Check for updates

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

Se Jong Cho[1]*, Diana L. Karwan[2], Katherine Skalak[3], James Pizzuto[4] and Max E. Huffman[4]

[1]U.S. Geological Survey, Water Resources Mission Area, Baltimore, MD, United States, [2]Department of Forest Resources, University of Minnesota, St Paul, MN, United States, [3]U.S. Geological Survey, Water Resources Mission Area, Reston, VA, United States, [4]Department of Earth Sciences, University of Delaware, Newark, DE, United States

Sediment connectivity is a conceptualization for the transfer and storage of sediment among different geomorphic compartments across upland landscapes and channel networks. Sediment connectivity and dysconnectivity 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 current sediment connectivity and modeling approaches evaluating and quantifying water and sediment transfer in catchment systems. Many studies highlight the interaction between sediment and water in defining landscape connectivity, but many efforts to quantify and/or simulate sediment connectivity rely on the topographic/structural controls on sediment erosion and delivery. More recent modeling efforts integrate functional and structural connectivity to capture hydrologic properties influencing sediment delivery. Though the recent modeling development is encouraging, a comprehensive sediment connectivity framework, which integrates geomorphic and hydrologic processes across spatiotemporal scales, has not yet been accomplished. Such an effort requires understanding the hydrologic and geomorphic processes that control sediment source, storage, and transport at different spatiotemporal scales and across various geophysical conditions. We propose a path for developing this new understanding through an integrated hydrologic and sediment connectivity conceptual model that broadly categorizes dominant processes and patterns relevant to understanding sediment flux dynamics. The conceptual model describes hydrologic–sediment connectivity regimes through spatial-temporal feedback between hydrologic processes and geomorphic drivers. We propose that in combining hydrologic and sediment connectivity into a single conceptual model, patterns emerge such that catchments will exist in a single characteristic behavior at a particular instance, which would shift with space and time, and with landscape disturbances. Using the conceptual model as a "thinking" tool, we extract case studies from a multidisciplinary literature review—from hydrology, geomorphology, biogeochemistry, and watershed modeling to remote-sensing technology—that correspond to each of the dominant hydrologic–sediment connectivity regimes. Sediment and water interactions in real-world examples through various observational and modeling techniques illustrate the advancements in the spatial

and temporal scales of landscape connectivity observations and simulations. The conceptual model and case studies provide a foundation for advancing the understanding and predictive capability of watershed sediment processes at multiple spatiotemporal scales. Plain language summary: Soil erosion and movement across the landscape are closely linked to rain events and flow pathways. Landscape connectivity is a way to consider how soil erosion from different parts of the landscape is connected to the streams. We explore where soil erosion occurs and how eroded soil moves across the landscape through the interaction with rainfall and drainage. The comprehensive understanding of sediment connectivity and its dependence on rainfall characteristics and watershed hydrology may help to inform the effective distribution of conservation funds and management actions to address water pollution from excess sediment.

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 delivery, as well as, for developing effective water quality management strategies. The concept of sediment connectivity gained increasing interest in the earth science community to consider the continuum and interplay of landscape features and processes in catchment sediment cascades (Wainwright et al., 2011; Fryirs, 2013; Bracken et al., 2015; Wohl et al., 2017). Sediment connectivity involves the processes and controls involved in the transfer of sediment from a source to a sink via the interplay of structural components (terrain/morphology) and process/functional components (flow of energy/transport vectors and materials) of the landscape (Wainwright et al., 2011; Bracken et al., 2015). Information about hydrologic processes, associated with functional components of connectivity, and landscape sediment sources and sinks, associated with structural components of connectivity, at multiple spatial and temporal scales over various environmental settings, can provide an important "toolkit" for unpacking dominant sediment sourcing and primary transport scenarios (Karwan et al., 2018). Additionally, understanding connectivity will inform water quality mitigation efforts through effective allocation of landscape management strategies that consider both "direct effects" associated with surface runoff, erosion, and transport of overland sediment sources (e.g., silt fencing) and "indirect effects" associated with subsurface flow and corresponding activation of sediment sources or deposits of in- and near-channel environments (e.g., stream restoration) (McEachran et al., 2021).

In this study, the conceptualization and application of sediment connectivity are reviewed in terms of how they frame the continuum of sediment sources, stores, and routes of transport operating under different hydrologic conditions. The sediment connectivity research in recent decades indicates that to move toward a better understanding of sediment transport processes, a conceptualization that accounts for both sediment and hydrologic

connectivity is needed to specify provenance, pathway, and storage along sediment cascades (e.g., Wainwright et al., 2011; Bracken et al., 2015; Keesstra et al., 2018). In the second part of the study, we propose a hydrologic and sediment connectivity conceptual model to broadly categorize dominant sediment and hydrologic processes and patterns relevant to understanding and predicting sediment flux dynamics. Conceptual models provide a tool for integrating information and a space for understanding complex environmental systems (Fortuin et al., 2011). Thus, using the hydrologic and sediment connectivity conceptual model as a "thinking" tool, we extract case studies from a multidisciplinary literature review—from hydrology, geomorphology, biogeochemistry, and watershed modeling to remote-sensing technology—to examine sediment and water interactions in real-world examples using various observational and modeling techniques.

The hydrologic and sediment connectivity conceptual model can guide a strategy for collecting environmental data, given the anticipated dominant sediment sources and hydrologic pathways derived from observable environmental characteristics. Numerical simulation of landscape connectivity with strategically acquired data can help to effectively diagnose and forecast sediment source, transport, and storage across spatial and temporal scales. We discuss future research steps to illustrate a broad application of the conceptual model before concluding.

2 Review of the concepts of connectivity

In this section, we review the connectivity concept from its foundation in geomorphology and hydrology to contemporary applications of structural and functional components of connectivity in both conceptual and numerical models. The aim of the review was to (i) provide an overview of how the conceptualization of sediment and hydrologic processes and their interactions has evolved over the years and (ii) identify gaps in the development of a systematic harmonization of hydrologic and geomorphic connectivity.

We approach the second aim by organizing spatial and temporal dimensions of sediment delivery into a single coherent framework.

The variable source area (VSA) or partial area concept of runoff production posits that the portion of a watershed contributing storm runoff can expand or contract during a rain event, depending on rainfall duration, return flow, and soil and topographic characteristics (Hewlett and Hibbert, 1963; Dunne and Black, 1970). The River Continuum Concept (RCC) considers the longitudinal structure and variation along a river system (Vannote et al., 1980), while the Process Domain Concept (PDC) considers the spatial and temporal variability in geomorphic influences and their links across process domains (e.g., hillslopes, hollows, channels, and floodplains) (Montgomery, 1999). Together, these foundational concepts form a useful framework for linking geomorphic structures and dynamics with environmental forcing or landscape disturbances to understand sediment detachment and transport processes. Since the introduction of these foundational concepts on spatial and temporal variability in the operation of sediment cascades, the *landscape connectivity concept* has been adopted from graph theory and ecological applications (Bunn et al., 2000) as a way to describe and quantify structural (e.g., topographic information capturing landscape paths, slope lengths, and buffers) and functional (hydrologic properties capturing runoff and stream routing) influences on the fluxes of water and sediment at different spatial and temporal scales (Wainwright et al., 2011; Bracken et al., 2015; Keesstra et al., 2018). For example, 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 across the watershed. Such a conceptual framing can help to systematically recognize various processes, their variabilities, and interactions involved in the sourcing, movement, and storage of sediment across the basin system to the outlet.

In addition to the conceptual framing of connectivity, there have been 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 (Borselli et al., 2008). 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. However, the formulation of IC does not explicitly express the functional component of connectivity [i.e., interaction between geomorphology and hydrology (Keesstra et al., 2018)]. To include the functional component, a modified formulation of IC was proposed (*hydrosedimentological connectivity index* or HCI), where precipitation-derived variables (rainfall intensity, runoff generation, and antecedent soil moisture) are represented to estimate the space–time variation of water and sediment connectivity in a catchment (Zanandrea et al., 2021). Both IC and HCI only consider runoff-generated sheet erosion on upland surface omitting contributions from near-/in-channel

sources (e.g., streambank erosion) on sediment yield. Near-/in-channel sources can be significant contributors to sediment yield in many watersheds (see examples in Section 3.2 and Table 2), with substantial economic and environmental importance for stakeholders who must select effective soil conservation actions (Cho et al., 2019). To address this management concern, Cho et al. (2018, 2022) developed a watershed-scale stochastic sediment delivery model that explicitly represents both upland *and* near/in-channel sources with topography-driven sediment connectivity formulations.

More recent modeling efforts have incorporated both structural and functional components of sediment connectivity by coupling topographic information with hydrologic simulation models (i.e., SWAT to estimate watershed hydrology and channel dynamics) (Mahoney et al., 2018). In Mahoney et al. (2020a,b) modeling application, sediment connectivity is quantified as spatially explicit intersecting 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. Many current geomorphometric and hydrosedimentological aspects of connectivity, and their application in watershed modeling, focus on topographic underpinnings to quantify sediment connectivity from upland sources to the stream network in overland flow-dominated systems. Hence, they omit the role of surface–subsurface connectivity in upland-channel coupling, as well as near/in-channel processes involving erosion, transport, and deposition along stream corridors within channel networks before reaching a gage location or sediment sink. A Lagrangian transport model based on dynamic connectivity framework addresses some of the limitations concerning the processes within stream networks (Czuba and Foufoula-Georgiou, 2015). This network-based river routing model with specific attributes of sediment source area incorporates network topology, channel characteristics, and transport-process dynamics within streams to simulate the transport of mixed-sized sediment (Czuba, 2018). Refer to Table 1 for further details regarding recent studies of sediment connectivity.

Our review of connectivity literature suggests it has long been recognized that the spatial and temporal variabilities in geomorphic influences are linked with distinct hydrologic processes and landscape features (Vannote et al., 1980; Montgomery, 1999; Fryirs, 2013). It also indicates that a systematic harmonization of hydrologic and geomorphic connectivity is needed to explain sediment dynamics in different environmental systems over appropriate time scales and disturbances (Wainwright et al., 2011; Bracken et al., 2015; Keesstra et al., 2018). Strategies and applications of numerical simulation emerged to quantify the topographic influences on sediment delivery, focusing on the structural component of sediment connectivity (e.g., Borselli et al., 2008; Cavalli et al., 2013; Cislaghi and Bischetti, 2019). Later numerical simulation efforts integrated surface hydrodynamics to structural components of sediment connectivity (e.g., Mahoney et al., 2018, 2020a,b; Zanandrea et al., 2021). This selective review of landscape sediment connectivity research undertaken in the last several decades reveals that representation of the interactions between hydrologic and sediment processes remains piecemeal and

TABLE 1 Review of landscape sediment connectivity concept and modeling.

References	Connectivity formulation	Hydrologic processes and sediment connectivity interaction/formulation	Spatial and temporal variabilities
Montgomery (1999)	*Process Domain Concept (PDC):* Spatial and temporal variabilities in geomorphic influences are linked, in which systematic, landscape-scale patterns to disturbances exert distinct influences on geomorphic, hydrologic, and ecologic processes. Basic set of process domains includes hillslopes, hollows, channels, and floodplains. Though the landscape connectivity concept has yet to be introduced to the field of geomorphology, PDC lays the foundation for thinking about different components of the landscape and various influences on sediment delivery and storage.	According to PDC, topographic convergences that focus on surface and subsurface flows, which elevate soil moisture and colluvial saturation, could lead to erosion and landslides. *River Continuum Concept (RCC)* (Vannote et al., 1980) considers routing processes in channels (i.e., "longitudinal linkages" defined by Fryirs, 2013).	Systematic, landscape patterns influence spatial and temporal variability in geomorphic processes. Spatial hierarchy for geologic and topographic control is used to define the dominant geomorphic process domain. i.e., Lithologies 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 lithologies are identified by local control on the structure.
Wainwright et al. (2011)	Structural and functional connectivities are distinguished in different environmental components. *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 the slope-channel coupling:* interactions between precipitation, soil moisture, infiltration, runoff, runon, stream stage, ephemeral streams, and springs 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 the landscape-scale flow fields (i.e., structural connectivity). And there are feedbacks between hydrologic 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, infiltration, erosion, and sediment transport.	The conceptualization accounts for temporal and spatial dynamics to understand different structural and functional connectivity and their feedback.
Fryirs (2013)	Structural and functional connectivities are distinguished into three forms of linkages. *Lateral linkages:* Hillslope-channel network interaction in a wider landscape. *Longitudinal linkages:* Upstream-downstream and tributary-trunk interactions 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 the types and strength of different linkages.
Bracken et al. (2015)	Hydrological processes and sediment connectivity are considered to understand (1) the spatial and temporal feedbacks between structural and process components 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 the catchment (i.e., over hillslopes, between hillslope and channels, and within channels) are considered as sediment behavior in *fully linked* to *fully unlinked* hydrologic processes.	The challenge to scale up small-magnitude processes to produce landscape form motivated the formulation of the conceptual framework to understand the processes involved in sediment transfer across multiple scales through the feedback between hydrologic and sediment connectivity.

