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Papers

Hydrosedimentological Connectivity in Watersheds: A Review of Concepts, Methods, and Models

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Abstract
The increasing application of numerical models and indices has significantly expanded the understanding of hydrosedimentological connectivity in river basins, as it allows the representation of the dynamics of water and sediment redistribution and the assessment of the effects of land use and land cover changes. This study presents a systematic review of the main concepts, methods, and models employed in the analysis of hydrosedimentological connectivity, highlighting the evolution of mathematical modeling from classical theoretical formulations to the incorporation of computational tools widely used in the scientific literature. Among the models discussed, the Soil and Water Assessment Tool (SWAT), the Topographic Model (TOPMODEL), and MIKE 11 stand out, among others, evidencing their applications, potentialities, and limitations in the simulation of hydrosedimentological processes. In addition, connectivity indices are analyzed, with emphasis on the Index of Connectivity (IC), widely applied in estimating the potential transfer of sediments between different landscape compartments and within geomorphological units. Finally, the importance of validating models and indices through field observations and empirical data is emphasized, reinforcing the complementarity between computational modeling and experimental investigation for the advancement of geomorphological, hydrological, and hydrosedimentological studies in river basins, contributing to the improvement of environmental planning and integrated water resources management.

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INTRODUCTION

Water and sediment flow in watersheds is a dynamic process influenced by climate, landforms, geology, and human activity. Natural or artificial flow obstructions warrant targeted studies to predict fluvial impacts across time and space (Almeida; Correa, 2020). In semiarid regions like Northeastern Brazil, rainfall and system energy variability, along with uneven precipitation, add complexity (Souza; Almeida, 2015; Souza; Correa, 2012).

The analysis of these processes is based on the landscape connectivity approach, defined as the capacity for interaction and circulation of matter and energy both between different landscape compartments and within them. Certain sections may be connected or disconnected (Blanton; Marcus, 2013; Brierley *et al*., 2006; Fryirs, 2013; Souza; Correa, 2012; Wohl, 2017), either in hydrological terms (hydrological connectivity) or sedimentological terms (sedimentological connectivity), operating in three dimensions: vertical (surface–subsurface), lateral (hillslope–floodplain–channel), and longitudinal (upstream–downstream) (Blanton; Marcus, 2013; Bracken *et al.,* 2013; Bracken; Croke, 2007).

Human activity has altered watershed connectivity and geomorphic sensitivity, changing water and sediment flows, erosive processes, and valley stability (Poeppl *et al*., 2020). Effects include agriculture, aquaculture, roads, wells, and especially dams, as these greatly change how energy and matter move in rivers Blanton; Marcus, 2013).

Given these changes in flow and geomorphic processes resulting from anthropogenic actions, the concept of connectivity has been widely employed across the hydrological, ecological, geological, and geomorphological sciences, addressing different types of connectivity—hydrological, sedimentological, and landscape—that require an integrated, interdisciplinary understanding. These connections are influenced by climatic, hydrological, and sedimentary factors (Bracken; Croke, 2007; Wohl *et al*., 2019).

Thus, this study aims to review and discuss the main numerical models, indices, and conceptual approaches used in the analysis of hydrosedimentological connectivity, addressing their development, applications, validation methods, and potential expansion in research focused on fluvial geomorphology in humid and semiarid regions. Conducting this review is essential given the growing diversity of models and indices used in connectivity studies, as well as existing gaps in selection criteria, application limits, and tool validation. By systematizing conceptual and methodological advances, this work strengthens the theoretical foundation of hydrosedimentological connectivity and guides more robust analyses across diverse environmental contexts.

CONNECTIVITY APPROACH IN THE ANALYSIS OF SURFACE BIOPHYSICAL FLOWS

The concepts of connectivity have been discussed in geographic research since the mid-20th century, with particular emphasis in geomorphology, where they are defined as the transfer of energy and matter between and within landscape compartments or along the fluvial system. In the 21st century, the topic gained greater prominence, expanding into fields such as Ecology, Geology, Hydrology, and Geomorphology (Bracken; Croke, 2007; Poeppl *et al.,* 2017; Wohl *et al.,* 2019).

