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Hydrological connectivity: a review and emerging strategies for integrating measurement, modeling, and management

Dipankar Dwivedi[1]*, Ronald E. Poeppl[2] and Ellen Wohl[3]

[1]Earth and Environmental Sciences, Lawrence Berkeley National Laboratory, Berkeley, CA, United States, [2]Institute of Hydrobiology and Aquatic Ecosystem Management, BOKU University Vienna, Vienna, Austria, [3]Department of Geosciences, Colorado State University, Fort Collins, CO, United States

This review synthesizes methods for measuring, modeling, and managing hydrologic connectivity, offering pathways to improve practices and address environmental challenges (e.g., climate change) and sustainability. As a key driver of water movement and nutrient cycling, hydrologic connectivity influences flood mitigation, water quality regulation, and biodiversity conservation. However, traditional field-based methods (e.g., dye tracing), indirect measurements (e.g., runoff analysis), and remote sensing techniques (e.g., InSAR) often struggle to capture the complexity of catchment-scale interactions. Similarly, modeling approaches—including process-based and percolation theory-based models, graph theory, and entropy-based metrics—face limitations in fully representing these interconnected processes. Both modeling and measurement techniques are constrained by inadequate spatial and temporal coverage, high data demands, computational complexity, and difficulties in representing subsurface connectivity. Subsequently, we critique current management practices that prioritize isolated variables (e.g., streamflow, sediment transport) over system-wide strategies and emphasize the need for adaptive, connectivity-based approaches in water resource planning and restoration. Moving forward, we highlight the importance of interdisciplinary collaboration, technological innovations (e.g., AI-driven modeling, real-time monitoring), and integrated frameworks to improve connectivity measurement, modeling, and adaptive management to restore fragmented hydrologic networks. This integrated approach sets the stage for transformative water resource management, fostering proactive policy development and stakeholder engagement.

KEYWORDS

hydrologic connectivity, interdisciplinary collaboration, catchment dynamics, climate change adaptation, geomorphological processes, ecohydrological models, environmental sustainability, ecosystem resilience

EDITED BY
Timothy O. Randhir,
University of Massachusetts Amherst,
United States

REVIEWED BY
Tianfang Xu,
Arizona State University, United States
Gianluca Botter,
University of Padua, Italy

*CORRESPONDENCE
Dipankar Dwivedi
✉ DDwivedi@lbl.gov

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1 Introduction

Hydrologic connectivity is defined as the water-mediated transfer of matter, energy, and organisms within or between elements of the hydrologic cycle (Pringle, 2001). It is a cornerstone of catchment science, governing the movement of water, nutrients, and organisms across subsurface areas, surface layers, river streams, and wetlands (Bracken et al., 2013; Zhang et al., 2021). As an emergent property shaped by complex ecological interactions—including hydrological, biogeochemical, and geomorphological processes—connectivity facilitates critical exchanges within and between ecosystems (Lehmann et al., 2007; Wohl et al., 2018; Harvey and Gooseff, 2015). Understanding hydrologic connectivity is essential for predicting water movement in response to climate variability, land-use changes, and increasing anthropogenic pressures on water resources. It plays an indispensable role in water resource management, directly influencing flood and drought mitigation (Maxwell et al., 2021), regulating water quality (Harvey et al., 2019; Fox et al., 2022), and maintaining vital biological habitats (Pringle, 2001). Hydrologic connectivity enhances system resilience by regulating water flow, reducing erosion, and supporting habitat restoration (Fortuna et al., 2006; Rains et al., 2016). It also sustains natural purification processes by enabling wetlands to filter pollutants through sediment trapping and microbial breakdown, mitigating the impacts of urbanization and deforestation (Haarstad et al., 2012; Lane et al., 2018; Bertassello et al., 2022; Fang et al., 2024).

To better understand hydrologic connectivity and its role in catchment dynamics, it is categorized in two ways: by spatial domains (system perspective) and by connectivity dimensions (connectivity types). The system perspective categorizes hydrologic connectivity based on spatial domains—surface, surface-subsurface, and subsurface—highlighting where exchanges occur. Surface connectivity governs the movement of water, sediments, and nutrients across landscapes via rivers, streams, and overland flow. Surface-subsurface connectivity represents interactions between surface water and groundwater, such as infiltration, percolation, and hyporheic exchange, which regulate groundwater recharge and solute transport. Subsurface connectivity describes water and solute flow within soil and groundwater, influencing aquifer recharge and groundwater-surface exchanges (Covino, 2017). These categories are not mutually exclusive, as interactions between surface and sub-surface processes regulate catchment responses across spatial scales.

In contrast, hydrologic connectivity types are classified based on the connectivity dimensions that characterize water movement within and between systems—including longitudinal, lateral, and vertical connectivity—each of which uniquely shapes catchment dynamics. These connectivity types influence functional processes; for example, longitudinal connectivity facilitates the downstream transport of water, organisms, sediments, and nutrients, ensuring both hydrological and ecological continuity along river networks (Buddendorf et al., 2017; Lee S. et al., 2023). Lateral connectivity links rivers to adjacent floodplains, wetlands, and groundwater zones, facilitating nutrient cycling, habitat exchange, and floodplain dynamics (Leibowitz et al., 2018). Vertical connectivity governs surface–sub-surface water and solute exchanges, regulating groundwater recharge and biogeochemical processes.