(Continued)

TABLE 1 (Continued)

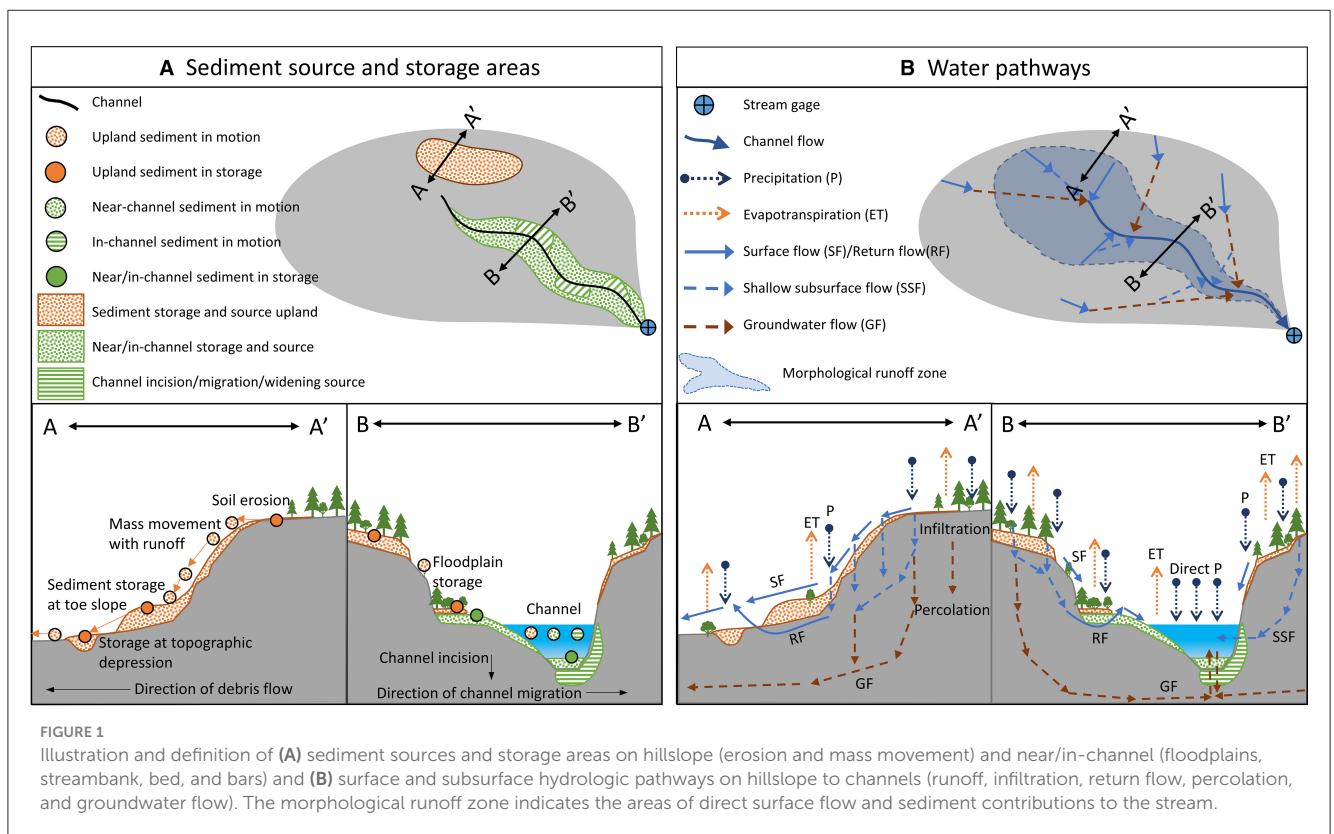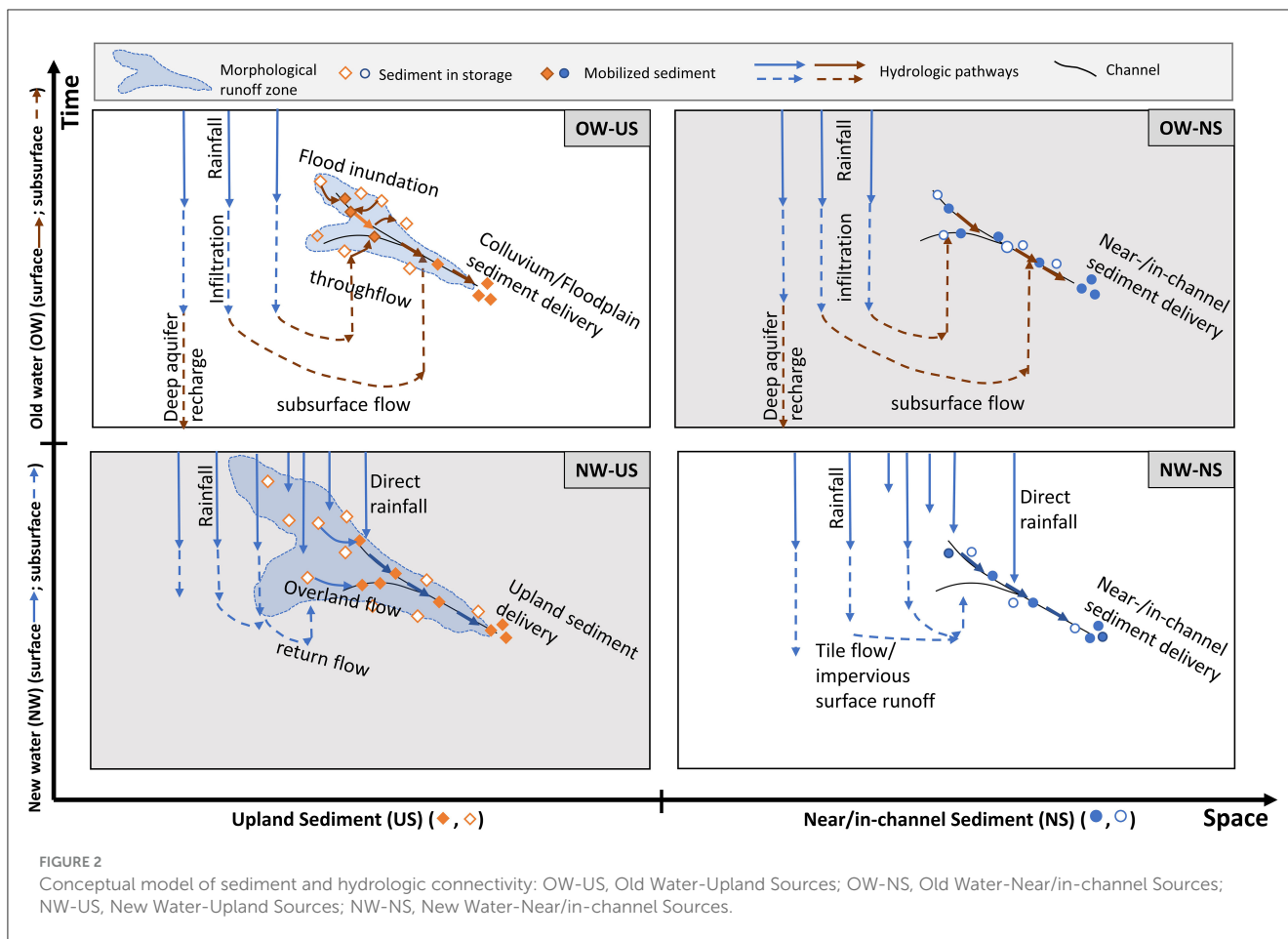| References	Connectivity formulation	Hydrologic processes and sediment connectivity interaction/formulation	Spatial and temporal variabilities
Borselli et al. (2008)	$IC = log_{10}\left(\dfrac{D_{up}}{D_{dn}}\right) = f\left(d_i, S_i, \overline{S}, A\right)$ *Where* $D_{dn} = \sum_i \dfrac{d_i}{W_i S_i}$ $D_{up} = \overline{W}\,\overline{S}\sqrt{A}$ $IC=$ *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 the ith cell [m/m]* $\overline{W} =$ *average weighing factor of the upslope contributing area [-]* $\overline{S} =$ *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 the upper parts of catchments and the corresponding sinks. The GIS approach is developed to quantify the structural connectivity in the downslope component based on topographic configuration (slope gradient and flow length). Upslope component of the connectivity is a function of the drainage area and slope gradient. Thus, the connectivity formulation captures landscape connectivity by surface runoff, which is controlled by topographic and drainage configurations on the upland. The rainfall characteristics (intensity, duration, and magnitude) and watershed hydrology are not explicitly captured in the formulation, but runoff generation and soil erosion are implicitly captured through use of USLE, RUSLE, or SCS-CN with IC to compute sediment yield.	The connectivity maps generated by this GIS approach are constant over time and do not vary with rainfall characteristics and the watershed's hydrological response. The method can be applied to any spatial scale to map hillslope connectivity to the channel network, but the in-channel source erosion and connectivity to the downstream point are not considered in this formulation.
Cavalli et al. (2013)	Modification to Borselli et al. (2008) formulation with a new weighting factor that considers the surface characteristics that influence runoff and sediment fluxes: $W = 1 - \left(\dfrac{RI}{RI_{MAX}}\right)$ $RI = \sqrt{\sum_{i=1}^{n^2} \dfrac{(x_i - x_m)^2}{n^2}}$ *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 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
Czuba and Foufoula-Georgiou (2015)	$d_{k,l}(t) = \|\mathbf{X}_{Pk}(t) - \mathbf{X}_{Pl}(t)\|_{Along\atop network}$, $M_j(t) = \sum_{\substack{parcels\ P_k,\ P_l \\ in\ cluster\ j \\ at\ time\ t}} m,\ s.t.d_{k,l}(t) \le d^*$, $L_j(t) = \sum_{\substack{parcels\ P_k,\ P_l \\ in\ cluster\ j \\ at\ time\ t}} d_{k,l}(t),\ s.t.d_{k,l}(t) \le d^*$ $CPI_i = \int\limits_{\substack{over\ all \\ times\ t}} M_j^i(t)\ dt$	Sediment connectivity is considered along the river network based on network topology (i.e., links, junctions, and outlet) and hydraulic and geomorphic attributes (i.e., length, geometry, drainage area, slope, and stream flow). Sediment mass contribution (m) is injected as parcel (P_k) in the basin at an initial time (t_0) and their trajectories ($\mathbf{X}(t)$) are followed over space and time ($m(\mathbf{X_i}, t_i)$). Travel time of sediment parcels (t_i) is computed by decomposing volumetric transport rate given hydraulic geometry, flow length, upstream drainage area, grain attributes, and streamflow velocity.	"Dynamic Connectivity" refers to how the connectivity of fluxes changes in time. The formulation rests on the link between Eulerian and Lagrangian transport formalism to establish the relation between the space–time trajectories of sediment connectivity along the river network. A set of consecutively connected river links over time is defined as "cluster." Cluster persistence index (CPI) is a measure of dynamic connectivity used to identify hotspots of fluvial geomorphic change and to evaluate driving mechanism of this change.

(Continued)

TABLE 1　(Continued)

References	Connectivity formulation	Hydrologic processes and sediment connectivity interaction/formulation	Spatial and temporal variabilities
	Where $d_{k,l}(t)$ = distance between adjacent parcel P_k and P_l $\mathbf{X}(t)$ = parcel (P_k) trajectory at time t $M_j(t)$ = total mass at cluster j at time t as the sum of all parcel mass (m) of inter-parcel distances $(d_{k,l})$ less than threshold distance (d^*) $L_j(t)$ = total upstream and immediate downstream length at time t along the network as the sum of inter-parcel distances $(d_{k,l})$ less than threshold distance (d^*) CPI_i = cluster persistent index as the cumulative effects of all clusters j on every link i from time $t=0$ until all parcels have left the system		
Mahoney et al. (2018, 2020a,b)	$$P(C) =$$ $$P(S) \cap P(G) \cap P(T) \cap \{1 - P(B)\}$$ 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 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. This 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 the downstream point, is not comprehensively considered in the model.
Keesstra et al. (2018)	Landscape connectivity and feedback between phases and fluxes are outlined. *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 structure, hydrology, geomorphology, ecology, and human interventions. It influences structural connectivity and self-organizing patterns. *System Fluxes:* Describes the transfer of water and sediment within a system. It influences functional connectivity and landscape patterns. *Equilibrium:* Responds to changes 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. Observational approaches to quantify water and sediment fluxes at various spatiotemporal scales are proposed.	Multiple spatial and temporal scales of the conceptual model application are considered.
Cislaghi and Bischetti (2019)	$$HSCI = P\left[FS < 1 \cap L > d_{\min}\right] =$$ $$P\left[L > d_{\min} \mid FS < 1\right] \cdot P\left[FS < 1\right]$$ where $HSCI$ = Hillslope-Stream Connectivity Index FS = Factor of Safety (i.e., $P[FS<1]$ indicates soil erosion or landslide) $P\left[L > d_{\min} \mid FS < 1\right]$ = 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 the downstream point is not considered in this formulation.

(Continued)

TABLE 1 (Continued)

References	Connectivity formulation	Hydrologic processes and sediment connectivity interaction/formulation	Spatial and temporal variabilities
Zanandrea et al. (2021)	$$IHC = \log_{10}\left(\frac{\overline{RSS}\, Ips \sum Q_{runoff}}{\sum_i \frac{d_i}{RS_i S_i}}\right)$$ where RS = Relative Smoothness calculated using the local Manning Coefficient [-] Ips = precipitation index for sediment [-] Q_{runoff} = surface runoff calculated using the SCS Runoff Curve Number (CN) method [L] d_i = length of the ith cell along downslope path [L] S_i = slope gradient of the ith cell [L/L]	Hydrosedimentological Connectivity Index (IHC) concerns both runoff generation with antecedent condition and structural features of the landscape. It builds on Borselli et al. (2008) formulation of Connectivity Index (IC) to include precipitation and surface runoff characteristics as functional component of the formulation.	IHC is mapped event-by-event cases for any spatial scales to map hillslope connectivity to channel network, but the in-channel source connectivity to the downstream point is not considered in this formulation.
McEachran et al. (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 altered long-term hydrologic behavior of the watershed, such as increased infiltration and baseflow recharge and heightened peak streamflow, and the consequent erosion of near- and in-channel sources.	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., temporally 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.

FIGURE 1
Illustration and definition of (A) sediment sources and storage areas 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). The morphological runoff zone indicates the areas of direct surface flow and sediment contributions to the stream.

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

subjective and depends on specific environmental circumstances (i.e., study site location, catchment characteristics, and methods of inference) (Bracken et al., 2015).

To measure and predict water quality at gage-relevant spatial scales (HUC 8 watershed scales, for example), a model is needed that includes elements for provenance, pathways, and storage along sediment cascades and addresses the response to different hydrologic forcings and landscape disturbances (McEachran et al., 2021). Quantification of sediment sources and delivery for a given landscape would require an effective synthesis of a range of conceptual approaches with monitoring and modeling techniques that integrate hydrologic processes and structural components of sediment connectivity. Spatial variability in geomorphic processes that influence temporal patterns of connectivity may be mapped by identifying sediment sources along with hydrologic pathways. A conceptual model in the following section can help to develop time- and space-variant connectivity scenarios and can guide data collection and model development needed to quantitatively evaluate them.