Connectivity describes hydrological and sediment transport in geosciences (Baartman *et al*., 2020). Thus, understanding Geology, Geomorphology, and Ecology together is key, since plant, sediment, and water interactions in channels shape habitats, flow, and geomorphic units in both humid and semiarid settings (Cadol; Wine, 2017).

In Geology and Geomorphology, three types of connectivity are often discussed: (i) Landscape Connectivity (Brierley *et al.,* 2006) refers to links between landforms, geomorphic units, and drainage networks; (ii) Hydrological Connectivity (Bracken; Croke, 2007) involves pathways of water movement among landscape compartments, affecting runoff; (iii) Sedimentological Connectivity (Wohl *et al.,* 2019; Poeppl *et al.,* 2020) concerns sediment transfer within the network, shaped by particle properties, path roughness, and transport ability.

Hydrological connectivity represents the capacity of water to mediate the transport of energy, matter, and organisms throughout the hydrological cycle. It is a useful tool for understanding spatial variations in surface and subsurface runoff (Bracken *et al*., 2013; Poeppl *et al*., 2017; Pringle, 2003), and it is classified into five layers: hillslope; hyporheic (the transition zone between surface water and the immediate subsurface water in the riverbed); river–groundwater interaction (deep exchanges between river flow and aquifers); floodplain/riparian plain; and longitudinal connectivity along channels (Covino, 2017; Wohl, 2017).

Sediment connectivity refers to links between source areas and depositional sites, governed by sediment movement among geomorphic units. Three key elements are: the magnitude–frequency of transport and deposition, the spatiotemporal sequence of sediment movement, and mechanisms of detachment and transport (Bracken *et al.*, 2015).

Hydrosedimentological processes, which involve the interaction between water and sediments, are fundamental for understanding connectivity. In tropical and subtropical environments, the transfer of these materials depends primarily on precipitation, which shapes spatiotemporal variations in response to event magnitude (Zanandrea *et al.,* 2021).

Links between hydrological and sedimentary processes have led to the concept of Hydrosedimentology, used in studies of hydrological and sedimentary dynamics in Brazilian watersheds in both humid and semiarid areas (Oliveira *et al.*, 2024; Silva, 2019; Silva; Souza, 2017; Souza; Marçal, 2015; Zanandrea *et al.,* 2021; Zanin *et al.,* 2018). However, clear definitions of Hydrosedimentology and Hydrosedimentological Connectivity are still rare (Dwivedi *et al.,* 2025; Zanandrea *et al.,* 2017).

Within a landscape, linkages may be coupled or decoupled. In this context, buffers, barriers, and blankets act by reducing connectivity: buffers block the transmission of sediments to channels; barriers interrupt longitudinal transport; and blankets cover surface layers, hindering vertical reworking. Conversely, boosters intensify the flow of energy and matter (Brierley *et al*., 2006; Fryirs *et al*., 2007). Thus, understanding connectivity implies a critical evaluation of climatic and geological events as a function of sedimentary structure interacting with surface runoff (Fryirs; Brierley, 2012).

Connectivity can be analyzed under different categories—hydrological, sedimentological, and hydrosedimentological—and dimensions—lateral, vertical, and longitudinal—according to the disciplinary approach (ecology, hydrology, geomorphology). However, a common distinction is made between structural connectivity, which describes spatial patterns of the landscape, and functional connectivity, which represents the interactions between these patterns and the processes of water and sediment transfer (Bracken; Croke, 2007; Bracken; Wainwright, 2006; Heckmann *et al*., 2018; Schopper *et al*., 2019; Zanandrea *et al*., 2021). Structural and functional dynamics operate across multiple spatial and temporal scales, requiring interdisciplinary approaches for their analysis in different environments (Wainwright *et al*., 2011).

As in landscape and hydrological connectivity, lateral, longitudinal, and vertical linkages influence sediment dynamics. A fourth dimension often highlighted is time, represented by the concept of Effective Timescales, which expresses the frequency and magnitude of geomorphic processes in catchment systems. This temporal dimension directly affects connectivity: the greater the event magnitude, the greater its transport capacity and, consequently, the stronger the connectivity (Boulton *et al.,* 2017; Schopper *et al.,* 2019).