Within surface and subsurface systems (i.e., the system perspective), hydrologic connectivity is shaped by structural and functional drivers (Turnbull et al., 2008). Structural drivers, such as topography and vegetation patterns, remain relatively static over short timescales, while functional drivers involve transient hydrologic processes, such as overland flow dynamics or storm-driven flow path formation. These structural and functional drivers regulate hydrologic exchanges across spatial domains, influencing the movement of water, solutes, and sediments throughout the catchment.

To capture the influence of transient hydrologic processes, some studies also consider temporal connectivity, which describes fluctuations in water movement driven by seasonal variations, precipitation events, and disturbances. These changes influence surface, subsurface, and vertical exchanges, shaping river discharge, sediment transport, and wetland hydrodynamics (Pringle, 2001; Lane et al., 2018; Lee E. et al., 2023; Wu et al., 2023). Recognizing the role of time in shaping hydrological connectivity, Ward (1989) introduced the four-dimensional perspective of lotic ecosystems, which conceptualizes their dynamic and hierarchical nature through longitudinal (upstream-downstream), lateral (channel-floodplain), and vertical (channel-groundwater) interactions, with time as the fourth dimension providing the temporal scale that governs ecosystem responses to disturbances.

Seminal works have shaped the understanding of various aspects of hydrologic connectivity (for a detailed list, see Pöppl et al., 2024). Key contributions by Schumm (1965), Taylor et al. (1993), Fryirs et al. (2007), Bracken and Croke (2007), Poeppl et al. (2017), and Wohl et al. (2019) have established connectivity as a driver of energy and material transfer, influencing sediment transport, landscape evolution, and hydrological regulation. For instance, Poeppl et al. (2017) proposed a framework integrating human impacts on fluvial systems, highlighting feedback loops between social and geomorphic systems. Similarly, Taylor et al. (1993) pioneered the concept of landscape connectivity, demonstrating its role in species dispersal and source-sink dynamics and urging planners to consider animal movement in conservation strategies. Despite these advancements, significant gaps remain in understanding and managing hydrologic connectivity, particularly in *foundational knowledge*, *methodological development*, and *management applications*.

Effective resource management and predictive modeling depend on a robust understanding of hydrologic connectivity, which requires bridging knowledge gaps in process interactions. Studies highlight the challenges posed by spatial and temporal scale variations, as hydrologic systems exhibit nonlinear behaviors and complex flow pathways (Lehmann et al., 2007; Wohl et al., 2018). Moreover, hydrologic connectivity is deeply intertwined with ecological systems, yet many studies fail to consider these linkages, emphasizing the need for interdisciplinary approaches integrating hydrology, ecology, geomorphology, and biogeochemistry (Bracken et al., 2013; Covino, 2017; Yu et al., 2023).

Accurate assessments of hydrologic connectivity require standardized methodologies to ensure consistent evaluations across spatial and temporal scales (Turnbull et al., 2018). Traditional techniques often fail to capture subsurface and dynamic flow complexities, while graph theory and entropy-based metrics offer novel solutions (Zuecco et al., 2019; Tejedor et al., 2015). Existing models frequently over-rely on static metrics, neglecting the real-time dynamic behaviors essential for managing subsurface flow and transport (Renard and Allard, 2013). Furthermore, the absence of standardized metrics has hindered collaboration and integration across research disciplines (Zhang et al., 2021; Bracken et al., 2013).

Many management applications need to adopt adaptive, connectivity-based approaches, resulting in significant gaps in managing hydrological systems and ensuring ecosystem resilience amid climate variability and human-induced changes (Poeppl et al., 2017; Keesstra et al., 2018; Poeppl et al., 2020; Aho et al., 2020; Roy, 2023; Herzog et al., 2024). Although the importance of such strategies is well-recognized, Lexartza-Artza and Wainwright (2009, 2011) emphasize the need for adaptive methods to manage sediment and water interactions whereas Wainwright et al. (2011) highlight the complex interplay of environmental regimes across spatial and temporal scales. Incorporating hydrologic connectivity is vital for global water resource management and climate adaptation. The absence of such approaches weakens flood mitigation, groundwater recharge management, and ecosystem conservation efforts, leading to increased risks of habitat loss and water quality degradation (Good et al., 2015; Tejedor et al., 2015; Maxwell et al., 2021; Chen et al., 2021; Li et al., 2024).

Given hydrologic connectivity's complexities and interdisciplinary nature, this mini-review synthesizes current knowledge on its spatial and temporal dynamics, methodological advancements, and implications for catchment dynamics, connectivity restoration, and water resource management amid climate change and human activities. While analyzing connectivity by system, type, or temporal scale provides a structured approach, its full impact on catchment dynamics emerges only when considered holistically. Therefore, this review examines how an integrated approach can enhance measurement, modeling, and management strategies (Figure 1).

