Sediment sources and connectivity linked to hydrologic pathways and geomorphic processes: a conceptual model to specify sediment sources and pathways through space and time

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Extended Abstract

Sediment connectivity is a framework for transfer and storage of sediment among different geomorphic compartments across upland and channel network of the catchment sediment cascade. Sediment connectivity and dysconnectivity (i.e., source delivery and storage processes) are linked to the water cycle and hydrologic systems with the associated multiscale interactions with climate, soil, topography, ecology, and landuse/landcover under natural variability and human intervention. We review the sediment connectivity concept and frameworks developed in the last few decades to examine and quantify water and sediment transfer in catchment systems. Past conceptual models of connectivity have attempted to integrate multiple processes into sediment domain, including geomorphic, hydrologic, and ecological processes (i.e., "holistic approach to connectivity"). In particular, multiple studies highlight the importance of sediment and water interaction in defining landscape connectivity. There are also efforts to quantify the topographic controls on sediment connectivity, in the advent of increasingly high-resolution digital terrain models. More recent modeling efforts have integrated structural and functional connectivity through coupling topographic information with hydrologic simulation models. Though this recent modeling development is encouraging, a comprehensive sediment connectivity framework that integrates geomorphic and hydrologic processes across spatiotemporal scales is yet to be conceived. Such an effort will require understanding the governing hydrologic and geomorphic processes that control sediment source, storage, and transport. A conceptual model is proposed to describe dominant hydrologic-sediment connectivity regimes through spatial-temporal feedbacks between hydrologic processes (rainfall, flow routing, and water residence time) and geomorphic drivers (upland soil erosion and deposition, and geomorphic channel erosion and deposition response). Recent advancements in landscape monitoring techniques using geochemical tracers, remote-sensing, increasing availability of hydrologic monitoring data, and the integration of various analytic methods (e.g., isotopic hydrograph separation, stormflow concentration-discharge, hysteretic behavior analysis) have the potential to broaden the spatial and temporal scales of geomorphic observations and understanding of landscape sediment connectivity. Using the conceptual model as a "thinking" space, we examine sediment and hydrologic interactions in real world examples of watershed studies using multiple lines of evidence and modeling techniques.

1. Introduction

The understanding of changing sediment and water dynamics over different spatial and temporal scales, under a range of environmental conditions, is critical for developing monitoring and modeling approaches to quantify and predict sediment loading. The concept of sediment connectivity gained increasing interest in the earth sciences community to consider the continuum and interplay of structural components (i.e., terrain/morphology) and functional components (i.e., flow of energy/transport vectors and materials) of a catchment sediment cascades (Bracken et al. 2015; Cavalli et al. 2019). However, existing concepts of sediment connectivity lack a comprehensive framework to describe the continuum of sediment sources, stores, and routes of transport operating under different hydrologic conditions across spatiotemporal scales. Though it is impossible to cover all spatial and temporal time combinations of source and transport processes, here we put forth an integrated hydrologic and sediment connectivity conceptual model to broadly categorize dominant sediment and hydrologic processes and patterns relevant to understanding and predicting sediment flux dynamics at USGS gages. Conceptual models provide a tool for integrating multiple information and a space for understanding complex environmental systems (Fortuin, van Koppen, and Leemans 2011) Using this conceptual model as a “thinking” space, we examine sediment and hydrologic interactions using real world examples of watershed studies along with multiple lines of evidence and modeling techniques found in the literature.