CONNECTIVITY ANALYSIS MODELS

In recent years, there has been an increase in studies based on numerical simulations of flows, followed by comparisons between model predictions and real-world measurements obtained from field studies or remote-sensing data. The use of qualitative versus quantitative measures, along with the specific aspects of connectivity being estimated, reflects the objectives of individual studies or management applications. Some limitations involve qualitative measures, which provide only a general perception of connectivity, and quantitative measures, which depend on detailed datasets whose absence or inadequate scale may compromise accuracy, model validation, and watershed management, thereby restricting the ability to quantify certain aspects of connectivity (Wohl, 2017).

To meet these objectives and quantify sediment connectivity, several techniques have been employed, including indices, models, and graph theory. However, most sediment connectivity research has focused more on structural connectivity and less on functional connectivity (Najafi *et al.,* 2021).

From this perspective, the main goal of models is to quantify the complex dynamics of water and sediment redistribution in a watershed, whereas indices typically combine multiple variables known to control flow intensity and spatial organization within a landscape. Indices are often more static than models, yet they can be broadly applied and modified for diverse purposes (Baartman *et al.,* 2020; Heckmann *et al.,* 2018). The following sections address the characteristics of several approaches, models, and connectivity indices.

Mathematical modeling has been used for decades to quantify and predict sediment transport and erosion, such as in scenarios of land-use change or conservation measures. Numerical models have been employed since the 1960s to describe hydrological processes and sediment transport in watersheds, including flow turbulence in fluvial channels (Baartman *et al.,* 2020; Churuksaeva; Starchenko, 2015).

Since the formulation of the Diffusion Theory of Turbulence—which investigated streams to assess the accuracy of mean-flow velocity measurements (between the 1930s and 1960s)—the increase in computational power has enabled the creation of more complex and accurate mathematical models, including methods for unsteady flows and flows over deformable beds (Churuksaeva; Starchenko, 2015). Despite earlier ideas proposed by researchers in the mid-20th century on runoff generation mechanisms and related topics, mathematical modeling took definitive form in the 1970s with the advent of computers capable of processing large volumes of information ((Mukharamova *et al.,* 2018).

Thus, the capacity to perform precise calculations of fluvial flow, sediment transport, associated morphological evolution, and water quality has become essential amid increasing concern for fluvial environments and human-induced alterations. Consequently, fluvial sediment transport remains a central topic in water-resources engineering, hydrology, environmental sciences, geography, and geology (Cao; Carling, 2002). Sediment-transport analyses often rely on hydrological modeling, which seeks to represent components of the hydrological cycle; therefore, the watershed is the fundamental unit of most hydrological models (Almeida; Serra, 2017; Rennó; Soares, 2008).

Hydrological modeling is used to deepen understanding of physical processes and to simulate and forecast scenarios. Hydrological models can be mathematically represented through flow pathways of water and its constituents across the Earth's surface and subsurface, incorporating systems of equations and procedures that integrate variables commonly used in environmental studies, thereby supporting the assessment of land-use impacts and the prediction of future landscape changes (Almeida; Serra, 2017; Araújo *et al.,* 2024).

There are several types of models (deterministic, stochastic, empirical, conceptual, lumped, and distributed) and applications (consistency analysis, gap filling, streamflow forecasting, planning scenarios) in hydrological modeling (Almeida; Serra, 2017). Among deterministic models, the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) stands out for simulating hydrological processes in watersheds, including infiltration, surface runoff, and flow routing (Usace, 2023). Conceptual models such as the Modèle du Génie Rural à 4 paramètres Journalier (GR4J) are commonly used to simulate watershed behavior and predict variables such as streamflow (Lujano *et al*., 2025). Another widely applied conceptual model is the Hydrologiska Byråns Vattenbalansavdelning (HBV), used to simulate watershed water balance and predict hydrological regimes (Ouatiki *et al.,* 2020). Empirical methods, such as the Curve Number (CN), remain useful for rapid surface runoff estimation (Albuquerque *et al.,* 2024). Distributed models such as MIKE SHE (Modelling Integrated Catchment Hydrology) allow detailed representation of spatial variability in soils, topography, and land use (Aysha; Fahim, 2024). Additionally, stochastic approaches remain essential for generating simulations and idealized representations of the physical mechanisms underlying rainfall processes (Northrop, 2023).