2 Measurement and modeling approaches for hydrologic connectivity

This section explores measurement techniques and modeling approaches, evaluates their strengths and limitations, and highlights the need for further advancements. We organize the following section around system perspective because it provides a tangible framework for measuring connectivity by integrating spatial and temporal scales and capturing multiple types (e.g., longitudinal, lateral, and vertical) across surface and subsurface systems. Below, we explore measurement techniques tailored to different systems, evaluating their strengths and limitations.

2.1 Techniques for measuring hydrologic connectivity

Hydrologic connectivity measurement techniques fall into field-based methods, proxies, and remote sensing techniques (Figure 1). While field-based methods and proxies can characterize connectivity in surface and subsurface systems, remote sensing techniques primarily assess surface connectivity, though some applications can indirectly infer subsurface changes.

2.1.1 Field-based methods

Among these approaches, field-based methods provide direct, high-resolution measurements of water movement, making them essential for understanding localized connectivity dynamics (e.g., Zimmer et al., 2020). For instance, dye tracing involves introducing a tracer dye into a water source to track flow pathways and residence times. This approach provides detailed insights into water movement and surface-subsurface interactions, particularly in wetlands and rivers (Zhang et al., 2022). Although highly precise, these methods are labor-intensive, temporally limited, and constrained in spatial coverage. These limitations reduce their effectiveness for large-scale assessments.

2.1.2 Indirect measurement through proxies

Proxies offer valuable tools for inferring hydrological connectivity by measuring environmental variables (Zhang et al., 2022). In surface systems, runoff patterns provide critical insights into hydrologic connectivity (Bracken and Croke, 2007). In sub-surface systems, soil moisture and plant distribution are key factors in assessing subsurface hydrologic connectivity (Yang et al., 2023). Beyond subsurface flow, they also regulate surface runoff, modifying surface connectivity (Liu et al., 2019). This interdependence reinforces that surface and sub-surface systems are not mutually exclusive but dynamically linked.

Sediment connectivity provides a more integrated perspective by linking sediment transport and retention across surface and sub-surface systems (Drummond et al., 2014; Olliver et al., 2020). Surface connectivity is assessed by measuring sediment transport through runoff, river channels, and overland flow (Julien and Simons, 1985; Prosser et al., 1995). For example, Bracken and Croke (2007) highlight hydrological connectivity in runoff-dominated systems, showing its influence on erosion and sedimentation. Building on this, Borselli et al. (2008) demonstrate using Geographic Information System (GIS) and field assessments to explore sediment and flow connectivity. GIS-based approaches, particularly those utilizing digital elevation models (DEMs), calculate connectivity indices that quantify flow pathways and identify areas of high and low connectivity based on topographic features (Borselli et al., 2008; Heckmann et al., 2018). Subsequently, Bracken et al. (2015) propose a sediment connectivity framework to understand sediment transfer across scales, directly influencing landscape stability. In contrast, subsurface connectivity is evaluated by examining sediment movement within soils, hyporheic zones, and groundwater pathways, emphasizing the complex interactions between surface and subsurface processes (Harvey et al., 2012; Lewandowski et al., 2015; Somers et al., 2016).

2.1.3 Remote sensing techniques

Complementing these approaches, remote sensing techniques, such as InSAR, provide large-scale, high-resolution monitoring