2. Connectivity Framework Review

Sediment connectivity is linked to portions of the water cycle that influence runoff and hydrologic systems with the associated multiscale interactions with climate, soil, ecology, and landcover under natural variability and human intervention (Montgomery 1999; Bracken et al. 2015). Thus, a "holistic approach to connectivity", which integrates a range of structural, functional and systems approaches, is fundamental to examining water and sediment fluxes and different behaviors across different structural settings (Wainwright et al. 2011). Fryirs (2013) developed a framework using spatial linkages operating in a catchment to assess different types of “(dis)connectivity”: longitudinal, lateral, and vertical linkages of the sediment cascade that dictate the strength of coupling between catchment compartments and sediment conveyance. There are also various efforts to quantify the structural controls on sediment delivery by defining *indices* of *connectivity* (IC) as a function of landscape terrain, in the advent of increasingly high-resolution digital terrain models, such as those derived from aerial LiDAR. For example, Cavalli et al. (2013) implemented IC computation in two small catchments in the Italian Alps to assess the degree of linkages between upland sediment sources to downstream drainage lines as functions of drainage area, slope, and surface path length. Though useful in quantifying sediment connectivity from upland sources to stream network in overland flow - dominated systems, this geomorphometric quantification of connectivity omits the role of surface-subsurface connectivity in upland-channel coupling, as well as near/in-channel processes involving erosion, delivery, and deposition along stream corridors. More recent modeling efforts have incorporated both structural and functional components of landscape connectivity by coupling topographic information with hydrologic simulation models (i.e., SWAT to estimate watershed hydrology and channel dynamics) (Mahoney et al. 2018). In this modeling application, sediment connectivity is quantified as spatially explicit probabilities for sediment supply, detachment, transport, and buffers to sediment loading as functions of watershed hydrology and geomorphic conditions, including runoff depth, soil conditions, excess shear stress, topography, and river discharge (Mahoney et al. 2020a; 2020b). (See Table 1 for more complete review of select connectivity literature.)

However, recognition of interaction of hydrological and sediment processes remains piecemeal and subjective, and depends on specific environmental circumstances (i.e., study site location, catchment characteristics, and methods of inference) (Bracken et al. 2015). A systematic harmonization of functional connectivity with structural connectivity is needed to explain sediment dynamics in different environmental systems over different appropriate time scales and disturbances (Wainwright et al. 2011; Bracken et al. 2015). Specifically, to diagnose and predict water quality at gage-relevant spatial scales (i.e., HUC 8 watershed) across different relevant time scales, a framework that accounts for both sediment and hydrologic connectivity is needed to describe provenance, pathways, and storage along sediment cascade.

3. Sediment-Hydrologic Connectivity Conceptual Model

To develop a conceptual model of sediment and hydrologic connectivity, we consider two major hydrologic pathways (surface vs. subsurface flows) and two major sediment sources (upland vs. near/in-channel) of an idealized watershed (Figure 1). Various combinations of hydrologic pathways and sediment sources are associated with different spatial distribution and timing of source erosion, storage, and loading. Figure 1(a) illustrates sediment source and storage areas in the upland (hillslope, toe slope, and valley bottom) and near/in-channel (floodplain, channel bed, migration, and widening). Active sediment sources include areas of excess stored mass (e.g., fallow field, colluvium at the bottom of hillslope, wetland and other areas of depression, deposits on floodplains, channel beds and bars) in interaction with watershed hydrology and/or geomorphic drivers. Active sources may change throughout a storm hydrograph (e.g., land surface erosion, flushing and weathering in-stream) and with different time scales (e.g., engineering time scale for management vs. geologic time scale). Figure 1(b) illustrates various hydrologic pathways and contributions to streamflow. Through the implications of isotopic compositional differences, streamflow may be separated into event water (often called "new water") and pre-event water ("old water") using the distinct isotopic signals in soil water and groundwater (Shanley et al. 2002). New water consists primarily of current precipitation event (e.g., surface runoff, snowmelt, and direct precipitation shown in blue arrows). Old water indicates water that is stored in the catchment prior to the stream flow generating precipitation event and delivered primarily through subsurface pathways (e.g., soil water and ground water in brown arrows in Figure 1(b)) (Klaus and McDonnell 2013).

