river corridors and throughout river networks (Grant et al., 2016; Cadol and Wine, 2016; Wohl et al., 2016; Kondolf and Pinto, 2016)
Landscape	Fluxes and storage of diverse forms of matter at the landscape scale (Nicholl and Brierly, 2016; Lane et al., 2016; May et al., 2016; Poepl et al., 2016)
Modeling	Quantification of diverse forms of connectivity via physical experiments and numerical simulations (Houssais and Jerolmack, 2016; Coulthard and Van de Wiel, 2016)

Fig. 1

A schematic representation of the diverse forms of connectivity and the fundamental interconnectedness of the critical zone. In this illustration, the italicized words represent materials and organisms in flux and the words in regular font represent forms of connectivity on which the geomorphic community tends to focus. Modeling of connectivity, whether conceptual or quantitative, is inherent in all expressions of connectivity. This illustration also reflects the fact that – although disconnectivity can be critically important to ecosystem functioning and to geomorphic process and form – matter, energy, and organisms within the critical zone are ultimately connected at the largest time and space scales.