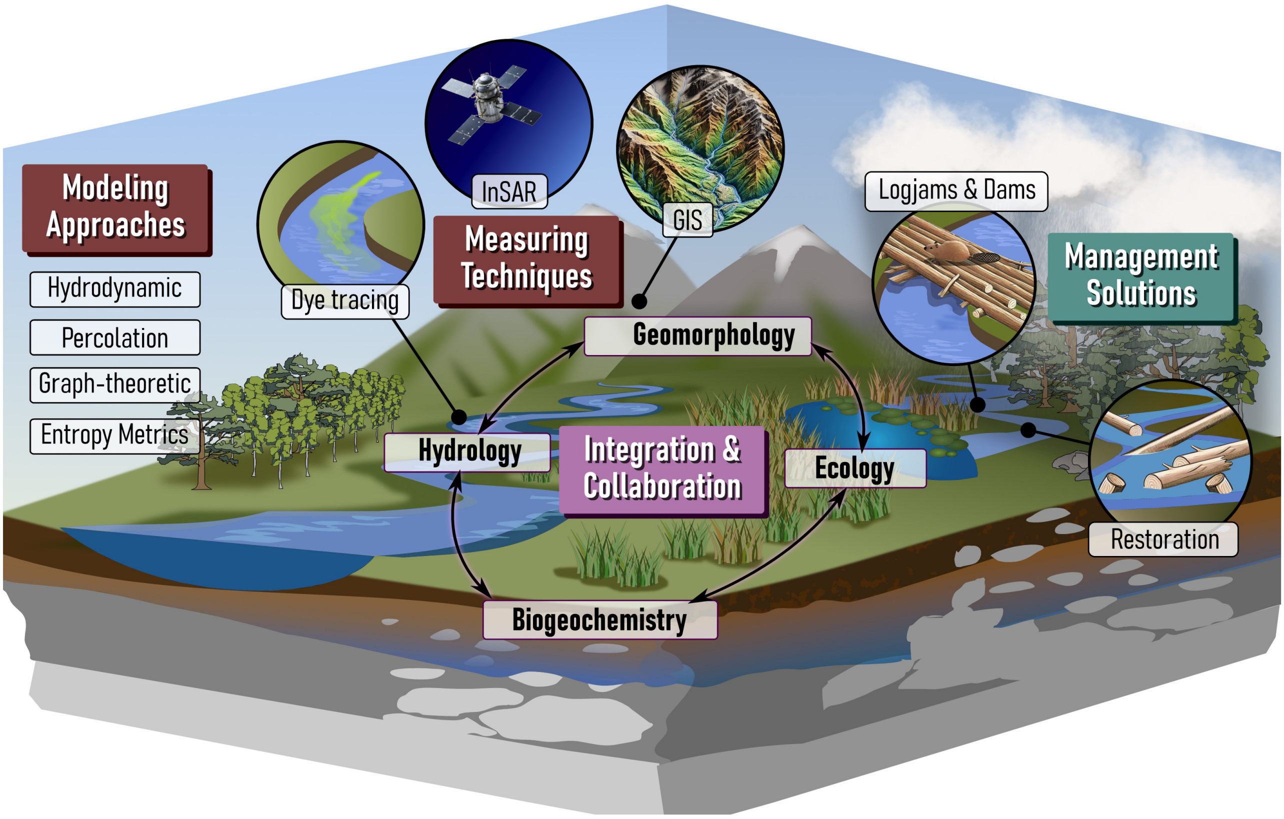

FIGURE 1
Hydrologic connectivity: advancing measurement techniques, interdisciplinary integration, and management strategies to deepen understanding and optimize water-mediated transfers in the hydrologic cycle, which are vital for river ecosystem health and critical for ensuring the sustainability and resilience of water resources in the face of environmental change.

of surface water connectivity, making them particularly useful for assessing fragmented landscapes (Liu D. et al., 2020). InSAR relies on satellite-based radar to detect surface elevation changes, enabling broad-scale monitoring of water movement and identifying fragmented or connected areas in river networks. While remote sensing methods primarily capture surface connectivity, some techniques (e.g., gravity-based satellite data like GRACE) can infer subsurface storage changes (Tapley et al., 2004). Optical imagery and LiDAR complement these approaches by detecting land cover changes, vegetation dynamics, and erosion patterns, indirectly influencing connectivity. However, remote sensing methods typically provide surface-level snapshots and often lack the resolution needed to represent subsurface dynamics accurately (Ameli and Creed, 2017).

2.2 Modeling approaches for hydrologic connectivity

Modeling approaches for hydrologic connectivity can be categorized into process-based models (for either surface or subsurface systems), network and graph-based models, and integrated models (Figure 1). While all these approaches can characterize surface and sub-surface connectivity, integrated models uniquely link surface and sub-surface processes, explicitly capturing feedback mechanisms at their interface.

2.2.1 Process-based models

Process-based models, such as hydrodynamic models (Liu Y. et al., 2020; Yang et al., 2021) and percolation theory (Lehmann et al., 2007), simulate physical flow processes and water quality across different spatial and temporal scales. Hydrodynamic models provide detailed simulations of water movement, including flow velocities, flood dynamics, and water quality, making them valuable for localized analyses of both surface and subsurface systems (e.g., Baram et al., 2013; Siqueira et al., 2018). However, they are highly data-intensive, sensitive to parameter errors, and often limited in scalability to larger systems (e.g., Rimon et al., 2011; Siqueira et al., 2018).

Percolation models focus on flow pathways and connectivity thresholds in porous media, primarily addressing subsurface systems (e.g., Lehmann et al., 2007; Rimon et al., 2011). They can be applied probabilistically to analyze runoff thresholds or identify key flow characteristics statistically. While effective for modeling nonlinear flow behaviors in hillslope hydrology and identifying significant runoff thresholds, percolation theory often oversimplifies hydrological systems by neglecting biogeochemical interactions critical for ecosystem management (Lehmann et al., 2007; Dahan et al., 2009).

2.2.2 Network and graph-based models

Network and graph-based models, including graph-theoretic models (Tejedor et al., 2015) and entropy-based metrics (Tejedor et al., 2015), represent hydrologic systems as networks, where nodes and edges depict connected water bodies. This enables clear visualization and quantification of connectivity across river basins and delta channels (Passalacqua, 2017; Garbin et al., 2019). These models effectively assess structural connectivity (Bertassello et al., 2020; Xingyuan et al., 2023; Huang et al., 2024) but require extensive input data and primarily focus on static representations (Durighetto et al., 2023), often overlooking dynamic hydrological behaviors, particularly during extreme events (Beven, 2012).