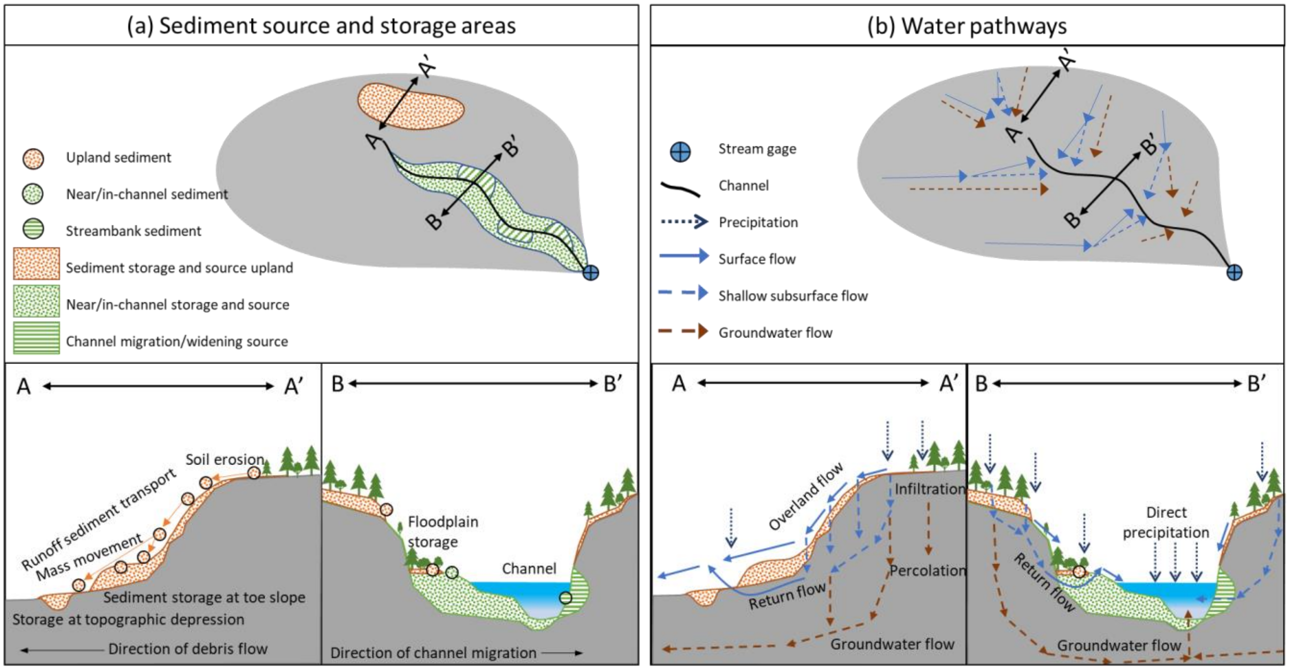

Figure 1: Illustration and definition of (a) Sediment source and storage area on hillslope (erosion and mass movement) and near/in-channel (floodplains, streambank, bed, and bars), and (b) surface and subsurface hydrologic pathways on hillslope to channels (runoff, infiltration, return flow, percolation, and groundwater flow)

Hydrologic processes through different pathways and timing across the watershed have different effects on structural connectivity as they have access to different sediment sources, storage areas, and transit pathways (i.e., “direct” vs. “indirect effects” in McEachran, Karwan, and Slesak 2021)). For overland flow, erosion and sediment delivery are likely controlled by slope hydrology and relationship between antecedent conditions, surface flow, subsurface flow, and ground water; as well as materials derived upslope and their proximity to channel network (Wainwright et al. 2011). Accordingly, the extent of overland flow and upland source availability would influence the sediment connectivity from upland sources to channel network, including slope-channel and channel-floodplain relationships (Wainwright et al. 2011; Fryirs 2013). For instance, landslide, gully and alluvial fan stability, and slope wash contributions could drive the strength of the lateral connectivity (Fryirs 2013). In channels, the extents of upstream-downstream connectivity reflect the ability of channel to erode and transfer sediments downstream, which may be assessed in terms of stream power, transport regime, and network structure given the baselevel or bed profile of a channel (Fryirs 2013; Bracken et al. 2015).

These complex upland-channel linkages within the watershed system are organized into four dominant sediment and hydrologic connectivity regimes in our conceptual model (Figure 2). Each regime illustrates distinct manners in which water and sediment interact, and they are named based on the primary hydrologic pathways (Old Water vs. New Water) and sediment sources (Upland vs. Near/in-channel Sources). We hypothesize that in combining hydrologic and sediment connectivity into a single conceptual model, patterns will emerge such that watersheds will exist in a single characteristic behavior at a particular instance, which would shift with space (e.g., reach scale vs. watershed scale) and time (e.g., seasonally with individual storm events vs. annual trend), and with landscape disturbance (e.g., wildfire, landslide, landuse/landcover change). Thus, the conceptual model can be used to describe dominant connectivity regime at a particular space and time and its response to landscape disturbance or natural variability. Furthermore, the conceptual model may provide guidance to management actions that will need to uniquely address the hydrology and/or sediment connectivity dominant in each watershed given different conservation objectives and timeframe (e.g., reduce mean daily sediment loading at a gage location)