3 Sediment-hydrologic connectivity

3.1 Conceptual model

While it is impossible to cover all spatial and temporal combinations of sources and transport processes, 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. We consider two major hydrologic pathway s (surface vs. subsurface) 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 1A illustrates sediment source and storage areas in the upland (hillslope and toe slope) and near/in-channel (floodplain and channel). Active sediment sources include areas of 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 over time, such as throughout a storm hydrograph (e.g., land surface erosion via rainfall impact to streambank erosion from peak flows), or over engineering timeframes with management implementations (e.g., grassed waterways and stream restorations) and up to geomorphic time scales (i.e., landscape evolution and stream morphology). As a result, event water composition and pathways can influence dominant sediment sourcing and routing and appropriate management strategies (McEachran et al., 2021). Therefore, adopted from the idea of *variable source area* (VSA) (Dunne and Black, 1970), we define the *morphological runoff zone* (MRZ) to indicate those areas in the watershed where runoff generation results in sediment delivery

from upland sources to the river network. Figure 1B illustrates various hydrologic pathways and contributions to streamflow. Through the empirical implications of isotopic compositional differences, streamflow may be separated into event water (often called "new water" indicated with blue arrows in Figure 1B) and pre-event water ("old water" indicated with brown arrows) using the distinct chemical (e.g., isotopic) signals in soil water and groundwater (Klaus and McDonnell, 2013). New water is primarily derived from an ongoing precipitation event (e.g., surface runoff, snowmelt, and direct precipitation). Old water consists primarily of 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) (Shanley et al., 2002).

Hydrologic processes through different pat hways and timing have different effects on structural connectivity as they have access to different sediment sources, storage areas, and transit pathways. For sediment sources in upland areas (A—A' of Figure 1A), the extent of overland flow and the availability of upland sources influences sediment connectivity to the channel network, including slope-channel (e.g., rain splash and sheet erosion) and channel floodplain (e.g., return flow flushing and flood inundation) relations (Wainwright et al., 2011; Fryirs, 2013). The strength and patterns of the connectivity are likely controlled by hillslope hydrology and relationships between precipitation characteristics, antecedent conditions, surface flow, subsurface flow, and ground water (A—A' of Figure 1B). Materials derived upslope and their proximity to the channel network may also be relevant (Wainwright et al., 2011). For sediment sources near/in-channels (B—B' of Figure 1A), the extent of upstream-downstream connectivity reflects the ability of the channel to erode and transfer sediments downstream, which may be assessed in terms of surface and subsurface flow contributions and their timing, stream power, transport regime, and network structure, given the base level or bed profile of the channel (B—B' of Figure 1B) (Fryirs, 2013; Bracken et al., 2015).

Various upland-channel-outlet linkages within a watershed are organized into four dominant sediment and hydrologic connectivity regimes in a conceptual model (Figure 2). The partition on the x-axis broadly categorizes structural characteristics of connectivity, linked to the landscape geomorphology and *spatial dimensions* of sediment sources. The partition on the y-axis characterizes the functional aspects, linked to the hydrological properties and *time-scale variation* in sediment connectivity. The conceptual model organizes these different categorizations of dominant sediment and hydrologic processes and patterns to navigate various spatial dimensions and time scales of connectivity. Each sediment and hydrologic connectivity regime illustrates distinct interactions between water and sediment, and they are named based on the primary hydrologic sources relative to the event scale (Old Water vs. New Water) and sediment source areas (Upland vs. Near/in-channel Sources).

We propose that in combining hydrologic and sediment connectivity into a single conceptual model, patterns will emerge such that catchments (i.e., small hydrologic units with identifiable dominant processes) will exist in a single characteristic behavior at a particular instance. Furthermore, the conceptual model can describe shifts in dominant processes with different spatial (e.g.,

reach scale vs. watershed scale of greater hydrologic units) and temporal scales (e.g., seasonally with individual storm events vs. annual trends), as well as with landscape disturbances (e.g., wildfire, landslide, and landuse/landcover change). In other words, the conceptual model can be used to describe the dominant connectivity regime at a particular space and time and its response to landscape disturbance and/or natural variability. As such, the conceptual model can 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 timeframes (e.g., control mean daily sediment loading at a gage location and determine effective Best Management Practices). For example, timber harvest or agriculture (or landcover changes more broadly) can result in increased surface runoff and increased upland sediment connectivity affecting local, reach-scale water quality. At the same time, shifts in hydrologic processes due to tree removal or tile drainage (e.g., alterations to evapotranspiration, infiltration, and runoff) may account for the increases in subsurface and surface flows to the stream such that the changes to downstream water quality are not predicated upon overland sediment delivery to the stream but is attributed to in-stream processes (e.g., stream bank erosion, channel meander, incision, and widening) over longer time scales (Foufoula-Georgiou et al., 2015; McEachran et al., 2021). In such cases, management of downstream water quality degradation does not only rely on management actions on uplands to trap sediment but also on controlling watershed hydrology and in-stream erosion processes (McEachran et al., 2021).

3.2 Sediment-hydrologic connectivity scenarios

Recent advancements in landscape observational techniques involving geochemical tracers, remote sensing, increasing availability and frequency of hydrologic monitoring data, and the integration of various data analytic methods (e.g., isotopic hydrograph separation, stormflow concentration–discharge, and hysteretic behavior analysis) and watershed modeling have broadened the spatial and temporal scales of geomorphic observations and understanding of 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 (Table 2 organizes the following examples by study location, study method, main geomorphic and hydrologic processes, and space/time scales of evaluation):

- **Connectivity Scenario: Old Water-Upland Sediment (OW-US)**
  The OW-US regime indicates that the primary hydrologic drivers consist of pre-event water from subsurface storage and pathways, and the dominant sediment sources consist of upland mass wasting processes and colluvial deposits at the bases of slopes. For example, in headwater streams in

TABLE 2 Sediment-hydrologic connectivity scenarios and case studies.

Sediment-hydrologic connectivity scenario	Case study	Study location	Study method	Main geomorphic and hydrologic processes	Space/time scales
Old Water- Upland Sediment (OW-US)	(Montgomery et al., 2002)	Study catchments in the Mettman Ridge of Oregon Coast Range in Oregon (US) consist of steep, highly dissected soil-mantled hillslopes with steep channels typical of the Pacific Northwest Coast Range. -Drainage area: 0.86 km² (CB1 catchment), 3.27 km² (CB2 catchment) -Land Use/Land Cover: Forested with young Douglas fir -Annual Rainfall: 1,500 mm -Lithology/soil: Fractured and weathered bedrock with increasingly thick soil toward hollows (1.4–2 m) with local variability	Experimental study compares two steep valleys to (1) document colluvium accumulation from landslide, (2) measure shallow bedrock flow in both storm runoff and base flow generation, and (3) observe the influence on debris-flow initiation in the colluvium-mantled sites. -Instrumentations: Bedrock and soil piezometers, automated piezometer nest, automated rain gauge along hillslope, and weirs at the bottom of hillslope in nested catchments -Experiments 1–2: February 1992 observations from experiments and natural storms -Experiments 3: May–June 1992 observations -Runoff measurement at the weir: December 1989–February 1992	Landslides are major geomorphic process and channels begin at landslide scars. Hydrologic interaction between colluvial soil and fractured bedrock influences runoff generation mechanism. Lateral saturated drainage through spatially heterogenous near-surface fractured bedrock system determines locations of debris-flow initiation.	-Event dynamics: Interplay between flow in the colluvial soil and underlying fractured bedrock was observed during intense storms in winter months. During lower intensity storm events in Spring months, nearly all runoff passes through the bedrock before emerging from the soil. Soil and bedrock conductivity distribution implies that the colluvial soil is highly conductive in general, depending on the gradients and bedrock/colluvium contact. -Seasonal variation: though consistent event-driven response was documented in the fractured bedrock, which varied depending on antecedent soil moisture and available bedrock storage, near-surface bedrock response showed seasonal dynamics, implying slow vertical unsaturated flow and lateral drainage of the near-surface bedrock.
	(Kukulak et al., 2022)	Central Western Carpathians and adjacent part of the Outer Western Carpathian, at the foothills of the Tatra Mountains (EU), where landslide sites intersect with Czarny Dunajec River and its tributaries in Wielki Rogoznik. -Drainage Area: 134 km² (Czarny Dunajec); 125 km² (Wielki Rogoznik) -Land Use/Land Cover: Dense forestation mixed with deforestation and agricultural conversion in low-mountain area -Annual Rainfall: 900–1,100 mm with seasonal variation and freeze-thaw cycle. -Lithology/soil: A tectonic basin with Neogene freshwater mudstones, claystones, and sandstones and overlying Quaternary alluvial sediments of the Podhale Flysch series	Geomorphic mapping: detailed soil profiles of the undercut landslide fronts, which are differently positioned in relation to rivers and rates/volumes of colluvium removal were measured using terrestrial LiDAR. Frequency of mapping: 6 times after spring thawing episodes (2013–2019) and 12 times after major water-level rises (2 times in 2013, 2015, and 2017; 6 times in 2019) Daily recording of water levels in 2013–2019 at river gauging stations.	A rotational landslide originated in 1980 and great displacements occurred episodically in 1997 and 2001, but the front of colluvium continue to descend to the river and being undercut by lateral erosion. Particularly with water level rising, erosion in the front of colluvium occurred, which was immediately replaced by new supplies of colluvium from the reactivated landslide. Transverse/diagonal landslide was triggered by undercutting of a concave bank of a migrating river bend over its whole length since 1934. Groundwater infiltration into mudstone from the overlying gravel contributed to the basal detachment of the landslide, and during high stage of river, erosion occurred in the massive cohesive mudstones and in the displaced and rotated colluvium.	Erosion and removal of colluvium and its mudstone foundation occurred episodically during high flow events with abundant rainfall or sudden thaw in 2014 (4–6 days) and again in 2017 when the water level reached similar values. Smaller sediment connectivity to colluvium in the landslide front occurred during the observation period of normal flow conditions with landslide saturation and small to normal water level oscillations. Many factors contributed to the timing and spatial extent of erosion and supply of colluvium, including intensity of precipitation, rate of water infiltration, lithology and mechanical properties of colluvium, landslide tongue mobility, shape and size of the river channel, and temporal dynamics of river discharge.

(Continued)

TABLE 2 (Continued)

Sediment-hydrologic connectivity scenario	Case study	Study location	Study method	Main geomorphic and hydrologic processes	Space/time scales
	(Rose et al., 2018)	White Clay Creek in the Delaware drainage basin (US) located within the Piedmont physiographic province. -Drainage Area: 7.25 km^2 -Land Use/Land Cover: Agriculture (pasture and row crop) with hardwood forest cover in riparian areas -Annual Rainfall: 860–1,320 mm -Lithology: Micaceous schist and gneiss to quartzite bedrock overlain by deep, unglaciated soils.	Samples of suspended particulate material (SPM) were collected during 15 storms from 2011 to 2012, including Hurricane Irene in August 2011 with 167 mm of rainfall over 30 h and Tropical Storm Lee 8 days later adding 171 mm of rain fall in 48 h. Hurricane Sandy occurred in October 2012 with 137 mm of rainfall over 66 h. -SPM collection: particulate organic carbon (POC) and nitrogen (PON) contents, stable isotopic composition, grain size, Brunauer-Emmett-Teller (BET) mineral surface area, and major elements. -Source material collection: same suite of physical and chemical analyses as SPM in landscape surface and subsurface materials, as well as from near/in-channel (streambank, gulley wall, and riparian trails).	Comparison of source materials with SPM samples collected during seasonal and hurricanes/tropical storms indicates different contributions of source materials. During high flows, landscape source areas throughout the watershed were the primary contributor through hydrologic connectivity and physical transport on land surface (see **NW-US** scenario). During low flows, groundwater flowpaths shifted throughout the hydrograph and the particulate material fingerprinting indicates resuspension and delivery of upland sediment in temporary storage within the stream.	Event sediment sourcing and dynamics were closely related to the magnitude and intensity of storm events in this small catchment system. Also, the sourcing of primary sediment depended on characteristics of previous storms and dominant flow paths. Thus, the understanding of the sediment dynamics over long periods relied on the individual events and their sequence.
New Water-Upland Sediment (NW-US)	(Alessio et al., 2021; Morell et al., 2021)	Burned hillslopes generated debris flow in six catchments above Montecito, California (US) -Drainage Area: 19.5 km^2 -Land Use/Land Cover: forest burned to ashy cover -Annual Rainfall: 460 mm -Lithology/soil: Juncal shale, Matilija Sandstone, Cozy Dell Shale, and Coldwater Sandstone. Loam with sand, silt, clay, silt loams	Field observation and soil samples were collected from rill channels and rill networks on both shale and sandstone units several weeks after a rainstorm. Structure from Motion (SfM) photogrammetry and LiDAR DEM were used for spatial analyses. Rill networks were mapped and measured using SfM-derived DEM using TopoToolbox. Interrill erosion estimates were made using regression equations for the solids-concentration in the runoff as a function of rainfall intensity and plot gradient. Catchment-wide soil evacuation volumes were estimated using the relationship that combine the effects of width, depth, and spacing of rill and interrill erosion to the average lowering of the hillslope surface. Runoff modeling was conducted given the infiltration capacity of the soil during the rainstorm (Philip infiltration equation), burn intensity and severity, and soil texture (Manning roughness coefficient). Topsoil stability and slurry discharge were estimated.	In post-fire conditions, the largest contribution of sediment was colluvium during rill formation and debris-flow deposit accumulation in streams activated by a brief, intense rainstorm. The extent, pattern, and volumes of post-fire hillslope erosion depended on rainfall, runoff, and landscape characteristics. Different lithological and topographic features affected the extent and dimensions of rills and volumes of slurry mixing of water and sediment.	The occurrence of wildfire altered the hydrologic and sediment connectivity for a long period afterwards.