Entropy-based metrics integrate both topological and dynamic complexity, making them valuable for evaluating system vulnerabilities and resilience. They quantify system disorder and assess dynamic connectivity under varying hydrological conditions, such as flood pulses or droughts, and have been widely applied in hydrologic connectivity and environmental sciences (e.g., Dwivedi and Mohanty, 2016; Arora et al., 2019; Bennett et al., 2019). While these methods can characterize subsurface connectivity, they are more suited for surface connectivity due to the natural network structure of river streams and the greater availability of surface data. However, subsurface connectivity can be analyzed using fracture networks or model outputs with sufficient data. Nonetheless, their computational complexity and lack of standardized metrics limit their broader applicability across diverse landscapes.

2.2.3 Integrated models

Integrated models couple sub-surface and surface hydrology while incorporating land surface processes (e.g., energy fluxes, soil moisture, runoff) and ecohydrology (e.g., plant-water interactions, ecological responses) (e.g., Coon and Shuai, 2022; Xu et al., 2022; Shuai et al., 2022; Ackerer et al., 2023). By simulating hydrological, climatic, and ecological interactions, these models provide a comprehensive understanding of water dynamics, energy exchange, and biogeochemical cycles across scales. These models capture hydrologic connectivity across surface, subsurface, and interface domains, distinguishing longitudinal, vertical, and lateral connectivity (Mikkelson et al., 2013; Camporese et al., 2019). Their ability to simulate biogeochemical processes aids in understanding catchment dynamics and tracing solute sources, differentiating biogenic and geogenic contributions in river systems (Dwivedi et al., 2018b; Arora et al., 2016; Godsey et al., 2019). They are also valuable for managing flood flows and enhancing ecosystem resilience, especially in sensitive regions like drylands (Şensoy et al., 2018).

Their ability to integrate ecohydrological interactions makes them highly relevant for interdisciplinary applications. They can leverage modular studies, such as ecohydrological frameworks (Maxwell et al., 2021; Van Meerveld et al., 2021) and dimensionless river connectivity metrics (Harvey et al., 2019), to predict outcomes like habitat connectivity and species distribution based on water availability and flow patterns.

These data-intensive models struggle to represent complex ecological-hydrological relationships due to the need for distributed parameters (Chen et al., 2021). Their computational demands limit global applicability and often lack adaptive management integration, reducing flexibility in changing environmental conditions.

2.3 Comparative strengths and limitations of measurement and modeling approaches

A comprehensive understanding of hydrologic connectivity requires integrating field-based methods, relevant state variables (proxies), remote sensing, and advanced modeling approaches. As discussed above, field methods are accurate but labor-intensive, while remote sensing offers broad coverage but lacks subsurface insights. Modeling translates these measurements into predictions: process-based models provide detailed simulations but demand extensive data and computing power; network models capture structure but struggle with dynamics and subsurface flow; integrated models offer the most comprehensive view but are data-intensive and computationally demanding. Advancing hydrologic connectivity assessments in the future requires improving data availability, scalability, dynamic modeling, and interdisciplinary integration.

3 Role of interdisciplinary approaches in enhancing hydrologic connectivity understanding

3.1 Need to integrate knowledge from multiple disciplines

Catchment systems are shaped by a complex interplay of processes (Figure 1), making interdisciplinary integration—across hydrology, ecology, biogeochemistry, and geomorphology—essential for both understanding hydrologic connectivity and developing effective restoration strategies that enhance ecosystem functioning (e.g., Hubbard et al., 2018). This approach provides deeper insights into how water movement affects key biogeochemical cycles, such as carbon and nitrogen cycling, which are vital for sustaining ecosystem health. For example, integrating geomorphological insights accounts for terrain evolution and sediment dynamics while incorporating biogeochemical processes captures feedback between water flow and nutrient availability (Liu D. et al., 2020). Appling et al. (2014) demonstrate the critical role of integrating geomorphology and hydrology, showing how the geomorphic history of floodplains influences nutrient movement and transformation through landscape structure and flow paths. The interaction between hydrologic flow and geomorphic configuration plays a crucial role in shaping water residence times and flow pathways (Helton et al., 2014). Integrating hydrology and biogeochemistry further enhances our understanding of nutrient cycling in river systems (Liu D. et al., 2020).

In the context of ecology, hydrologic connectivity plays a vital role in shaping biodiversity and ecosystem resilience. Ecological dynamics, such as species migration and habitat access, further refine spatial and temporal scales of connectivity, identifying critical thresholds for habitat connectivity in floodplain systems (Stoffers et al., 2022). Stoffers et al. (2022) underscore how fish populations in floodplain rivers depend on habitat connectivity, facilitating migration and access to critical habitats. Likewise, Uno et al. (2022) show that aquatic communities in floodplains reflect varying degrees of hydrological connectivity, highlighting the importance of integrating ecological and hydrological research to understand species' distributions and community structure. These studies highlight the need for interdisciplinary approaches to accurately model hydrological and biogeochemical interactions, improving calibration and predictions of nutrient transport and biodiversity responses to climate-driven hydrologic connectivity changes.