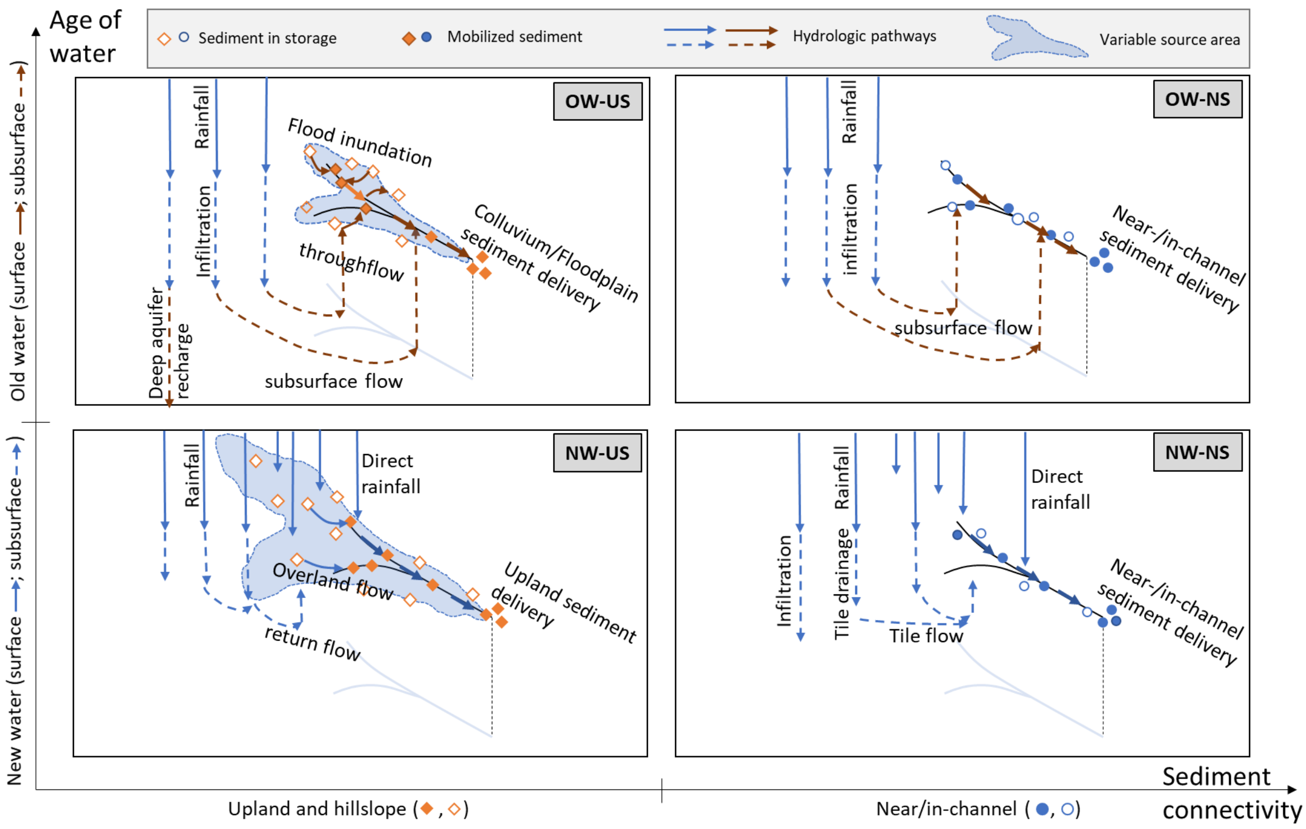

Figure 2: Conceptual model of sediment and hydrologic connectivity: Old Water- Upland Sources (OW-US); Old Water-Near/in-channel Sources (OW-NS); New Water-Upland Sources (NW-US); New Water-Near/in-channel Sources (NW-NS)

Recent advancements in landscape observational techniques in geochemical tracers, remote-sensing, increasing availability of hydrologic monitoring data, and the integration of various analytic methods (e.g. isotopic hydrograph separation, stormflow concentration-discharge, hysteretic behavior analysis) have broadened the spatial and temporal scales of geomorphic observations and understanding sediment connectivity. Through the descriptions of the anticipated dominant hydrologic and geomorphic regimes using the conceptual model (Figure 2), we examine sediment and hydrologic interactions in real world examples. (In this extended abstract, we only list and cite the examples; more detailed descriptions of the watershed studies will be presented at the conference):

- **Connectivity Scenario: Old Water-Upland Sediment (OW-US)**
  In a landscape system with high infiltration rates and limited overland flow, streams are mainly charged through throughflow and subsurface flow following a rain event (i.e., Old Water (OW)). Subsequently, streams gain access to sediment sources at the bottom of the river valley and/or floodplains with colluvial deposits (i.e., flushing and erosion via slope failure with return flow or flood inundation of valley bottom

establishing connectivity with Upland Sources (US)); at the same time, the stream delivery capacity is increased for a prolonged period after rainfall event through continued subsurface recharge. (real world examples of OW-US instances using various monitoring, modeling, and analytic methods can be found in: Montgomery, Dietrich, and Heffner 2002; Rose and Karwan 2021; Noe et al. 2022).