(Continued)

TABLE 2 (Continued)

Sediment-hydrologic connectivity scenario	Case study	Study location	Study method	Main geomorphic and hydrologic processes	Space/time scales
	(Blake et al., 2009)	A first order tributary of Blue Gum Creek in the Nattain National Park, New South Wales (AU) -Drainage area: 0.9 km^2 -Land Use/Land Cover: Native eucalypt woodland/forest conservation zone, which was burnt extensively in 1968, 1994, and 2001/2002 -Annual Rainfall: 840 mm -Lithology/soil: Hawkesbury Sandstone. Sandy loams and loamy sands.	Fallout radionuclides (^{210}Pb$_{xs}$, ^{7}Be, ^{137}Cs) tracers and sediment budget approaches were used to compare constituent landscape units.	Upland sources (ridgetops and steep valley sideslopes) made up the dominant part of the sediment budget given post-fire erosion susceptibility in hillslope according to a sediment budget analysis using fallout radionuclide (FRN) tracers in a post-fire catchment.	Compared to Morell et al. (2021) and Alessio et al. (2021) providing insights into post-fire hydrologic and sediment connectivity with a multi-watershed-scale study, this study, localized at first order stream, showed consistent runoff and sediment response to rainfall events.
	(Bartley et al., 2007)	Weany Creek is a subcatchment of the Burdekin Catchment in North Queensland (AU) -Drainage area: 13.5 km^2 -Land Use/Land Cover: Cattle grazing land with grass and canopy vegetation -Annual rainfall: 584 mm -Lithology/soil: granodiorite bedrock	Erosion measurement methods (erosion pins, flumes, and cross-section survey) were applied to estimate hillslope erosion, gully erosion and deposition, bank erosion, channel bed erosion and storage, and fine sediment export at the catchment outlet.	The sediment budget compiled for this arid and grazed small catchment during drought conditions indicates high sediment connectivity between hillslopes and the channel network particularly at headcut locations and gullies, where they make up the largest proportion of the sediment budget	In a semiarid environment, runoff is activated from summer convective storms, snowmelt runoff, and rainfall on snowpack. Overland flow generation is critical in soil erosion and delivery, and its patterns are influenced by infiltration. Thus, sediment connectivity is event-based, and the removal of sediment sourced from upland by overland flow depend on the spatial organization of the lithology, topography, surface roughness.
New Water-Near/in-channel Sediment (NW-NS)	(Gellis et al., 2020)	Dead Run urban watershed in Baltimore, Maryland (US): All natural stream channels were buried during urbanization in this Mid-Atlantic urban stream. -Drainage area: outlet of buried channel network (0.369 km^2) nested in the Dead Run watershed (1.63 km^2) -Land Use/Land Cover: About one-half of the area is impervious (roads, rooftops, and parking lots) and the other half is non-impervious and open space (lawns, parks, and green space) -Annual Rainfall: 1,500 mm -Lithology/soil: Mount Washington Amphibolite subunit of the Baltimore Complex of the Piedmont Physiographic province.	Rainfall, stormwater runoff, pavement sediment, soil, streambank material, and fluvial sediment were collected during three period between 2017 and 2018 seasons. Geochemical fingerprinting using radiogenic and elemental tracers (^{7}Be, ^{210}Pb$_{ex}$, and ^{137}Cs) in the rain, runoff, pavement sediment, and soil (surficial soil and eroding streambanks) samples was conducted. Fluvial sediment and bed material samples were collected at gage locations after rainfall.	All surface runoff was routed through buried channel network via numerous storm drains to open channels. Rainfall-runoff entrained a relatively small amount of sediment from impervious surfaces. Runoff from impervious surfaces and storm drain network resulted in high peak flows in open channels, leading to channel widening, streambank erosion, and channel incision (57% of the budget) as verified by the numerical tagging of ^{7}Be and ^{210}Pb$_{ex}$ activities. Pavement sediment contributed only 4% at the Dead Run watershed outlet demonstrating the relatively small contribution from upland connectivity.	The analysis evaluates event-scale urban hydrology and sediment connectivity of various sources, ranging from topsoil, pavement soil to streambank. The nested study design allowed evaluation of sediment connectivity at different spatial scales.

(Continued)

TABLE 2 (Continued)

Sediment-hydrologic connectivity scenario	Case study	Study location	Study method	Main geomorphic and hydrologic processes	Space/time scales
	(Cashman et al., 2018)	Difficult Run urban/suburban watershed, Virginia is one of the most urbanized and densely populated areas in US -Drainage area: 14.2 km^2 -Land Use/Land Cover: High intensity development, low-density residential, and forested and open land -Annual Rainfall: 1,100 mm -Lithology/soil: Gneiss and schist bedrock. Channels exhibit mill dam legacy sediment stratification	Sediment sampling from spring 2010 and summer 2011 at source locations (streambanks, forest soil, and road dust). Suspended sediment target and bed samples were collected at USGS gage location across 18 storm events (50 samples) from 2008 to 2012. Fingerprinting analysis was conducted using SEDiment Source Assessment Tool (SEDSAT). Sediment delivery ratio was calculated by taking the source-specific fraction of the suspended sediment load and dividing by source-specific erosion inputs.	With impervious surfaces across the watershed, streams exhibited flashy hydrograph through rapid draining of urban areas and increased volume of storm runoff delivered to the channel over short time frame, resulting in greater peak flows and energy. Streambank materials were in storage in bed and contributed to suspended sediment loads. Bank-derived sediment was remobilized from in-channel storage and made up the greatest proportion of the sediment budget (85%).	Compared to Gellis et al. (2020), this study covering a larger urban/suburban drainage area with mixed land use showed similar observation of streambank erosion and resuspension of fine sediment in bed storage in response to flashy hydrograph. The study site is affected by the historical agricultural land use and post-colonial sediment accumulations (i.e., legacy sediment) in valley bottoms, which affect the contemporary sediment budget, indicating the importance of long-term land use changes on both hydrological and sediment connectivity.
	(Dalzell and Mulla, 2018)	Seven Mile Creek, located in south-central Minnesota (US) -Drainage area: 90 km^2 -Land Use/Land Cover: Corn and Soybean agriculture -Annual Rainfall: 833 mm -Lithology/soil Poorly drained glacial geology with subsurface drainage tiles and ditches on flat terrain (<1%)	Precipitation, flow, and water quality data were collected at three locations (two at the drainage of flat upland and one at the watershed outlet) from 2002 to 2008. Sediment loads were generated with the FLUX model. Soil and Water Assessment Tool (SWAT) model was set up to operate at daily time-step and relies on both process-based and empirically based approaches to simulate agricultural management practices. The extent of tile drainage was mapped using aerial photograph analysis	∼96% of the cultivated land is in tile drainage. Under the current watershed condition, ∼76% of sediment loading originated from non-field sources, including streambanks and ravines with increased water yield and streamflow. And the modeling results demonstrate that a relatively minor shift in cropping system to include more perennial vegetation, or conservation practices to effectively store more water on the landscape, showed potential to reduce significant sediment export by changing the water budget of the landscape, illustrating the important coupling between sediment sources and watershed hydrology.	Watershed-scale hydrologic and sediment simulation model was used to aggregate the local effects of tile drainage on watershed hydrology and in-channel processes. The model was run at daily time step to simulate these processes from 2002 to 2008 to demonstrate long-term water and sediment impact of changing agricultural practices.

(Continued)

TABLE 2 (Continued)

Sediment-hydrologic connectivity scenario	Case study	Study location	Study method	Main geomorphic and hydrologic processes	Space/time scales
Old Water - Near/in-channel Sediment (OW-NS)	(Lloyd et al., 2016)	Comparative study of Hampshire Avon catchments in UK (here we focus on groundwater-dominated chalk catchment, Wylye). -Drainage Area: 50.22 km^2 -Land Use/Land Cover: Agriculture mixed with semi-natural woodland, pasture, and arable land -Annual Rainfall: 860-970 mm -Lithology/soil: chalk geology	15-min interval stage height, stream velocity, and turbidity measures. A 30-min interval nitrate-N (UV optical sensor) and total phosphorus (wet chemistry analyzer) data. A storm was defined as any hydrological response to rainfall which resulted in a rising and falling limb with discharge increase of 20% of baseflow. In 60 storms for turbidity were observed. Antecedent precipitation indices (API) and hysteresis indices (HI) were calculated for all the storms defined.	Wylye is primarily groundwater driven with slow-changing baseflow component of the hydrograph with flashy responses during storm events from overland contribution. Short-term discharge dynamic affected the hysteretic direction and strength, and the antecedent conditions influenced the hysteretic behavior indicating importance of hydrologic residence time on sediment sourcing and mobilization. Strong clockwise hysteresis occurred during larger storm events, indicating near- and in-channel sources or resuspension of fine-grained sediment stored in channel bed might dominate sediment loading in the river system.	Relative change in discharge influenced the hysteretic behavior more significantly than the absolute magnitude of the storm.
	(Rose and Karwan, 2021)	Plum Creek in northeastern Wisconsin, US -Drainage Area: 54.3 km^2 -Land Use/Land Cover: Mixed use agriculture (cultivated crops, grassland/pasture, developed areas, forest, and wetlands) -Annual Rainfall: 830 mm -Lithology/soil: silt loams, silty clays, and clay loams	Stream water for total suspended sediment (TSS) and soluble reactive phosphorus (SRP) were collected during five events at nested upper agricultural tributary and during eight events at the watershed outlet. Antecedent precipitation in the week prior to each event was quantified. Quantitative metrics: (1) linear best-fit slope of log(C)-log(Q) relationship to discern "enrichment" "dilution" or "chemostatic" patterns; (2) the ratio of the coefficient of variation of concentration and discharge (CV_C/CV_Q) to differentiate chemostatic and non-linear chemodynamic patterns; (3) HI to characterize hydrologic and biogeochemical dynamics using visual inspection; Flushing Index (FI) to examine dilution or enrichment on the rising limb; linear regression to evaluate the relationships between precipitation and event characteristics and TSS/SRP responses.	In the upstream portion of the watershed primarily in agricultural land use, strong anti-clockwise hysteresis was observed associated with streambank failure in the falling limb as the storm water receded. At the downstream portion, characterized by steep slope channels and high streambank erosion, clockwise hysteresis was dominant, indicating mobilization of sediment stored in stream or near-channel.	Non-linear chemodynamic TSS response may have reflected occurrences of mass streambank failure during non-peak flow periods. A longer recovery period between events increased the pool of sediment available for transport during subsequent events. Main source of sediment (upland vs. near-channel) depended on watershed wetness (i.e., API) from previous events. Thus, **OW-NS** can readily shift to a different sediment-hydrologic connectivity regime (e.g., N—US), event by event. Thus, the understanding of the sediment dynamics over long periods relies on individual events and their sequence.

(Continued)

TABLE 2 (Continued)