Generally, any spatially explicit model capable of producing maps of terrestrial flow and sediment redistribution can be used to infer connectivity, whether it is erosion-based, hydrological, or landscape-evolutionary (Baartman *et al.,* 2020). From this perspective, there is no single "best model," given the inherent uncertainty in environmental predictions. Therefore, multiple plausible solutions exist depending on the purpose and required complexity. Model selection often depends more on user familiarity than on suitability (Ogden, 2021).

One of the most widely used mathematical models for estimating sediment production and surface runoff volume is the hydrosedimentological model Soil and Water Assessment Tool (SWAT), developed by the Agricultural Research Service of the United States (ARS–USDA). SWAT is designed to predict the impacts of current and future land use and management practices by analyzing the spatiotemporal distribution of water, sediment, and nutrient production in watersheds, incorporating precipitation, temperature, humidity, soil, land-use, digital elevation, and other data (Da Silva *et al.*, 2018; Dantas *et al.*, 2015; Lima *et al.*, 2021; Martins *et al.*, 2020).

In addition to SWAT, several other models can be used for different objectives in hydrosedimentological connectivity analysis in watersheds, such as the grid-based conceptual hydrological model Topography-Based Hydrological Model (TOPMODEL), initially proposed by Beven and Kirkby (1979). TOPMODEL is a semi-distributed hydrological model that uses topography to estimate spatial variation in soil moisture and identify saturation-prone areas, allowing simulation of runoff generation (Beven; Freer, 2001; Goudarzi *et al.*, 2023; Reid *et al.*, 2007). Other examples include the one-dimensional hydrodynamic model MIKE 11 for simulating water-depth variations and discharge along rivers and floodplains (Karim *et al.*, 2014); the TAPES-C model, used to simulate Hortonian and saturation overland flow and the spatiotemporal dynamics of shallow groundwater responses (Sidle, 2021); soil-erosion and runoff-generation models such as USLE, RUSLE, and SCS-CN (Borselli *et al.*, 2008); as well as the Precipitation Runoff Modeling System (PRMS) and the Variable Infiltration Capacity (VIC) model, among others (Bennett *et al.*, 2019).

As with hydrological and hydrosedimentological models, several formulas have been proposed to quantify sediment connectivity based on geomorphological parameters that condition sediment transfer. Indices contribute to advancing understanding of connectivity because a range of variables can be incorporated into hydrosedimentological connectivity indices, including hydrological (precipitation, erosivity, infiltration rate, soil moisture), geomorphological (slope, flow-path length, roughness, land cover, topography, drainage area), and sedimentological variables (erodibility, grain size, cohesion) (Zanandrea *et al.*, 2020).

Many empirical approaches and theoretical discussions have been developed to assess surface-runoff connectivity in watersheds (Bracken; Croke, 2007; Brierley *et al.*, 2006; Fryirs *et al.*, 2007; Hooke, 2003). However, the Index of Connectivity (IC) has been one of the most widely used approaches. The IC was developed by Borselli *et al.*, (2008) and later tested, modified, and applied to assess hydrological connectivity at catchment scales (Cavalli *et al.*, 2013; Sidle, 2021). As a result, the hydrological and/or sedimentological connectivity index has been widely applied and adapted in various studies involving water and sediment transfer at the catchment scale (Baartman *et al.*, 2020). The sediment-connectivity index is simple and easy to use, indicating the potential for sediment transfer within and between landscape compartments (Najafi *et al.*, 2021).

The Connectivity Index provides an estimate of the potential connection between eroded hillslope sediments and the flow network. This involves land-use distribution and patterns, as well as topographic and surface characteristics capable of producing or storing water and sediment. Thus, the IC allows the assessment of actual connections during events of different magnitudes and can also be used to simulate scenarios. This latter application is useful for evaluating the efficiency of conservation measures against soil erosion and sediment transport, which are strongly associated with connectivity (Borselli *et al.*, 2008). According to Heckmann *et al.*, (2018), two problems may lead to the development of the connectivity index: the first is the difficulty of directly measuring sediment transfer, and therefore inferring connectivity in the field; and the second is the need to predict the behavior of geomorphic systems in the future, or in research areas where measurements are not available (Heckmann et al., 2018).