- **Connectivity Scenario: Old Water-Near Channel Sediment (OW-NS)**
  In a landscape dominated by steep confined valleys with little to no flood accommodation areas, where stream flow is mainly charged through subsurface flow (OW), the erosivity and delivery capacity of the river are heightened with increased stream flow for a prolonged period following a rain event. In such a system the major sediment contribution consists of near/in-channel sediment sources (NS) (i.e., incision, widening, and meandering). (e.g., Lloyd et al. 2016; Kelly and Belmont 2018; Gran et al. 2019; McEachran, Karwan, and Slesak 2021; Rose and Karwan 2021)
- **Connectivity Scenario: New Water-Near Channel Sediment (NW-NS)**
  In a landscape system with small infiltration rates, overland precipitation runoff and drainage management (e.g., ditches, tiles, and other artificial drainage) control rapid overland movement of water. Subsequently, streams are flooded with large quantities of New Water (NW) increasing erosivity and delivery capacity of the channel during the rain event. With limited availability of overland sediment sources (e.g., impervious surface, vegetative cover and/or erosion control measures), main sediment source consists of Near-channel Sediment (NS). (e.g., Karen Gran et al. 2009; Kelley and Nater 2000; Belmont et al. 2011; Gellis et al. 2020; Rose and Karwan 2021)
- **Connectivity Scenario: New Water-Upland Sediment (NW-US)**
  In a landscape dominated by overland flow with little infiltration, storm flow consists of New Water (NW). With limited availability of near-channel sources (e.g., vegetative buffers, gabion walls and/or other erosion control measures), main sediment source consists of Upland Sources (US). (e.g., Dunne and Black 1970; Leighton-Boyce et al. 2007; Sandercock, Hooke, and Mant 2007)

Table 1: Review of Connectivity Concept and Modeling

Author	Year	Connectivity Formulation	Sediment and Water Interactions	Spatial and temporal variabilities
Montgomery	(1999)	**Process Domain Concept (PDC):** Spatial and temporal variability in geomorphic influences is linked, in which systematic, landscape-scale patterns to disturbances exert distinct influences on geomorphic, hydrologic, and ecologic processes. Basic set of process domain includes hillslopes, hollows, channels, and floodplains. Though landscape connectivity concept has yet to be introduced to the field of Geomorphology, PDC lays the foundation for thinking about different components of landscape and their geomorphic influences on sediment delivery and sinks.	According to PCD, topographic convergences that focus surface and subsurface runoff, which elevates soil moisture and colluvial infilling, could lead to erosion and landslides. River Continuum Concept (RCC) considers routing processes in channels (i.e., "longitudinal linkages" defined by Fryir (2012)).	Systematic, landscape patterns influence spatial and temporal variability in geomorphic processes. Spatial hierarchy for geologic and topographic control is used to define dominant geomorphic process domain. i.e., Lithotopo units define finer-scale area with similar topography and geology and within which similar suites of geomorphic processes occur. At the highest level of this hierarchy, tectonic setting defines the long-term uplift rates and boundary conditions that drive physiographic evolution. Next level of hierarchy is geomorphic provinces given climate, geology, and topography control on geomorphic processes. Within the geomorphic province, different lithotopo units are identified by local control on the structure.