| Sediment-hydrologic connectivity scenario	Case study	Study location	Study method	Main geomorphic and hydrologic processes	Space/time scales
	(Belmont et al., 2011)	The incised downstream portion of the Le Sueur River Basin in southcentral Minnesota, US -Drainage Area: 2,880 km^2 -Land Use/Land Cover: row crop agriculture with tile drainage -Annual Rainfall: 833 mm -Lithology/soil: a series of stacked fine-grained tills, deposited over several glacial cycles, interbedded with glaciofluvial sands and gravels.	Sediment budgets constrained through analyses of high-resolution LiDAR topography data and dating of strath terraces. Geochemical fingerprinting using naturally occurring radiogenic tracers measured in suspended sediment samples at multiple gages and Lake Pepin sediment cores.	Increased river discharge in the watershed–from landscape modification with agricultural tile drainage coupled with changing rainfall patterns–has accelerated erosion of streambanks and bluffs, amplifying natural incisional process initiated by baselevel drop that occurred at the beginning of Holocene. Near/in-channel sources (streambank, bluff erosion, channel) became the greatest contributor of the sediment budget (80%) of the watershed.	Long-term changes in the main sediment sources determined using multiple lines of evidence highlight the complexity of large watershed as well as changes in climate and land use that alter both watershed hydrology and sediment supply.
	(Day et al., 2013a,b)	Le Sueur River Basin (see Belmont et al., 2011)	Aerial photographs from 1938 and 1971 were digitized and georeferenced then compared against 2005 photographs. LiDAR topographic data is used to map bluffs, and their retreat rates extrapolated using historic aerial photographs. Terrestrial laser scanning data were collected annually from 2007–2010 at 15 sites to produce high-resolution data on 482 surveyed bluffs.	Bluffs as tall as 65 m line ~80 km of the incised channel in downstream portion of the Le Sueur River Basin and are the largest sediment source (46–54% of the total sediment load). Sapping from groundwater and freeze-thaw processes, along with toe erosion through fluvial abrasion and shear, weaken and erode till material on bluffs. Additionally, given the analysis of stable water isotopes in agricultural landscape in Minnesota (Zhang et al., 2022) and the watershed configuration, river discharge in the incised channel in the downstream portion of the Le Sueur River Basin consist of water that traveled through tiles, ditches, and subsurface pathways from the flat terrain in the upper portion of the watershed over many months.	Long-term changes in channel morphology using historical photographs at watershed-scale and short-term high-resolution study at specific bluff locations were used to quantify the impact of watershed hydrology on near-channel contribution. Synthesis of these various observational methods provided robust estimates of erosion over varying time scales, and the effects of anthropogenic changes to landcover and hydrology.
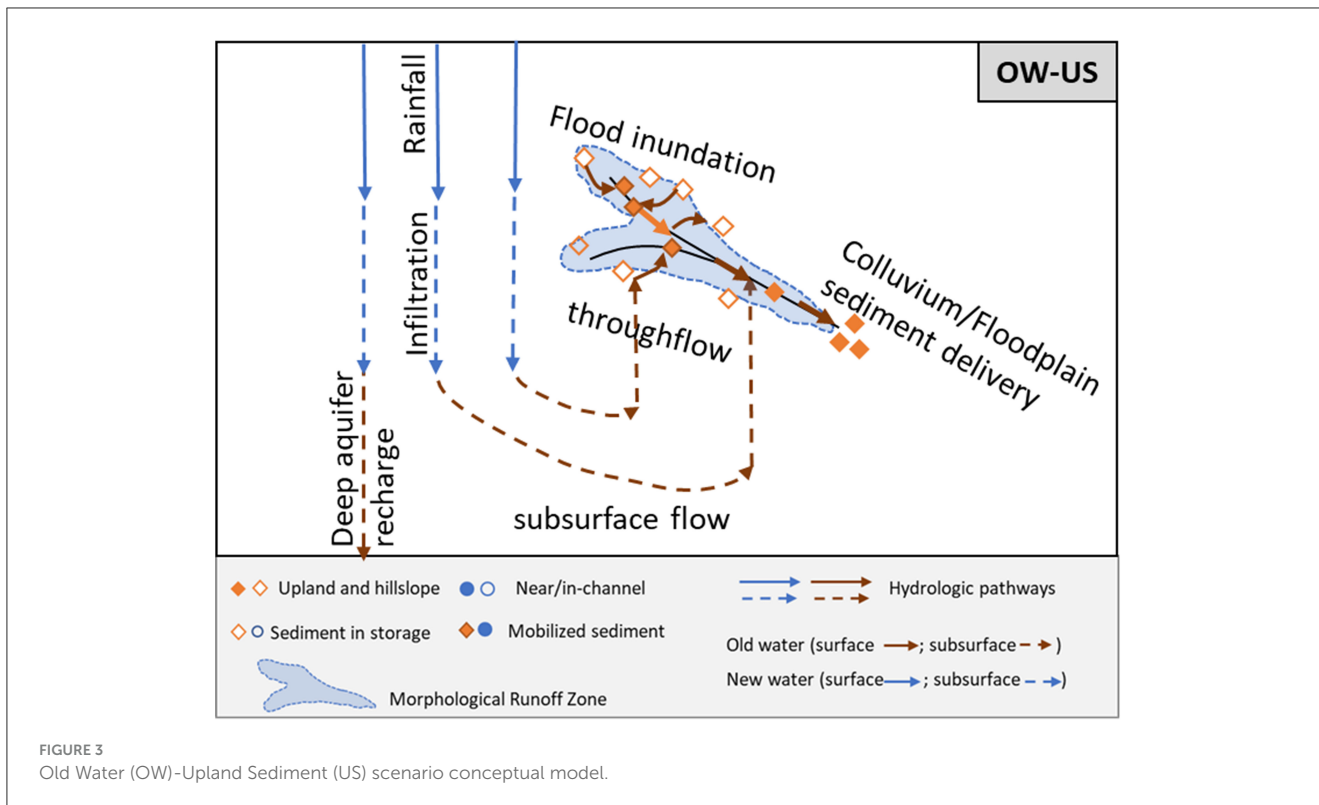
FIGURE 3
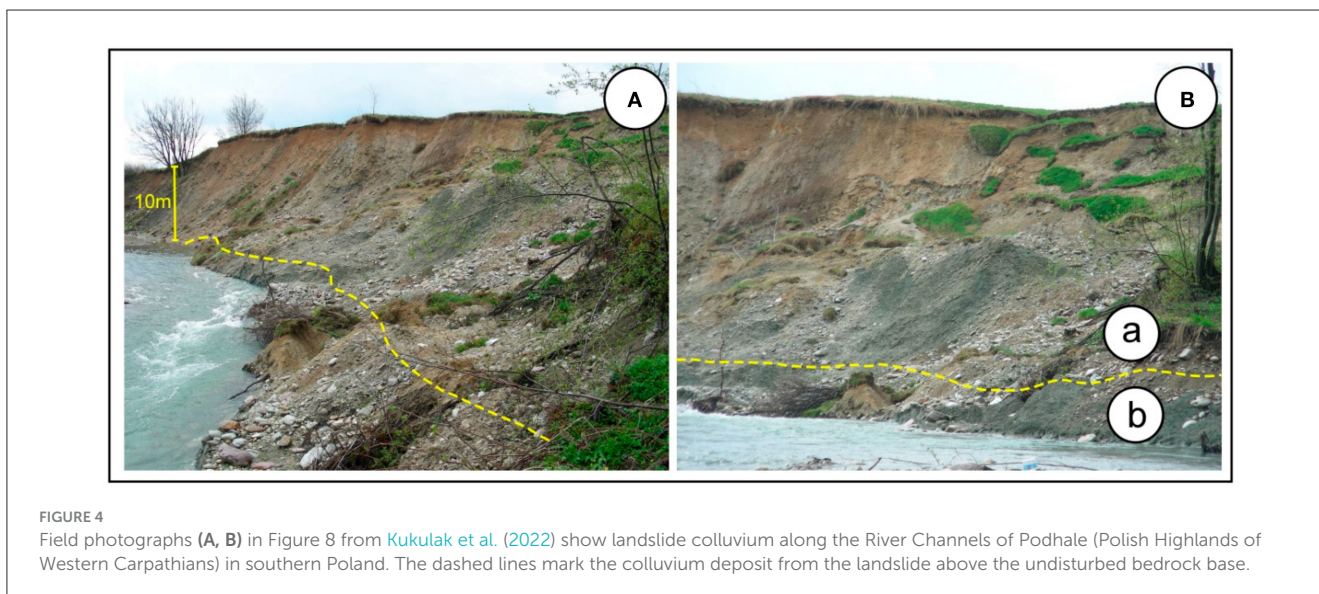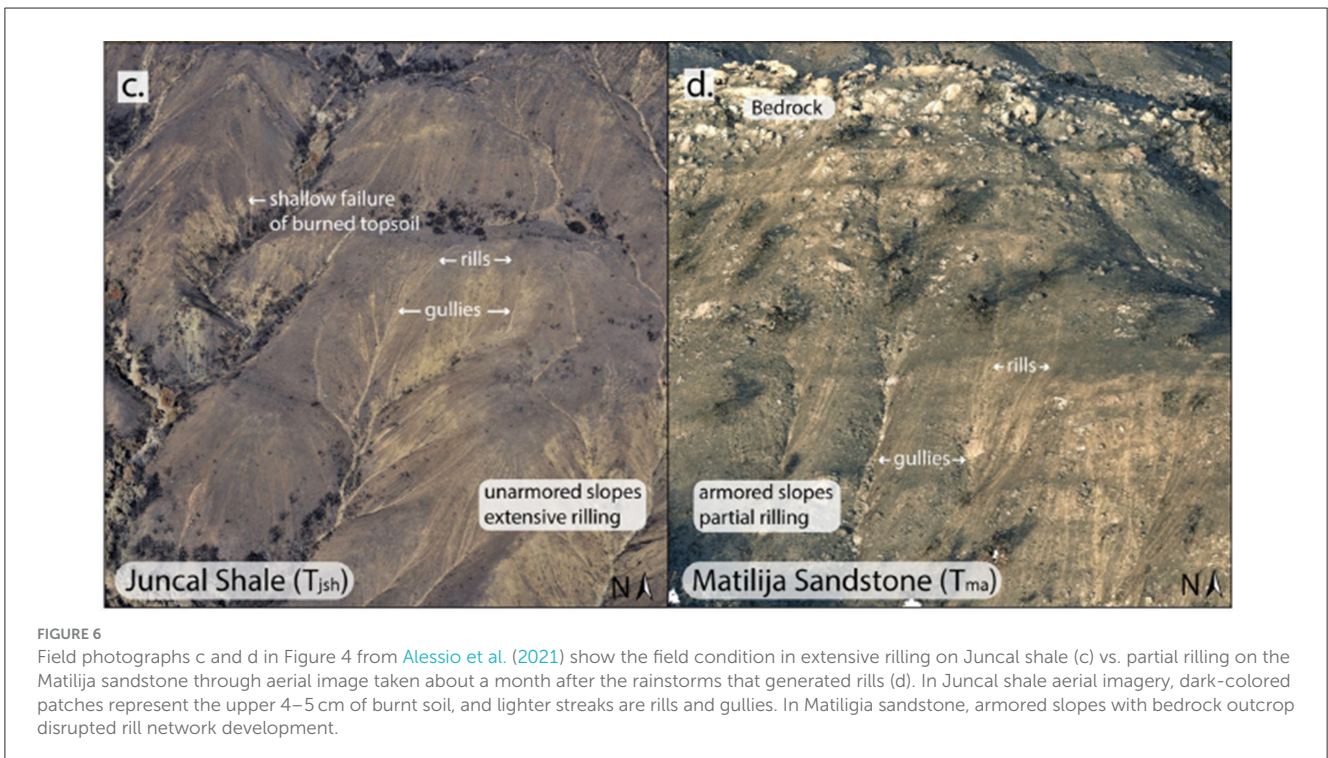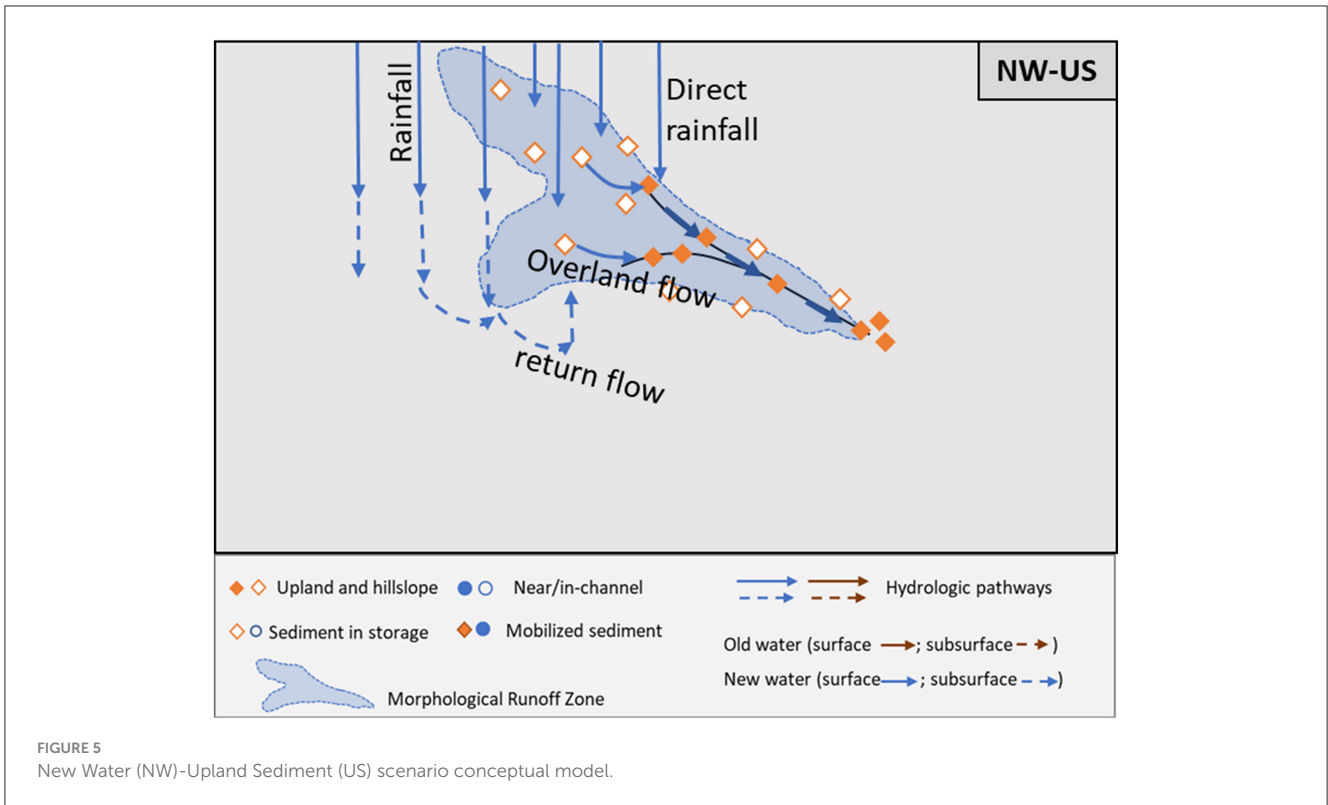Old Water (OW)-Upland Sediment (US) scenario conceptual model.

FIGURE 4
Field photographs **(A, B)** in Figure 8 from Kukulak et al. (2022) show landslide colluvium along the River Channels of Podhale (Polish Highlands of Western Carpathians) in southern Poland. The dashed lines mark the colluvium deposit from the landslide above the undisturbed bedrock base.

mountainous regions dominated by steep confined valleys with little to no flood accommodation areas, landslides and debris flows are important sources of sediment (Ward, 1997). Additionally, if the landscape exhibits high infiltration rates and limited overland flow, streams are mainly charged through groundwater discharge [i.e., Old Water (OW)]. In such a system, stream stages are maintained by baseflow, and connectivity is established with Upland Sediment (US) through flushing temporarily stored colluvium in the valley bottom or through slope failure following rainfall events

(e.g., infiltration and drainage, resulting in increased pore pressure, and landsliding). At the same time, the stream sediment delivery capacity is increased for a prolonged period after rainfall events through continued subsurface recharge (Figure 3).

The OW-US scenario may be observed in both colluvial headwater channels and floodplain channels, depending on a site's topographic, geologic, and climatic characteristics. For example, Montgomery et al. (2002) document the accumulation of colluvium from landslides and the

FIGURE 5
New Water (NW)-Upland Sediment (US) scenario conceptual model.