Regarding the validation of connectivity indices, Zanandrea *et al.*, (2020, p. 453) argue that “existing connectivity indices have been little explored in Brazilian basins and therefore have not yet been adequately validated for different climates and biomes.” Overall, validation remains challenging due to the difficulty of quantitatively identifying the processes underlying connectivity. Consequently, validation is often based on field data on sediment-transfer pathways and processes, which are frequently associated with extreme events. Furthermore, identifying sediment source and deposition areas can support validation efforts depending on the complexity of known sediment-connectivity processes (Najafi *et al.*, 2021).

Given that numerical models adopt computational approaches that may differ substantially, validation protocols may be necessary to facilitate model comparison and improve model development (Biondi *et al.*, 2012). In addition, model validation is essential to address irregularities that may arise from extensive method acquisition and technique application, as well as from the potential inclusion of erroneous or conflicting information. Such issues can lead to inaccurate simulation results, requiring the identification and correction of problematic data (Rink *et al.,* 2013).

Because field observations remain limited in space and time, modeling has been widely used to quantify erosive processes and sediment transport. Advances in field-data acquisition techniques, combined with improvements in computational modeling, have created new opportunities to study connectivity, map, and quantify water and sediment pathways across multiple spatial and temporal scales (Cavalli *et al.,* 2019).

Alongside the increasing use of computational tools, modeling has influenced Geomorphology by enabling the testing of previously untestable hypotheses, sometimes relegating fieldwork to a secondary role. However, field observations cannot be replaced by computational modeling or laboratory techniques in geomorphological analyses (Salgado; Salgado, 2020).

In field-based research—especially studies with strong field components—data collection, analysis, and interpretation go far beyond modeling, as terrain information can correct or validate spatiotemporal datasets, given that some natural components cannot be modeled. Fieldwork is therefore essential for informing geomorphological models and encouraging researchers to think beyond model boundaries when collecting new data. Furthermore, fieldwork strengthens interdisciplinary relationships by examining process–form linkages (Allen, 2014).

Model outputs require validation; thus, Hooke and Souza (2021) recommend combining mapping and modeling, as model outputs remain hypotheses without testing. The authors emphasize that many researchers highlight the need for field mapping or ground observations for validation, even when modeling is the main focus of a study. Despite these efforts, there is still no clear structure for validating connectivity indices, mainly due to varying approaches and research objectives.

From this perspective, Brierley *et al.,* (2013) proposed a field-based geomorphic approach to fluvial-system analysis through a four-stage procedure for reading the landscape and deriving local insights into fluvial systems. This method consists of identifying geomorphic units, interpreting process–form relationships, analyzing the controls acting at the reach scale and their temporal adjustment, and integrating these insights at the catchment scale to interpret connectivity patterns and river evolutionary trajectories. The authors highlight the importance of examining linkages (connectivity) between landscape compartments to interpret spatial relationships within the system.

To facilitate understanding of the different approaches used in hydrosedimentological connectivity analysis, the following table presents a chronological synthesis of selected models and indices, along with their objectives and authors who applied them. This list includes only examples referenced in this article and does not constitute an exhaustive compilation (Chart 1).

Chart 1 - Chronological examples of models and indices applied to the analysis of hydrosedimentological connectivity in watersheds, with their objectives and some of the authors who used them

Year / Period	Model / Index	Objective / Application	Authors
1930–1960	Diffusive Turbulence Theory	Evaluate mean flow velocity in streams; foundation for flow modeling	Churuksaeva; Starchenko (2015)
1960–1970	Early Hydrological Modeling	Quantification and prediction of water and sediment transport in watersheds	Mukharamova *et al.*, (2018)
1970–2000	Classical numerical models of flow and sediment transport	Representation of hydrological processes and erosion in watersheds	Cao; Carling (2002)
2001	TOPMODEL	Simulation of runoff based on topography; analysis of hydrological connectivity	Beven; Freer (2001) Reid *et al.*, (2007)
2008	IC (Connectivity Index)	Quantification of potential sediment connectivity between landscape compartments	Borselli *et al.*, (2008)
2010–2020	SWAT	Evaluate impacts of land use on water, sediments, and nutrients; scenario analysis	Da Silva *et al.*, (2018) Dantas *et al.*, (2015) Martins *et al.*, (2020)
2014	MIKE 11	One-dimensional hydrodynamic simulation of water depth and discharge along rivers	Karim *et al.*, (2014)
2019–2021	Applications of IC and related variations	Assessment of hydrological and sedimentological connectivity; validation with field data	Zanandrea *et al.*, (2020, 2021) Najafi *et al.*, (2021)
2021	TAPES-C	Simulation of Hortonian and saturation overland flow and shallow groundwater dynamics	Sidle (2021)

Source: The authors (2025).