Wainwright et al.,	(2011)	Structural and functional connectivities are distinguished in different environmental systems to explain the patterns and feedbacks between their structures and processes: **Groundwater and surface-water connectivity:** Reach-scale subsurface flowpaths influence hyporheic flowpaths, benthic ecosystem, stream and groundwater hydrochemistry and biogeochemical processes. Spatial variability of flow interactions and solute exchange in groundwater and surface-water connectivity is influenced by geomorphic and hydrogeologic constraints. **Surface and subsurface connectivity in slope-channel coupling:** interactions between precipitation, soil moisture, infiltration, runoff, runon, stream stage, ephemeral streams and springs, etc. affect landscape processes, including erosion, sedimentation, and sediment transport and storage. **Surface connectivity in land degradation:** Ecological and hydrologic responses to landscape disturbance influence landscape connectivity	"Holistic approach to connectivity", based on the integration of a range of structural, functional and systems approaches, examines water and sediment fluxes and different behaviors across different structural settings of the case studies. In groundwater and surface-water connectivity, continuous variations in lithology and structure control landscape-scale flow fields (i.e., structural connectivity). And there are feedbacks between flow and sediment transport, as well as ecological forcings (i.e., functional connectivity). The timing and duration of storms, as well as direct antecedent conditions, affect runoff, erosion, and sediment transport.	The conceptualization account for temporal and spatial dynamics to understand different structural and functional connectivity and their feedback.
Fryir	(2013)	**Later linkages:** Hillslope-channel network interaction in the wider landscape **Longitudinal linkages:** Upstream-downstream and tributary-trunk interaction in channel network **Vertical linkages**: Surface-subsurface interaction of water and sediment	Connectivity is defined as "water mediated transfer of sediment" across the catchment sediment cascade, and the defined linkages consider the interaction of water and sediment.	Sediment cascade and variability over large spatial areas or temporal scales are influenced by types and strength of different linkages.
Braken et al.,	(2015)	**Hydrological connectivity** and **Sediment connectivity** are considered different but must be considered harmoniously to understand 1) the spatial and temporal feedbacks between structural and process component of landscape connectivity; 2) mechanisms of sediment detachment and transport; and 3) frequency-magnitude distribution of sediment detachment, transport, and storage processes.	Sediment and water interactions are central to this conceptual framing of landscape connectivity. Sediment transfer from a source to a sink in a catchment, and movement of sediment between different zones within catchment (i.e., over hillslopes, between hillslope and channels, and within channels) are considered as sediment behavior in *fully linked* to *fully unlinked* hydrological and sediment connectivity.	The challenge to scale up small-magnitude processes to produce landscape form motivated the formulation of the conceptual framework to understand processes involved in sediment transfer across multiple scales through the feedback between hydrological and sediment connectivity.

Borselli et al.,	(2008)	$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) = f(d_i, S_i, \bar{S}, A)$ where $D_{up} = \sum_i \frac{d_i}{W_i S_i}$ $D_{dn} = \bar{W}\bar{S}\sqrt{A}$ $IC =$ index of connectivity [-] d_i = length of the ith cell along downslope path [m] W_i =weight of the ith cell [-] S_i = *slope gradient of teh ith cell [m/m]* $\bar{W}$ = average weighing factor of the upslope contributing area [-] $\bar{S}$ = average slope gradient of the upslope contributing area [-] A = *upslope contributing area*	"Hydrological connectivity" is defined as the internal linkages between runoff and sediment sources in upper parts of catchments and the corresponding sinks. The GIS approach is developed to quantify the structural connectivity in downslope component based on topographic configuration (slope gradient and flow length). Upslope component of the connectivity is a function of drainage area and slope gradient. Thus, the connectivity formulation captures landscape connectivity by surface runoff, which is controlled by topographic and drainage configurations on upland. The rainfall characteristics (intensity, duration, and magnitude) and watershed hydrology are not explicitly captured in the formulation, but runoff generation effect on soil erosion is implicitly captured through use of USLE, RUSLE, or SCS-CN with IC to compute sediment yield.	The connectivity maps generated by this GIS approach is constant over time and does not vary with rainfall characteristics and the watershed's hydrological response. The method can be applied to any spatial scales, but the in-channel source connectivity to downstream point is not considered in this formulation. So the model does not scale appropriately as the study site is scaled up from reach scale to watershed scale.
Cavalli et al.,	(2013)	Modification to Borselli et al., (2008) formulation with new weighting factor that considers the surface characteristics that influence runoff and sediment fluxes: $W = 1 - \left(\frac{RI}{RI_{MAX}}\right)$ $RI = \sqrt{\sum_{i=1}^{n^2} \frac{(x_i - x_m)^2}{n^2}}$ where W = *weighting factor* RI = *roughness index* n^2 = number of the processing cells within nxn cells moving window x_i = value of one specific cell of the residual topography x_m = *mean of the* n^2 *cells values*	The new weighting factor implicitly considers of hydrologic influence on sediment delivery. Roughness index as standard deviations of residual topography values to consider the terrain influence on runoff. But similar to Borselli et al., (2008) method, there is no explicit consideration of rainfall characteristics and watershed hydrology to quantify infiltration, runoff, erosion, and sediment transport.	see above