3.2 Interdisciplinary collaborations driving scientific progress

Successful interdisciplinary collaborations have led to significant breakthroughs in understanding hydrologic connectivity (Turnbull et al., 2018; iConn Network, 2024). For instance, the collaboration between hydrologists and biogeochemists has helped address the "old water paradox" in hydrology (Kirchner, 2003), where streamflow is often found to contain a significant proportion of older water. Using geochemical tracers, as Cartwright and Morgenstern (2012) describe, has enabled researchers to unravel the sources of this older water, which is critical for understanding the dynamics between surface and subsurface hydrological systems. Similarly, collaboration between geomorphologists and hydrologists has advanced deltaic stability and sustainability knowledge (Figure 1). Passalacqua et al. (2021) emphasize that delta sustainability requires understanding the spatial scale of sediment transport and hydrodynamic processes, which are best assessed through interdisciplinary methods. Overall, these interdisciplinary collaborations—resolving the old water paradox and advancing delta sustainability—highlight how integrating expertise improves hydrologic understanding, modeling accuracy, and restoration strategies.

4 Management implications and opportunities

Effective management requires not only modeling hydrologic connectivity but also implementing restoration strategies, such as floodplain reconnection, wetland rehabilitation, and riparian corridor restoration (Stoffers et al., 2022), to enhance water and nutrient flow across landscapes (Figure 1). As demonstrated, current approaches often fail to consider how multiple ecological, hydrological, and geomorphological variables interact within an ecosystem. This is an especially problematic oversight when accounting for thresholds, feedback loops, and interactions vital to ecosystem health. Consequently, management efforts often focus on individual variables (e.g., streamflow regulation, sediment transport, or nutrient cycling) in isolation rather than adopting a holistic framework that accounts for system-wide interactions (Zhang et al., 2021). The underutilization of predictive capabilities hampers effective nutrient management, habitat restoration, and flood mitigation. For example, although engineered structures like logjams and beaver dam analogs are increasingly implemented to enhance nitrate removal in headwater streams (e.g., Krause et al., 2024; Wade et al., 2020; Dewey et al., 2022), no reliable method exists to predict the optimal number or placement of these obstructions for achieving desired outcomes (Covino, 2017).

Moreover, current management approaches often need to pay more attention to the complexity of hydrologic connectivity in areas like habitat restoration and flood control (Poeppl et al., 2017, 2020). Restoration projects that reestablish natural water flow—including levee setbacks, wetland rehydration, and beaver dam analogs—are typically based on incomplete models that need to account for hydrological impacts on species migration or vegetation growth. Similarly, flood mitigation strategies often neglect the significance of river corridors and floodplain connectivity, which are critical for water storage and nutrient filtering during high-water events (Wohl et al., 2018; Harvey et al., 2019).

5 Discussion

We evaluated the strengths and limitations of current measurement and modeling techniques, emphasizing the need to integrate hydrologic connectivity restoration efforts into management strategies. We highlighted the importance of predictive modeling, interdisciplinary collaboration, and system-wide approaches to enhance hydrologic resilience and inform adaptive water management. We noted that an integrated and interdisciplinary perspective on hydrologic connectivity is key to effective management, drawing from hydrology, biogeochemistry, geomorphology, and ecology to address system-wide complexities. The discussion in the following subsections underscores the need for future research to develop integrated frameworks that combine hydrological, ecological, and biogeochemical processes to tackle pressing environmental challenges like climate change.

5.1 Challenges and solutions in measurement and modeling techniques

Despite advancements in measuring and modeling hydrologic connectivity, several challenges have remained. For instance, traditional field-based methods (e.g., dye tracing) provide high-resolution data but lack broad spatial coverage (see Section 2.1), while remote sensing offers wide spatial coverage but limited temporal resolution (see Section 2.2). Models are limited by high data requirements (e.g., process-based models), computational complexity (e.g., integrated models), and oversimplified representations (e.g., percolation theory-based models), all of which reduce accuracy. Additionally, they often struggle with inadequate subsurface characterization. Addressing these challenges requires improved spatial and temporal coverage for a more comprehensive understanding of hydrologic connectivity. Researchers increasingly rely on remote sensing and predictive modeling to bridge this gap and complement traditional measurement approaches.

Researchers have increasingly integrated automated sensors and drones into field-based methods to enhance spatial coverage, reduce labor costs, and provide consistent real-time data collection (Hubbard et al., 2018; Chen et al., 2021). Advancements in visual surveys and high-temporal-resolution camera-based approaches offer promising solutions for reconstructing stream network dynamics (Noto et al., 2024; Manfreda et al., 2024). Efforts should focus on expanding visual surveys, developing machine learning (ML) tools for image analysis, and integrating high-resolution data into models to improve hydrological predictions. To improve subsurface characterization, Wireless Underground Sensor Networks (WUSN) capable of providing subsurface properties should be leveraged (e.g., Barnhart et al., 2010; Ajo-Franklin et al., 2018).