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CONNECTIVITY: CURRENT PERSPECTIVES AND CHALLENGES – DISCUSSION OF EXISTING DIFFICULTIES

Understanding connectivity enhances understanding of landscape processes, enabling the development of improved analytical and modeling approaches. Connectivity-based frameworks offer the potential for holistic solutions and serve multiple disciplines (Geomorphology, Hydrology, Geology, Ecology, Chemistry, and Archaeology). However, even in the twenty-first century, scientists continue to strive to develop better methods to quantify connectivity in the field of water and sediment transfer (Keesstra *et al.,* 2018).

Despite advances in developing numerous techniques to identify, analyze, and quantify connectivity, challenges remain in implementing and evaluating their applicability to specific environments or research problems. The two main connectivity indices appear to be more suitable for different environments; for example, the Borselli (2008) index for vegetated settings and the Cavalli (2013) index for exposed bedrock and mountainous environments (Hooke; Souza, 2021).

In this case, the roughness-type index proposed by Cavalli (2013) underestimates the effects of vegetation, which—even when sparse—may significantly influence connectivity depending on the landscape type. The use of slope thresholds (introduced in the Cavalli model) is not recommended for vegetated areas. Consequently, connectivity indices reflect the type of area in which they were developed; therefore, caution is required when applying them to different environments (Hooke *et al.,* 2021). More recent advances have sought to overcome these limitations, such as the model proposed by Zanandrea *et al.,* (2021), which incorporates multiscale metrics and greater sensitivity to different land-cover types, although it still presents restrictions in heterogeneous environments. Similarly, Kalantari *et al.,* (2017) developed indicators integrating hydrological soil properties, while López-Vicente and Ben-Salem 2019) proposed probabilistic approaches that enhance the representation of spatial variability—both contributing to greater robustness, yet still dependent on specific calibration conditions.

Recent studies on the use of connectivity indices and models highlight several challenges and limitations. Heckmann *et al.,* (2018) emphasize the difficulty of directly measuring sediment transfer, the need to predict geomorphic system behavior in data-scarce areas, and the dependence on specific calibration conditions. Oliveira, Nero and Macedo (2024) recommend incorporating more functional parameters and improving the representation of surface roughness, noting that the use of geomorphological data, particularly from digital elevation models, yields more accurate results when combined with drone imagery and high-resolution photogrammetric processes, although limitations remain regarding computational capacity and processing time. Zanandrea *et al.,* (2021) point out limitations, including the reliance on tabulated values dependent on user expertise, the lack of representation of interactions between structural and functional components, and the inability to quantify the actual amount of sediment available, indicating only the relative probability of greater transport compared to other events.

Additionally, Batista *et al.,* (2021) highlight the difficulty of applying these tools in heterogeneous areas and the dependence on well-calibrated hydrological and geomorphological parameters. Moreno-de-las-Heras *et al.,* (2020) complement this by noting that the assessment of functional connectivity remains limited, as many analyses focus primarily on structural connectivity and rely greatly on field observations for validation.

Overall, one of the main challenges in assessing and quantifying connectivity is verifying the presence of linkages between units within each part of the system to determine whether they are connected. Moreover, finer-scale characteristics may strongly influence results—for example, small slopes or curbs in urban areas. The central challenge lies in resolving the dilemma between large-area coverage and the need for detailed information: obtaining imagery with broad spatial coverage and high resolution simultaneously, as spatial-scale issues are particularly problematic for mapping and validation. Furthermore, most connectivity analyses remain structural, whereas functional analyses are often the most relevant. Therefore, understanding the characteristics of disconnecting elements is crucial, and the thresholds for disconnection must be identified (Hooke; Souza, 2021).