Mahoney et al.,	(2018; 2020a; 2020b)	$P(C) = P(S) \cap P(G) \cap P(T) \cap \{1 - P(B)\}$ where $P(C)$ = *Probability of spatial connectivity* $P(S)$ = *Probability of transportable sediment supply* $P(G)$ = *Probability of sediment detachment and entrainment in flow* $P(T)$ = *Probability of transport of sediment* $P(B)$ = *Probability of a buffer/disconnectivity*	Discretized *P(C)* for each space-time unit incorporates both structural and functional components of landscape connectivity. *P(G)* considers hydrologic detachment of sediment and *P(T)* hydrologic transport of sediment. *P(G)* is a binary probability (i.e., 1 if soil is detached; 0 otherwise) as a function of excess shear stress given runoff depth and soil conditions. *P(T)* is a binary probability (i.e., 1 if hydrologic transport happens; 0 otherwise) as a function of gradient slope and critical slope for transport, which is a function of upstream drainage area, CN, and rock fragment cover of the soil.	The probabilistic landscape connectivity is a function of watershed's surface hydrology with computation of runoff generation via CN method through the application of SWAT model. Thus, the landscape connectivity varies with different hydrological events. The method routes sediment from upland sources to stream network, and in-stream sediment transport is computed using SWAT algorithm. Longitudinal connectivity, or how in-channel sediment sources are connected to downstream point is not comprehensively considered in the model.
Keesstra et al.,	(2018)	Landscape connectivity concept and approaches are reviewed, and water and sediment dynamics approach is proposed considering: **External Drivers:** Tectonic, climate, fire regime, and human intervention in the landscape (e.g., landuse/landcover, and water management) drive connectivity conditions. **System Phase:** Defines the structural connectivity at particular moments in time, depending on the system's geology, soil, hydrology, geomorphology, ecology, and human interventions. It influences structural connectivity and self-organizing patterns. **System Flexes:** Describes the transfer of water and sediment within a system. It influences functional connectivity and landscape patterns. **Equilibrium**: Responds to change in connectivity conditions.	Interacting phases and fluxes are conceptually represented as co-evolution of system state, such that structures emerge in response to fluxes within the system and the patterns of fluxes are influenced by the structure.	Multiple spatial and temporal scales of the conceptual model application are considered.

Cislaghi and Bischetti	(2019)	$HSCI = P[FS < 1 \cap L > d_{min}]$ $= P[L > d_{min} \mid FS < 1] \cdot P[FS < 1]$ where $HSCI$ = *Hillslope-Stream Connectivity Index* $FS =$ *Factor of Safety (i.e., P[FS<1]* indicates soil erosion or landslide) $P[L > d_{min} \mid FS < 1]$ = *Probability of total travel distance to reach channel*	Factor of Safety is calculated as a ratio between resisting forces (basal resistance force, shear resistance, tensile root reinforcement acting on the upslope side minus force acting on the upslope wedge) and driving forces (downslope component of the block weight). This formulation extends beyond topographic factors influencing landscape connectivity and includes the soil physics, 3D slope stability and geometry, and vegetation factor.	The method can be applied to any spatial scales, but in-channel source connectivity to downstream point is not considered in this formulation. So the model does not scale appropriately as the study site is scaled up from reach scale to watershed scale.
McEachran, Karwan, and Slesak	(2021)	**Direct Effects** are associated with overland flow, erosion, and sediment transport, where topography, drainage area, soil, landcover, and rainfall characteristics influence the extent of sediment connectivity. **Indirect Effects** are caused by increased stream flow and erosion from long-term hydrologic behavior of the watershed, such as infiltration and baseflow recharge.	Sediment and water interactions are built into the direct/indirect effect framework. Hydrologic connectivity on hillslope and in-channel is considered along with sediment connectivity from both hillslope and in-channel sources, as well as the feedback between the structural and functional components.	The framework makes it explicit that the hydrologic and sediment connectivity are not coincident in both space and time. Direct effects are observed at the hillslope scale in the timespan of single storm or season (i.e., localized effect). With increasing variable source area and disturbance extent, direct effects can dominate sediment yield drivers. Indirect events are at the watershed-scale changes in hydrologic flowpaths and distribution, and generally larger in spatial scale than the direct effects.

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