Although automated sensors, drones, visual surveys, high-temporal-resolution cameras, and WUSN offer deeper insights into localized hydrological processes, their full potential can only be realized through scaling and broader application. Remote sensing advancements improve temporal resolution, such as increased satellite monitoring frequency and combining multiple data types (optical, thermal, radar). Incorporating subsurface sensing technologies will further enrich our understanding of surface and subsurface dynamics.

Artificial Intelligence (AI) and ML are already being used to enhance hydrodynamic models by optimizing calibration and reducing dependence on large datasets (Shen et al., 2023). To achieve global applicability, these models require ongoing refinement to address scalability. Incorporating biogeochemical fluxes into percolation theory would make these models more ecologically relevant; meanwhile, integrating real-time monitoring into graph-theoretic models would capture adaptive changes in connectivity. Although graph-theoretic models often use a fixed structure to represent connections, they can be adapted dynamically by integrating real-time monitoring data (Durighetto et al., 2022; Bertassello et al., 2022). For instance, real-time measurements of flow conditions, water levels, or seasonal variations can update edge weights or node attributes, allowing the graph to reflect temporal changes in connectivity, such as flow interruptions or restored connectivity after precipitation events (Himmel et al., 2017; Casteigts et al., 2021). Integrating this real-time monitoring would enhance the models' ability to capture adaptive changes in connectivity (Casteigts et al., 2021). Similarly, ongoing efforts to simplify entropy-based metrics and embed them into flexible frameworks are progressing, yet further refinement is urgently needed to make them more accessible across various ecosystems (Bennett et al., 2019). Similarly, adaptive river connectivity metrics that factor in real-time environmental changes will enhance assessment precision, provided they are consistently implemented across diverse settings (Godsey and Kirchner, 2014).

Significant strides have been made in developing globally applicable ecohydrological models that account for regional ecological dynamics (e.g., Xu et al., 2022; Shuai et al., 2022), yet further efforts are needed to ensure their consistency and broader applicability. Developing integrated frameworks that combine remote sensing, field methods, and modeling will improve assessments and predictive capabilities and enhance adaptive management of hydrologic connectivity by addressing scale, complexity, and metric standardization gaps. However, achieving these advancements requires not only technical innovations but also interdisciplinary collaboration. Hydrologists, ecologists, and data scientists must work together to integrate diverse methodologies and ensure that emerging tools are effectively implemented across various ecosystems.

5.2 Challenges and solutions in interdisciplinary research and management

Despite the clear benefits of interdisciplinary approaches, several challenges remain (e.g., Hubbard et al., 2020). A major issue is the lack of data standardization across fields (Varadharajan et al., 2019; Faybishenko et al., 2022; Simmonds et al., 2022; Arora et al., 2023), as researchers employ diverse data collection and analysis methods, leading to inconsistencies that hinder integration. For example, hydrologists use high-frequency sensor networks to measure water fluxes at 5-min intervals, whereas geochemists rely on seasonal field sampling to analyze water chemistry (Faybishenko et al., 2022). Similarly, in overland flow connectivity studies, hydrologists focus on processes like infiltration and runoff. At the same time, geomorphologists examine structural factors such as slope and gradient—both essential for understanding hydrologic connectivity (Reaney et al., 2014). Maximizing the impact of interdisciplinary collaboration to advance hydrologic connectivity research requires standardized measurement strategies, particularly in data frequency and spatial distribution, to improve research integration and applicability.

In addition, data availability and accessibility remain challenges, as many datasets are fragmented, discipline-specific, or lack open access. Expanding data-sharing platforms and cross-institutional collaborations can help bridge these gaps. Initiatives like the Department of Energy's Environmental System Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE), United States Geological Survey (USGS) data repositories, and journal-driven open-access mandates aim to improve data accessibility and support interdisciplinary research (Clark et al., 1993; Varadharajan et al., 2019; Simmonds et al., 2022; Lightsom et al., 2022).

Communication barriers further complicate interdisciplinary research, including hydrologic connectivity studies. Scientists from different fields often use distinct terminologies (e.g., runoff in hydrology vs. overland flow in ecology for the same process) and different measurement frameworks (e.g., infiltration measured using infiltrometers in hydrology vs. soil water recharge assessed in ecology through plant water potential), making collaboration difficult. Addressing these challenges requires fostering a culture of interdisciplinary thinking through education and training. Several studies have advocated for educational frameworks that equip scientists with the skills to work across disciplines, enabling them to understand better complex Earth system interactions (e.g., Arora et al., 2022; Dwivedi et al., 2022; Arora et al., 2024).

Hydrologic connectivity research must develop quantifiable metrics and standardized frameworks through interdisciplinary research and collaboration to enable comparisons across space and time. These tools will enable managers to assess connectivity across diverse regions and time periods, plan accordingly, and simulate future scenarios under changing climate conditions. However, more empirical research is needed to quantify the relationships between hydrologic connectivity and ecological diversity, including habitat heterogeneity and biodiversity (Liu D. et al., 2020; Stoffers et al., 2022).