FIGURE 6
Field photographs c and d in Figure 4 from Alessio et al. (2021) show the field condition in extensive rilling on Juncal shale (c) vs. partial rilling on the Matilija sandstone through aerial image taken about a month after the rainstorms that generated rills (d). In Juncal shale aerial imagery, dark-colored patches represent the upper 4−5 cm of burnt soil, and lighter streaks are rills and gullies. In Matiligia sandstone, armored slopes with bedrock outcrop disrupted rill network development.

importance of shallow bedrock flow in both storm runoff and base flow generation, from which the influence on debris-flow initiation was observed in the colluvium-mantled sites. Similarly, Kukulak et al. (2022) report hydrological factors affecting the rate and patterns of fluvial erosion of landslide colluvium at its contact with river flows along river channels of Podhale in southern Poland. In this study site, groundwater seepage through the landslide tongue toward the channel instigated creep and steep scarp formation within the colluvium exposed at the channel banks. The colluvium
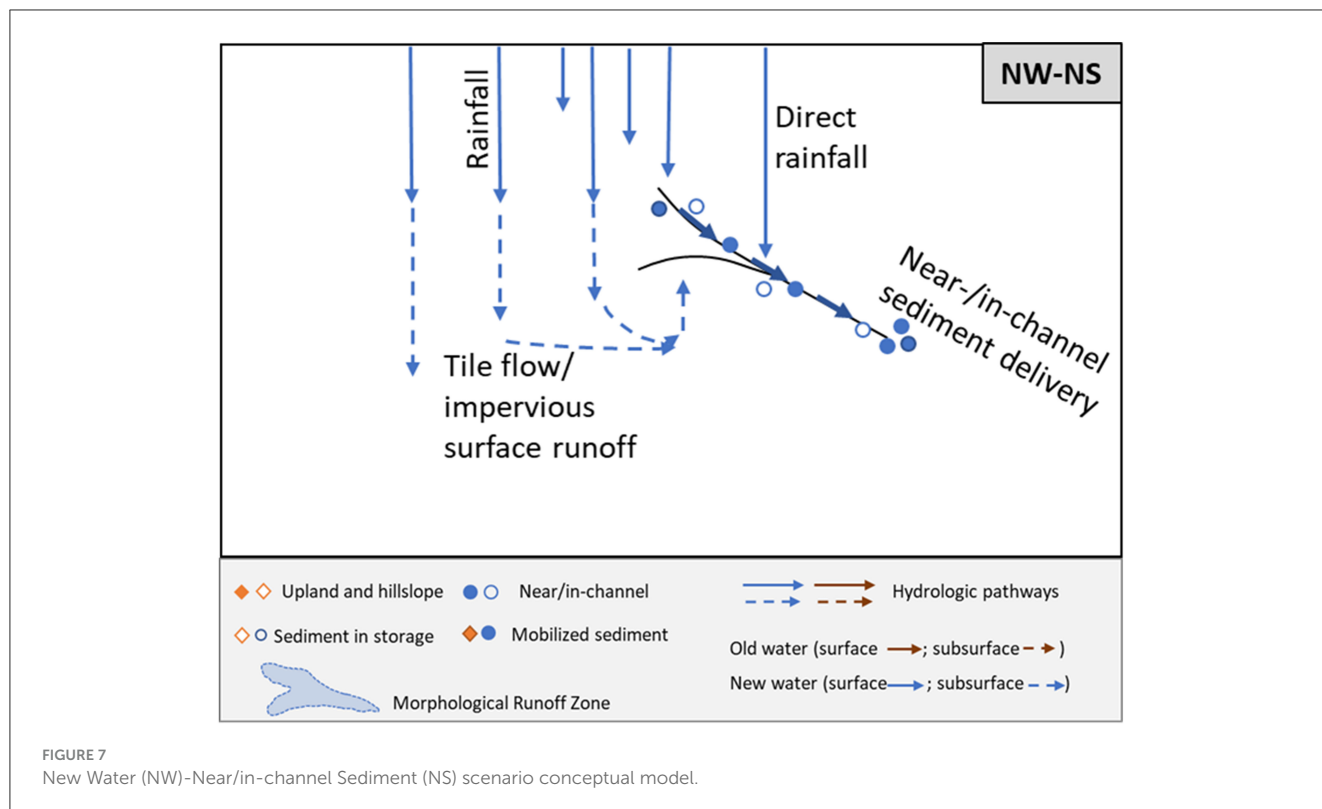
FIGURE 7
New Water (NW)-Near/in-channel Sediment (NS) scenario conceptual model.

deposited from landslide events (in Figure 4, dashed lines mark the colluvial deposit from the landslide above the undisturbed bedrock) was accessed during high flows as the enduring high river stages over many days forced rises of phreatic level in colluvium adjacent to the channel and lowered its friction resistance to failure. On the falling limb, the river water continued to erode the colluvial layer as the pore water drained during a rapid fall of the flood wave when the river is mainly recharged through baseflow. Rise in the groundwater level through infiltration within landslides after a rainfall event also led to the reactivation of slope failure and increased the supply of colluvium to the channels (Kukulak et al., 2022).

In another exampl e from a small stream in the Mid-Atlantic USA, Rose et al. (2018) observed the combination of OW and US loading during an extreme climate event (ECE). During Hurricane Sandy (137 mm of rainfall from 23 to 30 October 2012), spatially variable groundwater inputs to the stream throughout the hydrograph were observed (Sawyer et al., 2014), and fingerprinting of particulate material indicated resuspension and delivery of US in temporary storage within the stream. However, during a previous ECE (Hurricane Irene with 167 mm rainfall over 30 h on 27–28 August 2011), upland source areas throughout the watershed were the primary contributor through precipitation runoff and physical transport on the land surface (see **NW-US** scenario). This study illustrates that event sediment sourcing and dynamics are closely related to the magnitude and intensity of storm events. In addition, the sourcing of primary sediment depends on characteristics of previous storms and their impact on the extent and rates of erosion in both upland and near-/in-channel. Thus, the understanding of the sediment dynamics over long periods relies on individual events and their sequence.

- **Connectivity Scenario: New Water-Upland Sediment (NW-US)**

The NW-US regime indicates that primary hydrologic drivers consist of event water from precipitation runoff on surface pathways, and the dominant sediment sources consist of upland mass wasting and colluvium stored at the bases of slopes. For example, in a landscape dominated by overland flow with little infiltration, storm flow consists of New Water (NW). Given limited infiltration where rainfall contributes mostly to runoff generation, the MRZ is where overland flow-activated upland sources are greatest in extent, which contrasts with the OW-US scenario. Particularly with the limited availability of near-channel sources (e.g., bedrock, vegetative buffers, gabion walls, and/or other erosion control measures), the main sediment source would consist of US (Figure 5).

The NW-US scenario may be observed in a semiarid environment, where runoff is activated from summer convective storms, snowmelt runoff, and rainfall on snowpacks, which can initiate incision of montane arroyos and gullies (Gellis, 1998). Overland flow generation is critical in soil erosion and delivery, and its patterns are influenced by infiltration (Kirkby and Chorley, 1967; Dunne and Leopold, 1978). Numerical simulation models of hydrological connectivity conducted in semi-arid environments demonstrate that three factors are important in determining the form of discharge hydrographs: topography (slope length, gradient, flow paths, and convergence),

lithology (infiltration rates), and vegetation (roughness) at the hillslope-channel connection (Reaney et al., 2014). Thus, detachment and transport of sediment from uplands by overland flow depend on the spatial organization of lithology, topography, and surface roughness (Blackburn, 1975; Reaney et al., 2014). For example, a sediment budget compiled for an arid and grazed small catchment during drought conditions indicates high sediment connectivity between hillslopes and the channel network particularly at headcut locations and gullies (Bartley et al., 2007). At the same time, vegetation in the stream promotes the process of sedimentation and increases the resistance to erosion in dryland river channels (Sandercock et al., 2007). In these conditions, the main sediment contribution is the erosion of upland sources from runoff generation where streams act as a net sediment sink.

Landscape disturbance, such as wildfire, can alter watershed hydrology, leading to the NW-US regime. Saturation overland flow develops in the topographic convergence of valley axes (Dunne and Black, 1970) and in areas of soil water repellency, a common post-fire condition (MacDonald and Huffman, 2004). In such conditions, overland flow and soil erosion processes are enhanced, as observed in an *in situ* study coupled with rainfall simulation modeling in a fire-prone bluegum eucalyptus (*Eucalyptus globulus*) plantation in Portugal (Leighton-Boyce et al., 2007). In another study using LiDAR differencing and field observation to map volumes and sources of sediment mobilization from mountain canyons by large post-wildfire debris flows in Montecito, California, it is shown that the largest contribution of sediment was bouldery colluvium and debris-flow accumulation activated by a brief, intense rainstorm (Morell et al., 2021). The extent, pattern, and volumes of post-fire hillslope erosion depended on rainfall, runoff, landscape characteristics, and burn severity. In the same study site in Montecito, the distribution of rills and cross-sectional geometries was mapped on burned hillslopes in the source catchments to demonstrate that different lithological and topographic features affect the extent and dimensions of rills and volumes of slurry mixing of water and sediment (Alessio et al., 2021). Figure 6 illustrates post-rainstorm rill erosion on burned hillslopes of different bedrock compositions from Alessio et al. (2021). Though in-stream erosion can contribute to the overall sediment loading during post-fire storm events, upland sources (ridgetops and steep valley sideslopes) made up the dominant part of the sediment budget given post-fire erosion susceptibility in hillslopes according to a sediment budget analysis using fallout radionuclide (FRN) tracers by Blake et al. (2009). In fact, post-fire conditions can shift dominant sediment sources from gully and riverbank erosion to topsoil derived from hillslope surface erosion. With fire occurrences, transport-limited conditions can be created in channel conduits, where in-channel and floodplains are more likely to store sediment, particularly with high interannual hydrologic variability (Wilkinson et al., 2009).

Additionally, anthropogenic lands cape disturbances, such as urbanization and intensive agriculture, particularly without effective soil conservation in upland areas, can accelerate

FIGURE 8
Channel enlargement (location of tree roots indicate original location of channel bank) caused by urban runoff in an urban stream in Baltimore, Maryland [Photo Source: Allen Gellis (USGS) as appear in Figure 2B of Gellis et al. (2020)].

erosion of topsoil, creating NW-US scenarios. Wolman (1967) presented the process of urbanization of the landscape, particularly from the period of construction, linked to large pulses of sediment yield. Agriculture can also accelerate upland and hillslope erosion, compared to native vegetation and long-term geologic erosion (Montgomery, 2007). Prior to the widespread adoption of agricultural soil erosion control measures (e.g., conservation tillage, grassed waterways, and buffers), upland sources have contributed dominantly to sediment budgets (Trimble, 1985). For example, a sediment fingerprinting study in the Upper Mississippi River Basin demonstrates a pulse of soil erosion from agricultural fields during the mid-20th century, followed by a subsequent shift back toward near-channel sources (i.e., see **NW-NS** scenario) in the recent decades after widespread agricultural soil erosion control measures were adopted in the region (Belmont et al., 2011).

- **Connectivity Scenario: New Water-Near/in-Channel Sediment (NW-NS)**

  The NW-NS regime indicates that primary hydrologic drivers consist of event water from precipitation runoff on surface pathways, and the dominant sediment sources consist of near/in-channel erosional processes. For instance, in a landscape system with small infiltration rates, overland precipitation runoff, and drainage management (e.g., ditches, tiles, and other artificial drainage) control the rapid overland movement of water. Subsequently, streams are flooded with large quantities of NW increasing the erosivity and delivery capacity of the channel during the rainfall event. With the limited availability of overland sediment sources (e.g., impervious surface, vegetative cover, and/or erosion control measures), the primary sediment sources consist of Near-channel Sediment (NS) (Figure 7).

  Anthropogenic landscape disturbance, such as urbanization or intensive agriculture, can alter watershed hydrology and
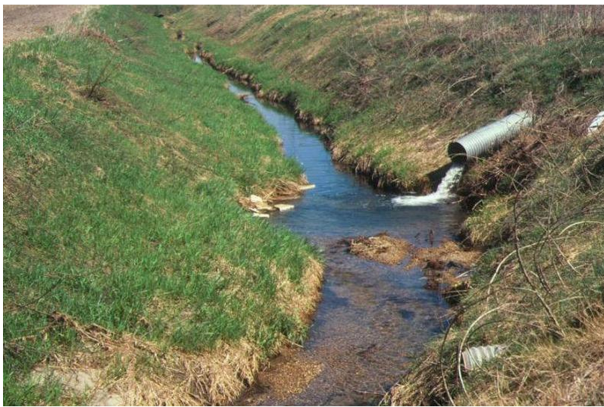
FIGURE 9
Agricultural artificial subsurface tiles draining to a ditch system (photo source: University of Minnesota Extension; https://extension.umn.edu/agricultural-drainage/how-agricultural-drainage-works).

impact dominant sediment sources, leading to a NW-NS scenario. In a study that examines the effects of urbanization on hydrology, it is shown that impervious surfaces and stormwater drainage systems increase and drive runoff (i.e., NW) and amplify the overall peak flood discharge and duration (Paul and Meyer, 2001), which is followed by channel erosion and channel widening or enlargement (i.e., NS), while the sediment production from urbanized landscapes is minimal (Chin, 2006). In a Mid-Atlantic urban stream in Maryland, runoff from impervious surfaces and storm drain network have resulted in high peak flows in open channels, leading to channel widening, streambank erosion, and channel incision (Figure 8) as verified by the numerical tagging of ^{7}Be and ^{210}Pb$_{ex}$ activities (Gellis et al., 2020). Similarly, studies using sediment sampling, elemental tracers, and radionuclide analysis in urban watersheds in Maryland and Virginia show that streambank contributed the greatest quantity of fine sediment (Devereux et al., 2010; Cashman et al., 2018) to the Chesapeake Bay.

Additionally, agricultural tile drainage (Figure 9), particularly at shallow depths or with narrow spacing, is often considered to carry a characteristic concentration–discharge signature of surface runoff (Radcliffe et al., 2015; Smith et al., 2015, 2019). Tile drainage networks and ditch systems have artificially extended the drainage of many watersheds with low permeability on the flat terrain of the headwaters of the Mississippi River Basin (Kelley and Nater, 2000). A modeling study with stream monitoring data from various locations across south-central Minnesota, in which ∼96% of the cultivated land is in tile drainage, evaluates the impacts of altered hydrology on sediment sources (Dalzell and Mulla, 2018). Under current watershed conditions, ∼76% of sediment loading originates from non-field sources, including streambanks and ravines because of increased water yield and streamflow. The modeling results of alternate landscape management demonstrate that a relatively minor shift in cropping systems to include more perennial vegetation, or

conservation practices to effectively store more water on the landscape, showed the potential to reduce significant sediment export by changing the water budget of the landscape, illustrating the important coupling between sediment sources and watershed hydrology (Dalzell and Mulla, 2018).

- **Connectivity Scenario: Old Water-Near/in-Channel Sediment (OW-NS)**

The OW-NS regime indicates that the primary hydrologic drivers consist of pre-event water from subsurface storage, and the dominant sediment sources consist of near/in-channel erosional processes. For instance, 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) through incision, widening, and lateral channel migration of meander (Figure 10).