Chart 2 - Positive aspects and weaknesses of connectivity indices (CI)

Author(s)	Approach	Positive aspects	Main limitations
Borselli *et al.*, (2008)	Classic IC	Simple, widely used, efficient for estimating potential connectivity	Resolution-sensitive; does not represent functional processes; does not account for hydrological dynamics or rainfall-event variability
Cavalli *et al.,* (2013)	Roughness-based IC	Suitable for mountainous areas and exposed surfaces	Underestimates vegetation; slope threshold poorly applicable in vegetated areas
Zanandrea *et al.*, (2021)	Hydrosedimentological connectivity index (IHC)	Integrates temporality and hydrological conditions, approximating real sediment dynamics	Use of tabulated values dependent on user knowledge; does not represent physical interaction between components; does not quantify available sediment
Heckmann *et al.*, (2018)	IC applications	Provides estimates of potential connectivity in areas without direct data	Difficulty in directly measuring sediment transfer; dependence on calibration and site-specific conditions
Moreno-de-las-Heras *et al.,* (2020)	Structural/functional connectivity	Combines spatial patterns and processes; effective in dry hillslopes	Requires field observations; difficult to represent functional processes
Batista *et al.*, (2021)	IC applications	Can be applied to identify critical erosion areas	Limited applicability in heterogeneous areas; dependence on well-calibrated parameters

Source: The authors (2025).

The chart presented summarizes the strengths and weaknesses identified in some recent studies on connectivity indices (IC), without the intention of covering all available approaches in the literature (Chart 2). Nevertheless, it provides a useful comparative view of the potential, limitations, and methodological requirements of these models, aiding in selecting the most suitable tools for different hydro-sedimentological contexts.

FINAL CONSIDERATIONS

This study aimed to conduct a theoretical survey on the concept of connectivity, considering its multiple terminologies, disciplinary perspectives, and applications in different approaches and models. The hydrological, sedimentary, and hydro-sedimentological categories were discussed under the structural and functional perspectives of the landscape, enabling an understanding of the behavior of energy and matter flows in lateral, vertical, and longitudinal dimensions.

Climatic seasonality proved to be a determining factor in connectivity and hydrological responses, as precipitation regulates the dynamics of flow and geomorphological processes. Among the connectivity models, the IC by Borselli *et al.,* (2008) and its adaptation by Cavalli *et al.,* (2013) do not include precipitation, as they are based solely on geomorphological attributes. Other advances, however, have incorporated this variable: Zanandrea *et al.,* (2021) include accumulated rainfall and intensity in hydro-sedimentological response scenarios; Kalantari *et al.,* (2017) use precipitation in coupled hydrological models; and López-Vicente and Ben Salem (2019) include parameters related to rainfall-dependent erosivity. Therefore, precipitation inclusion varies across models, being more common in hydrological approaches than in purely structural indices.

In humid environments, flow continuity and predictability are greater, while in semi-arid environments, the irregularity, frequency, and magnitude of rainfall events exert dominant control over sediment transport and system connectivity. In arid regions at high latitudes, the seasonal thaw of mountainous and plateau areas constitutes the main source of water recharge, highlighting significant spatial and temporal contrasts between environmental types.

The diversity of computational models available for connectivity analysis requires caution in their selection and application, as each has limitations and is better suited to specific natural conditions and research objectives. Therefore, prior knowledge of the study area is essential for proper parameterization and identification of disconnection thresholds. Nevertheless, field observations remain fundamental for validating, calibrating, and adjusting theoretical models, thereby ensuring more realistic interpretations of flow transmission and retention processes in the landscape.

In summary, connectivity consolidates as a key concept to integrate hydrological, sedimentological, and geomorphological studies, especially in contexts of climate change and intensified anthropogenic pressures. Future research should advance the quantification and integrated modeling of connectivity across multiple scales, combining field data, remote sensing, and spatial modeling to enhance the understanding of fluvial processes and their implications for watershed management and conservation.

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Adonai Felipe Pereira de Lima Silva: Conceptualization, Research, Original manuscript writing, Data analysis.
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DATA AVAILABILITY: The data that support the findings of this study can be made available, upon reasonable request, from the corresponding author. [Adonai Felipe Pereira de Lima Silva].