5.3 Hydrologic connectivity: processes, disruptions, and strategies for management, policy, and practical applications

As discussed in this review, Hydrologic connectivity, encompassing the interplay of hydrological, biogeochemical, ecological, and geomorphological processes, plays a fundamental role in shaping catchment dynamics and resilience. However, both natural processes—such as drought, flooding, and sediment deposition—and human interventions—such as dam removal, fish passage installations, levee setbacks, floodplain reconnection, beaver reintroduction, and wetland rehabilitation—can alter these networks, potentially impacting catchment functionality. Effectively managing these changes requires an integrated approach that combines scientific research with practical applications.

Many field-based studies—such as wetland monitoring (e.g., Ury et al., 2023), river corridor assessments (e.g., Dwivedi et al., 2018a), and beaver dam analog (e.g., Dewey et al., 2022) studies—do not always explicitly assess hydrologic connectivity but still provide valuable insights into its dynamics. These studies can supplement hydrologic connectivity measurements and be used to evaluate restoration interventions by tracking changes in water flow, sediment transport, groundwater levels, and floodplain inundation.

Enhancing or restoring hydrologic connectivity is essential for sustaining water flow regulation, ecosystem resilience, and water quality. Restoring connectivity—reestablishing natural flows within a catchment by removing physical barriers, enhancing natural storage, and improving hydrologic linkages—is a key strategy for effective catchment management and climate adaptation (Jacobson et al., 2022). Key techniques for restoring hydrologic connectivity include longitudinal connectivity restoration, dam removal, fish passage installations, culvert replacement, and sediment transport restoration to improve water, sediment, and organism movement along rivers and streams (Heckmann et al., 2018; Rogosch et al., 2024). Lateral connectivity restoration focuses on reconnecting floodplains through levee setbacks, wetland restoration, and riparian buffer establishment to enhance flood storage and infiltration (Covino, 2017; Ameli and Creed, 2017). Vertical connectivity improvements aim to restore surface-subsurface interactions through soil conservation, permeable urban surfaces, and groundwater flow path restoration to support infiltration and water retention. Ecological connectivity enhances habitat continuity by reintroducing beavers, creating side channels, and managing invasive species to restore natural hydrologic dynamics (Zimmer and McGlynn, 2018; Walker and Hassall, 2021).

While policy measures—such as wetland protection laws, river corridor zoning—and financial incentives for floodplain restoration, and ecological interventions—such as dam removal, riparian buffer restoration, and reintroducing beavers—can help restore hydrologic connectivity, successful implementation depends on a robust understanding of the complex interactions among water, sediment, and ecosystems across landscapes (Magilligan et al., 2016; Kendall, 2023; Brown et al., 2024). Because these interactions are complex and abstract, analogies—such as social networks, ecological corridors, and fluid flow—help visualize connectivity patterns (Masselink et al., 2017; Rinaldo et al., 2018; Gooseff et al., 2017). Similarly, hydrologic connectivity can be likened to an electric circuit, where water flow resembles electrical current, obstacles such as vegetation and rocky outcrops act as resistors, and wetlands function as capacitors, temporarily storing and regulating water (Al-Sayouri et al., 2018; Hasanah et al., 2022). These interdisciplinary frameworks provide valuable tools for research and management, though further refinement is needed for effective real-world application.

6 Concluding insights

This review synthesizes current approaches to measuring, modeling, and managing hydrologic connectivity, focusing on the importance of interdisciplinary collaboration (e.g., between hydrologists and ecologists) and the potential of emerging technologies such as drones and imagery. Traditional measurement and modeling approaches for hydrologic connectivity struggle to capture complex catchment interactions, constrained by spatial, temporal, and computational limitations, as well as the inherent difficulty of integrating subsurface processes with surface hydrology. Other challenges are posed by fragmented datasets, limited open-access data, and communication barriers across disciplines. Without broader implementation and comparability across different regions and scales, the true potential of hydrologic connectivity in water resource management cannot be realized, yet the absence of standardized connectivity metrics and methodologies hampers progress. All of these issues require urgent attention.

A comprehensive approach to hydrologic connectivity should integrate emerging technologies—including camera imagery, drones, AI, and WUSN—to enhance data collection and improve spatial and temporal coverage. Expanding standardization efforts, including open-access data platforms (e.g., ESS-DIVE, USGS repositories) and unified measurement strategies, will facilitate interdisciplinary collaboration and improve data integration. A unified framework is required to facilitate interdisciplinary collaboration and enhance science-based decision-making in water resource management. Conceptual simplifications, such as the electric circuit analogy, can provide such a framework by illustrating hydrologic connectivity holistically within a catchment and fostering a shared perspective, common language, and integrated approach across disciplines. Future research should prioritize high-resolution and long-term monitoring as well as adaptive management to restore hydrologic connectivity in fragmented landscapes. Management strategies must integrate predictive modeling to account for system-wide connectivity, anticipate climate-driven shifts, and enhance ecosystem resilience. Ultimately, this review inspires the catchment science community to transform hydrologic connectivity research into practical management tools that guide policy decisions and promote adaptive, resilient water resource strategies.

Author contributions

DD: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. RP: Conceptualization, Writing – review & editing. EW: Conceptualization, Writing – review & editing.

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