In a comparative study of hydrogeological control on hysteresis, Lloyd et al. (2016) demonstrate that in a groundwater-dominated mixed-landuse watershed, slow-changing baseflow with relatively attenuated but flashy responses is observed during storm events. Short-term discharge dynamics affected the hysteretic direction and strength, and the antecedent conditions influenced the hysteretic behavior, indicating the importance of hydrologic residence time on sediment sources and mobilization (Lloyd et al., 2016). Strong clockwise hysteresis occurred during larger storm events, indicating that flushing of readily erodible near- and in-channel sources might dominate sediment loading in the river system. Alternately, Rose and Karwan (2021) infer major sediment sources from concentration–discharge relationships and chemodynamics of Plum Creek in northeastern Wisconsin: Strong anti-clockwise hysteresis is associated with streambank failure observable in the incised channels, which can mobilize large amounts of suspended materials to the stream, as the storm water recedes under baseflow conditions (i.e., Old Water/Near-channel Sediment). These examples demonstrate that the main sources of sediment (upland vs. near-channel) depend on watershed wetness (i.e., antecedent precipitation indices) from previous events. Thus, OW-NS can readily shift to a different regime event by event. The understanding of the sediment dynamics over long periods relies on individual events and their sequence.

In another example, a comprehensive sediment budget was developed using multiple lines of evidence, ranging from field surveys, stream gaging, and sediment fingerprinting to remote-sensing analysis in the Le Sueur River Basin of south-central Minnesota, which is undergoing a transient incisional process following the initial carving of the landscape ∼13,000 years ago that created the baselevel drop of up to 65 m from the surrounding drainage basins to the Minnesota River Valley (Gran et al., 2013). As a result, bluffs as tall as 65 m comprise 1,280 km of channel in the knick zone of the watershed–a high-gradient reaches that have adjusted to the new baselevel (Figure 11). Sapping from groundwater
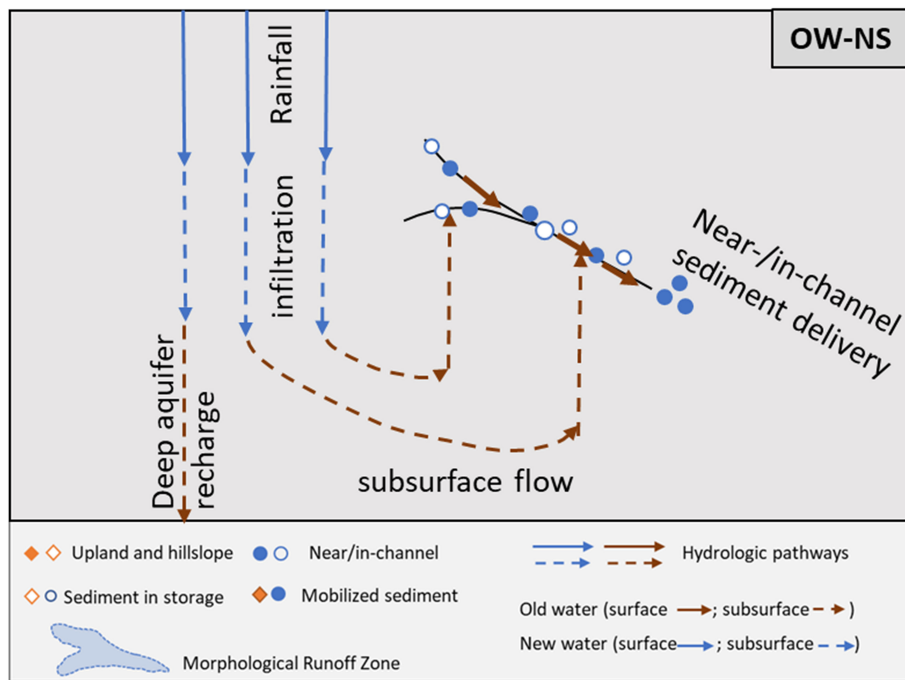
FIGURE 10
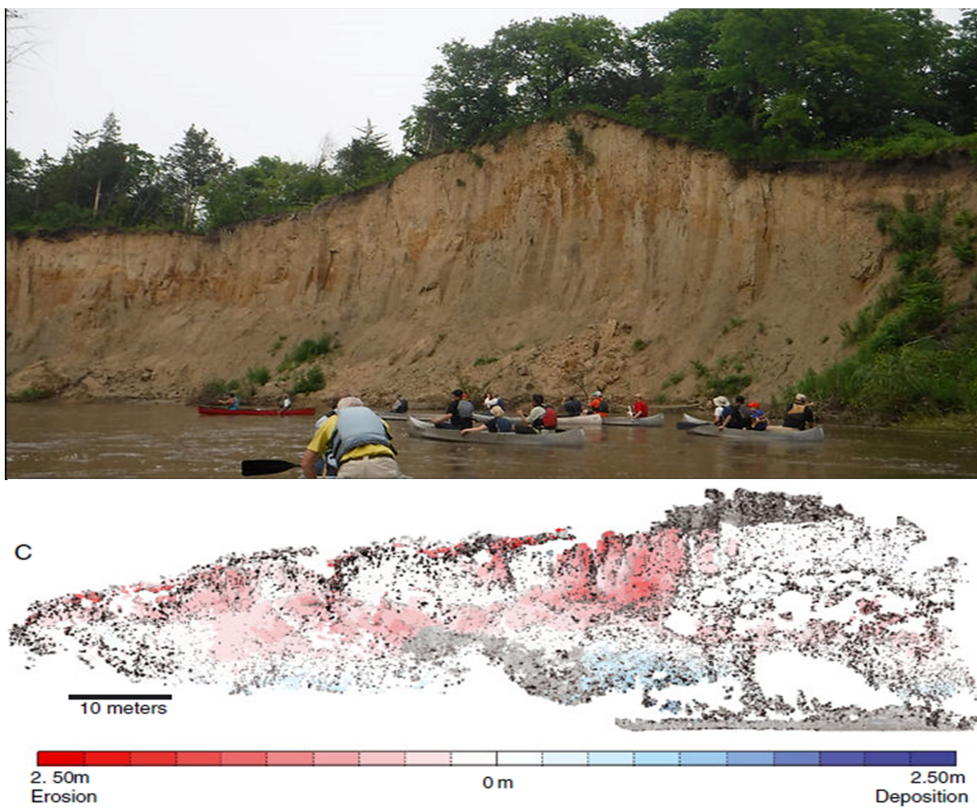Old Water (OW)-Near/in-channel Sediment (NS) scenario conceptual model.

FIGURE 11
Field photograph from Mankato State University Water Resource Center **(top)** shows a typical bluff face along the Le Sueur River with kayakers as a scale. Image C in Figure 7 from Day et al. (2013a) **(bottom)** shows a normally consolidated till bluff where erosion at the top face of the bluff and deposition at the toe are mapped between 2007 and 2008 with terrestrial laser scanning (TLS).

and freeze-thaw processes, along with toe erosion through fluvial abrasion and shear, have weakened and eroded till material on bluffs of the Le Sueur River (i.e., NS) (Day et al., 2013b). Evaluation of the sediment supply in the watershed, derived from geochemical fingerprinting and a suite of geomorphic change detection techniques, indicates that although agricultural soil erosion remains large, the dominant sediment source has shifted from agricultural field erosion to accelerated erosion and over steepening of stream banks and bluffs, driven by increased river discharge (Belmont et al., 2011). In a regional analysis of stable water isotopes, deuterium, and oxygen-18 data from agricultural landscapes of western South Dakota to eastern Minnesota show that precipitation took an average of 9 months to move through different pathways (Zhang et al., 2022). Given the watershed configuration that progressively narrows toward the outlet, along with the independent assessment of water residence time in the region, the water discharge in the incised section of the Le Sueur River likely consists of water that traveled through tiles, ditches, and subsurface pathways from the flat upper portion of the watershed over many months (i.e., OW).

4 Next steps: applying the sediment-hydrologic connectivity conceptual model

The conceptual model and case studies using various observational and modeling techniques can provide guidance for collecting and assembling environmental data. For instance, through the synthesis of existing datasets and monitoring sites with new, coordinated sampling, we can investigate how hydrologic and sediment connectivity affect sediment mobilization at different spatiotemporal scales as illustrated in the selected case studies. In addition, an understanding of how dominant processes shift with different environmental forcing and/or landscape disturbances may be derived from strategic data assemblage using the conceptual model (e.g., various observational and modeling approaches to characterize post-fire sediment delivery described in the NW-US scenarios). Specifically, the collection of distinct isotopic signals in stream water samples collected for various storm events across the watershed can help to characterize dominant flow pathways and residence times at different spatial scales from reaches to basin outlets. Remote-sensing analysis coupled with stream gaging and chemical tracers collected and aggregated over different spatial and temporal scales can provide critical guidance on dominant sediment sources and how they shift with storm size and with changing temporal and spatial scales. For more discussion on environmental measurement techniques for system fluxes (e.g., water discharge and sediment delivery) vs. system phases (e.g., geology, soil, ecology, and geomorphology) to design effective measurement schemes and models at different scales, refer to Keesstra et al. (2018) and the various observational approaches highlighted in the case studies of the previous section.

Numerical simulation of landscape connectivity combined with strategic data collection can help to effectively evaluate and forecast sediment delivery, transport, and storage across spatial and temporal scales and to predict how connectivity shifts with different environmental forcing and landscape disturbances. The conceptual model will be particularly useful when compiling relevant data to characterize water and sediment connectivity using data-driven analyses such as machine-learning (ML) applications. For example, ML models have been developed to predict sediment transport from a wide range of publicly available environmental features by training them with physically collected water and sediment samples (Lund et al., 2022). The more efficient assemblage of available geospatial data could help model interpretation and prediction accuracy. It has been noted that dataset biases occur in ML applications when the training data are not fully representative of the landscape characteristics and planned uses, and the results can be contaminated with the desired outcome and user biases (Zhong et al., 2021). The conceptual model proposed here can be used to check the implicit biases toward desired outcomes by considering the broad spectrum of sediment and hydrologic processes.

5 Conclusion

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, as well as, for developing effective water quality management strategies. The conceptualization and application of sediment connectivity are reviewed in terms of how they frame the continuum of sediment sources, stores, and routes of transport operating under different hydrologic conditions. The landscape connectivity research in recent decades indicates that both sediment connectivity and hydrologic processes affect provenance, pathways, and storages along the sediment cascade and influence their timing and magnitude. We propose 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. Using the conceptual model as a "thinking" tool, we extract case studies from a multidisciplinary literature review—from hydrology, geomorphology, biogeochemistry, and watershed modeling to remote-sensing technology—that correspond to each of the dominant hydrologic–sediment connectivity regimes to examine sediment and water interactions in real-world examples using various observational and modeling techniques. The conceptual model and case studies provide an important foundation for advancing the understanding and predictive capability of watershed sediment processes at multiple spatiotemporal scales and various environmental conditions.

Author contributions

SJC, DLK, KS, JP, and MEH contributed to conception and design of the study. SJC organized and reviewed the literature and wrote the first draft of the manuscript. SJC and DLK wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

Acknowledgments

Conflict of interest

Publisher's note

References

Alessio, P., Dunne, T., and Morell, K. (2021). Post-wildfire generation of debris-flow slurry by rill erosion on colluvial hillslopes. *J. Geophys. Res.* 126, e2021JF006108. doi: 10.1029/2021JF006108

Bartley, R., Hawdon, A., Post, D. A., and Roth, C. H. (2007). A sediment budget for a grazed semi-arid catchment in the Burdekin basin, Australia. *Geomorphology* 87, 302–321. doi: 10.1016/j.geomorph.2006.10.001

Belmont, P., Gran, K. B., Schottler, S. P., Wilcock, P. R., Day, S. S., Jennings, C., et al. (2011). Large shift in source of fine sediment in the Upper Mississippi River. *Environ. Sci. Technol.* 45, 8804–8810. doi: 10.1021/es2019109

Blackburn, W. H. (1975). Factors influencing infiltration and sediment production of semiarid Rangelands in Nevada. *Water Resources Research* 11, 929–937. doi: 10.1029/WR011i006p00929

Blake, W. H., Wallbrink, P. J., Wilkinson, S. N., Humphreys, G. S., Doerr, S. H., Shakesby, R. A., et al. (2009). Deriving hillslope sediment budgets in wildfire-affected forests using fallout radionuclide tracers. *Geomorphology* 104, 105–116. doi: 10.1016/j.geomorph.2008.08.004

Borselli, L., Cassi, P., and Torri, D. (2008). Prolegomena to sediment and flow connectivity in the landscape: a GIS and field numerical assessment. *Catena* 75, 268–277. doi: 10.1016/j.catena.2008.07.006

Bracken, L. J., Turnbull, L., Wainwright, J., and Bogaart, P. (2015). Sediment connectivity: a framework for understanding sediment transfer at multiple scales. *Earth Surface Proc. Landf.* 40, 177–188. doi: 10.1002/esp.3635

Bunn, A. G., Urban, D. L., and Keitt, T. H. (2000). Landscape connectivity: a conservation application of graph theory. *J. Environ. Manag.* 59, 265–278. doi: 10.1006/jema.2000.0373

Cashman, M. J., Gellis, A., Sanisaca, L. G., Noe, G. B., Cogliandro, V., and Baker, A. (2018). Bank-derived material dominates fluvial sediment in a suburban Chesapeake Bay watershed. *River Res. Applic.* 34, 1032–1044. doi: 10.1002/rra.3325

Cavalli, M., Trevisani, S., Comiti, F., and Marchi, L. (2013). Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. *Geomorphology* 188, 31–41. doi: 10.1016/j.geomorph.2012.05.007

Chin, A. (2006). Urban transformation of river landscapes in a global context. *Geomorphology* 79, 460–487. doi: 10.1016/j.geomorph.2006.06.033

Cho, S. J., Wilcock, P., and Gran, K. (2022). Implementing landscape connectivity with topographic filtering model: a simulation of suspended sediment delivery in an agricultural watershed. *Sci. Total Environ.* 836, 155701. doi: 10.1016/j.scitotenv.2022.155701

Cho, S. J., Wilcock, P., and Hobbs, B. (2018). Topographic filtering simulation model for sediment source apportionment. *Geomorphology* 309, 1–19. doi: 10.1016/j.geomorph.2018.02.014

Cho, S. J., Wilcock, P. R., Belmont, P., Gran, K. B., and Hobbs, B. F. (2019). Simulation model for collaborative decision making on sediment source reduction in an intensively managed watershed. *Water Resour. Res.* 55, 1544–1564. doi: 10.1029/2018WR024324

Cislaghi, A., and Bischetti, G. B. (2019). Source areas, connectivity, and delivery rate of sediments in mountainous-forested hillslopes: a probabilistic approach. *Sci. Total Environ.* 652, 1168–1186. doi: 10.1016/j.scitotenv.2018.10.318

Czuba, J. A. (2018). A lagrangian framework for exploring complexities of mixed-size sediment transport in gravel-bedded river networks. *Geomorphology* 321, 146–152. doi: 10.1016/j.geomorph.2018.08.031

Czuba, J. A., and Foufoula-Georgiou, E. (2015). Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change. *Water Resour. Res.* 51, 1401–1421. doi: 10.1002/2014WR016139

Dalzell, B. J., and Mulla, D. J. (2018). Perennial vegetation impacts on stream discharge and channel sources of sediment in the minnesota river basin. *J. Soil Water Conserv.* 73, 120–132. doi: 10.2489/jswc.73.2.120

Day, S. S., Gran, K. B., Belmont, P., and Wawrzyniec, T. (2013a). Measuring bluff erosion part 1: terrestrial laser scanning methods for change detection. *Earth Surface Proc. Landforms* 38, 1055–1067. doi: 10.1002/esp.3353

Day, S. S., Gran, K. B., Belmont, P., and Wawrzyniec, T. (2013b). Measuring bluff erosion part 2: pairing aerial photographs and terrestrial laser scanning to create a watershed scale sediment budget. *Earth Surface Proc. Landforms* 38, 1068–1082. doi: 10.1002/esp.3359

Devereux, O. H., Prestegaard, K. L., Needelman, B. A., and Gellis, A. C. (2010). Suspended-sediment sources in an urban watershed, Northeast Branch Anacostia River, Maryland. *Hydrol. Proc.* 24, 1391–1403. doi: 10.1002/hyp.7604

Dunne, T., and Black, R. D. (1970). Partial area contributions to storm runoff in a small new England watershed. *Water Resour. Res.* 6, 1296–1311. doi: 10.1029/WR006i005p01296

Dunne, T., and Leopold, L. B. (1978). *Water in Environmental Planning*. New York: W.H. Freeman and Co.

Fortuin, K. P., Van Koppen, C. S. A., and Leemans, R. (2011). The value of conceptual models in coping with complexity and interdisciplinarity in environmental sciences education. *BioScience* 61, 802–814. doi: 10.1525/bio.2011.61.10.10

Foufoula-Georgiou, E., Takbiri, Z., Czuba, J. A., and Schwenk, J. (2015). The change of nature and the nature of change in agricultural landscapes: hydrologic regime shifts modulate ecological transitions. *Water Resour. Res.* 51, 6649–6671. doi: 10.1002/2015WR017637

Fryirs, K. (2013). (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. *Earth Surface Proc. Landforms* 38, 30–46. doi: 10.1002/esp.3242

Gellis, A. C. (1998). *Characterization and Evaluation of Channel and Hillslope Erosion on the Zuni Indian Reservation, New Mexico, 1992-95*. U.S. Department of the Interior, U.S. Geological Survey.

Gellis, A. C., Fuller, C. C., Van Metre, P. C., Mahler, B. J., Welty, C., Miller, A. J., et al. (2020). Pavement alters delivery of sediment and fallout radionuclides to urban streams. *J. Hydrol.* 588, 124855. doi: 10.1016/j.jhydrol.2020.124855

Gran, K. B., Finnegan, N., Johnson, A. L., Belmont, P., Wittkop, C., and Rittenour, T. (2013). Landscape evolution, valley excavation, and terrace development following abrupt postglacial base-level fall. *Bulletin* 125, 1851–1864. doi: 10.1130/B30772.1

Hewlett, J. D., and Hibbert, A. R. (1963). Moisture and energy conditions within a sloping soil mass during drainage. *J. Geophys. Res.* 68, 1081–1087. doi: 10.1029/JZ068i004p01081

Karwan, D. L., Pizzuto, J. E., Aalto, R., Marquard, J., Harpold, A., Skalak, K., et al. (2018). Direct channel precipitation and storm characteristics influence short-term fallout radionuclide assessment of sediment source. *Water Resour. Res.* 54, 4579–4594. doi: 10.1029/2017WR021684

Keessstra, S., Nunes, J. P., Saco, P., Parsons, T., Poeppl, R., Masselink, R., et al. (2018). The way forward: Can connectivity be useful to design better measuring and modelling schemes for water and sediment dynamics? *Sci. Total Environ.* 644, 1557–1572. doi: 10.1016/j.scitotenv.2018.06.342

Kelley, D. W., and Nater, E. A. (2000). Historical sediment flux from three watersheds into Lake Pepin, Minnesota, USA. *J. Environ. Quality* 29, 561–568. doi: 10.2134/jeq2000.00472425002900020025x

Kirkby, M. J., and Chorley, R. J. (1967). Throughflow, overland flow and erosion. *Int. Assoc. Sci. Hydrol. Bull.* 12, 5–21. doi: 10.1080/02626666709493533

Klaus, J., and McDonnell, J. J. (2013). Hydrograph separation using stable isotopes: review and evaluation. *J. Hydrol.* 505, 47–64. doi: 10.1016/j.jhydrol.2013.09.006

Kukulak, J., Augustowski, K., and Olszak, J. (2022). Factors affecting the rates and modes of landslide colluvium removal in river channels of Podhale (Western Carpathians). *Water* 14, 3577. doi: 10.3390/w14213577

Leighton-Boyce, G., Doerr, S. H., Shakesby, R. A., and Walsh, R. P. D. (2007). Quantifying the impact of soil water repellency on overland flow generation and erosion: a new approach using rainfall simulation and wetting agent on in situ soil. *Hydrol. Proc.* 21, 2337–2345. doi: 10.1002/hyp.6744

Lloyd, C. E., Freer, J. E., Johnes, P. J., and Collins, A. L. (2016). Using hysteresis analysis of high-resolution water quality monitoring data, including uncertainty, to infer controls on nutrient and sediment transfer in catchments. *Sci. Total Environ.* 543, 388–404. doi: 10.1016/j.scitotenv.2015.11.028

Lund, J. W., Groten, J. T., Karwan, D. L., and Babcock, C. (2022). Using machine learning to improve predictions and provide insight into fluvial sediment transport. *Hydrol. Proc.* 36, e14648. doi: 10.1002/hyp.14648

MacDonald, L. H., and Huffman, E. L. (2004). Post-fire soil water repellency. *Soil Sci. Soc. Am. J.* 68, 1729–1734. doi: 10.2136/sssaj2004.1729

Mahoney, D. T., Fox, J., Al-Aamery, N., and Clare, E. (2020a). Integrating connectivity theory within watershed modelling part i: model formulation and investigating the timing of sediment connectivity. *Sci. Total Environ.* 740, 140385. doi: 10.1016/j.scitotenv.2020.140385

Mahoney, D. T., Fox, J., Al-Aamery, N., and Clare, E. (2020b). Integrating connectivity theory within watershed modelling part II: Application and evaluating structural and functional connectivity. *Sci. Total Environ.* 740, 140386. doi: 10.1016/j.scitotenv.2020.140386

Mahoney, D. T., Fox, J. F., and Al Aamery, N. (2018). Watershed erosion modeling using the probability of sediment connectivity in a gently rolling system. *J. Hydrol.* 561, 862–883. doi: 10.1016/j.jhydrol.2018.04.034

McEachran, Z. P., Karwan, D. L., and Slesak, R. A. (2021). Direct and indirect effects of forest harvesting on sediment yield in forested watersheds of the United States. *JAWRA* 57, 1–31. doi: 10.1111/1752-1688.12895

Montgomery, D. R. (1999). Process domains and the river continuum. *JAWRA J.* 35, 397–410. doi: 10.1111/j.1752-1688.1999.tb03598.x

Montgomery, D. R. (2007). Soil erosion and agricultural sustainability. *Proc. Natl. Acad. Sci.* 104, 13268–13272. doi: 10.1073/pnas.0611508104

Montgomery, D. R., Dietrich, W. E., and Heffner, J. T. (2002). Piezometric response in shallow bedrock at CB1: Implications for runoff generation and landsliding. *Water Resour. Res.* 38, 10–11. doi: 10.1029/2002WR001429

Morell, K. D., Alessio, P., Dunne, T., and Keller, E. (2021). Sediment recruitment and redistribution in mountain channel networks by post-wildfire debris flows. *Geophys. Res. Lett.* 48, 24. doi: 10.1029/2021GL095549

Paul, M. J., and Meyer, J. L. (2001). Streams in the urban landscape. *Ann. Rev. Ecol. System.* 32, 333–365. doi: 10.1146/annurev.ecolsys.32.081501.114040

Radcliffe, D. E., Reid, D. K., Blombäck, K., Bolster, C. H., Collick, A. S., Easton, Z. M., et al. (2015). Applicability of models to predict phosphorus losses in drained fields: a review. *J. Environ. Quality* 44, 614–628. doi: 10.2134/jeq2014.05.0220

Reaney, S. M., Bracken, L. J., and Kirkby, M. J. (2014). The importance of surface controls on overland flow connectivity in semi-arid environments: results from a numerical experimental approach. *Hydrol. Proc.* 28, 2116–2128. doi: 10.1002/hyp.9769

Rose, L. A., and Karwan, D. L. (2021). Stormflow concentration–discharge dynamics of suspended sediment and dissolved phosphorus in an agricultural watershed. *Hydrol. Proc.* 35, e14455. doi: 10.1002/hyp.14455

Rose, L. A., Karwan, D. L., and Aufdenkampe, A. K. (2018). Sediment fingerprinting suggests differential suspended particulate matter formation and transport processes across hydrologic regimes. *J. Geophys. Res.* 123, 1213–1229. doi: 10.1002/2017JG004210

Sandercock, P. J., Hooke, J. M., and Mant, J. M. (2007). Vegetation in dryland river channels and its interaction with fluvial processes. *Progr. Phys. Geogr.* 31, 107–129. doi: 10.1177/0309133307076106

Sawyer, A. H., Kaplan, L. A., Lazareva, O., and Michael, H. A. (2014). Hydrologic dynamics and geochemical responses within a floodplain aquifer and hyporheic zone during hurricane sandy. *Water Resour. Res.* 50, 4877–4892. doi: 10.1002/2013WR015101

Shanley, J. B., Kendall, C., Smith, T. E., Wolock, D. M., and McDonnell, J. J. (2002). Controls on old and new water contributions to stream flow at some nested catchments in Vermont, USA. *Hydrol. Proc.* 16, 589–609. doi: 10.1002/hyp.312

Smith, D. R., King, K. W., Johnson, L., Francesconi, W., Richards, P., Baker, D., et al. (2015). Surface runoff and tile drainage transport of phosphorus in the midwestern United States. *J. Environ. Quality* 44, 495–502. doi: 10.2134/jeq2014.04.0176

Smith, D. R., Macrae, M. L., Kleinman, P. J. A., Jarvie, H. P., King, K. W., and Bryant, R. B. (2019). The latitudes, attitudes, and platitudes of watershed phosphorus management in North America. *J. Environ. Quality* 48, 1176–1190. doi: 10.2134/jeq2019.03.0136

Trimble, S. W. (1985). Perspectives on the history of soil erosion control in the eastern United States. *Agric. Hist.* 59, 162.

Vannote, R. L., Minshall, G. M., Cummins, K. W., Sedell, J. R., and Cushing, C. E. (1980). The river continuum concept. *Canad. J. Fisher. Aquat. Sci.* 37, 130–137. doi: 10.1139/f80-017

Wainwright, J., Turnbull, L., Ibrahim, T. G., Lexartza-Artza, I., Thornton, S. F., and Brazier, R. E. (2011). Linking environmental regimes, space and time: Interpretations of structural and functional connectivity. *Geomorphology* 126, 387–404. doi: 10.1016/j.geomorph.2010.07.027

Ward, J. V. (1997). An expansive perspective of riverine landscapes: pattern and process across scales. *GAIA Ecol. Perspect. Sci. Soc.* 6, 52–60. doi: 10.14512/gaia.6.1.6

Wilkinson, S. N., Wallbrink, P. J., Hancock, G. J., Blake, W. H., Shakesby, R. A., and Doerr, S. H. (2009). Fallout radionuclide tracers identify a switch in sediment sources and transport-limited sediment yield following wildfire in a eucalypt forest. *Geomorphology* 110, 140–151. doi: 10.1016/j.geomorph.2009.04.001

Wohl, E., Magilligan, F. J., and Rathburn, S. L. (2017). Introduction to the special issue: connectivity in geomorphology. *Geomorphology* 277, 1–5. doi: 10.1016/j.geomorph.2016.11.005

Wolman, M. G. (1967). A cycle of sedimentation and erosion in urban river channels. *Geografiska Annaler* 49, 385–395. doi: 10.1080/04353676.1967.11879766

Zanandrea, F., Michel, G. P., Kobiyama, M., Censi, G., and Abatti, B. H. (2021). Spatial-temporal assessment of water and sediment connectivity through a modified connectivity index in a subtropical mountainous catchment. *Catena* 204, 105380. doi: 10.1016/j.catena.2021.105380

Zhang, L., Magner, J., and Strock, J. (2022). Exploring a climate gradient of Midwestern USA agricultural landscape runoff using deuterium (δD) and oxygen-18 (δ18O). *Water* 14, 1629. doi: 10.3390/w14101629

Zhong, S., Zhang, K., Bagheri, M., Burken, J. G., Gu, A., Li, B., et al. (2021). Machine learning: new ideas and tools in environmental science and engineering. *Environ. Sci. Technol.* 55, 12741–12754. doi: 10.1021/acs.est.1c01339