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Review

Integrating fluvial geomorphology into river hydrological connectivity: Implications for carbon emissions

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ABSTRACT

Rivers serve as critical components of the carbon cycle and hotspots for carbon emissions, while changes in hydrological connectivity can significantly modulate carbon emission processes. Through literature analysis, we elaborate the concept of hydrological connectivity, and proposes a refined definition that incorporates fluvial geomorphology. This redefined concept characterizes the integrated transport of materials, energy, and biota within river systems, encompassing both structural and functional connectivity dimensions, along with their temporal-spatial dynamics and relative stability. Based on this theoretical foundation, we propose a framework for assessing carbon emissions under changing hydrological connectivity patterns. The framework integrates empirical formulations with remote sensing data interpretation to delineate the river areas of carbon emissions, while incorporating field-measured carbon fluxes to establish a Monte Carlo model for emission estimation. Furthermore, anthropogenic activities alter hydrological connectivity, thereby affecting watershed-scale carbon budgets. Consequently, future research should incorporate advanced technologies to integrate socioeconomic factors into hydrological connectivity assessments, and facilitate the development of intelligent monitoring, evaluation, and prediction systems at the watershed or regional scale, enabling comprehensive emission assessments.

1. Introduction

Rivers play a critical role in connecting terrestrial, marine, and atmospheric carbon pools (Cole et al., 2007; Rocher-Ros et al., 2023). As critical components of the carbon cycle, rivers represent hotspots for carbon emissions, with their release of carbon dioxide (CO_2) and methane (CH_4) constituting significant sources of greenhouse gases (Hotchkiss et al., 2015). Research indicates that most river systems maintain CO_2 supersaturation, annually emitting approximately 1.8 Pg CO_2 to the atmosphere, offsetting about 80 % of terrestrial ecosystems' annual net carbon uptake (Raymond et al., 2013). A global assessment of 595 rivers further revealed substantial emissions from fluvial ecosystems, with annual CO_2 fluxes ranging from 6.5 to 9.9 Pg and CH_4 fluxes ranging from 19.3 to 41.4 Tg, demonstrating their non-negligible contribution to global warming (Li et al., 2021).

Hydrological connectivity plays a critical role in influencing carbon emissions through biogeochemical response to climatic factors, the physics governing gas transfer across the water-air interface, and seasonal variations in the spatial extent of drainage networks (Palmer and Ruhi, 2019; Liu et al., 2022). (*i*) From a fluvial geomorphological perspective, river channel network structure, and directional streamflow influence the movement of drifting organisms and materials downstream (Charlton, 2007). This indicates the wetting-drying cycles, induced by water level fluctuations, can alter the carbon sink or source in the river system (Zhu et al., 2022). (*ii*) Runoff changes during floods and droughts indicate not only volume differences but also variations in recharge sources on a seasonal and interannual scale (Peterson et al., 2021). The differences in recharge source indicate the alteration of the material basis for carbon emissions (Humborg et al., 2010). Recent years have witnessed increasing extreme drought events driven by climate change, combined with intensive anthropogenic disturbances, which have significantly altered river hydrological connectivity patterns (Li

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et al., 2024; Liu et al., 2024; Zhang et al., 2024), and consequently introduced substantial uncertainties in river carbon emissions.

Fluvial geomorphology provides the fundamental physical framework for river hydrological connectivity. However, previous studies have primarily focused on the degree of water connectivity when defining river hydrological connectivity (Malard et al., 2002; Changjiang Water Resources Commission, 2005; Xia et al., 2012), while neglecting the influence of fluvial geomorphology on hydrological connectivity. Moreover, water surface dynamics and flow variability are inherent characteristics of aquatic ecosystems such as rivers and lakes, especially under the influence of climate change and human activities (Feng and Gleason, 2024; Xu et al., 2024; Xu, 2025). Current approaches defining river carbon emission zones based on wetted areas at specific time points fail to consider the impacts of dynamic hydrological connectivity on whole-river carbon emissions (Rasera et al., 2008; de Melo et al., 2023). These oversights may introduce inaccuracies in river carbon emission estimates, potentially hindering effective protection and enhancement of riverine ecological functions.

Consequently, through a literature analysis, we investigate current research priorities and clarify the concept of hydrological connectivity. Building on this foundation, we (*i*) redefine hydrological connectivity incorporating the fluvial geomorphology; (*ii*) elucidate how altered hydrological connectivity affects river carbon emissions; and (*iii*) develop a framework for assessing carbon emissions under dynamic hydrological connectivity patterns. Furthermore, we also identify future research priorities regarding hydrological connectivity patterns and their impacts on river carbon emissions. The remaining sections of the present study are organized as follows: Section 2 employs bibliometric analysis to characterize current research priorities of hydrological connectivity; Section 3 synthesizes the conceptual framework of hydrological connectivity, and introduces a concept of hydrological connectivity incorporating fluvial geomorphology; Section 4 examines the implications of hydrological connectivity for river carbon emissions; Section 5 develops an assessment framework for quantifying carbon emissions under dynamic hydrological connectivity regimes; and Section 6 presents key conclusions and future research directions.

2. Research priorities analysis

2.1. Data sources and analytical methods

Bibliometric analysis demonstrates that keywords represent research

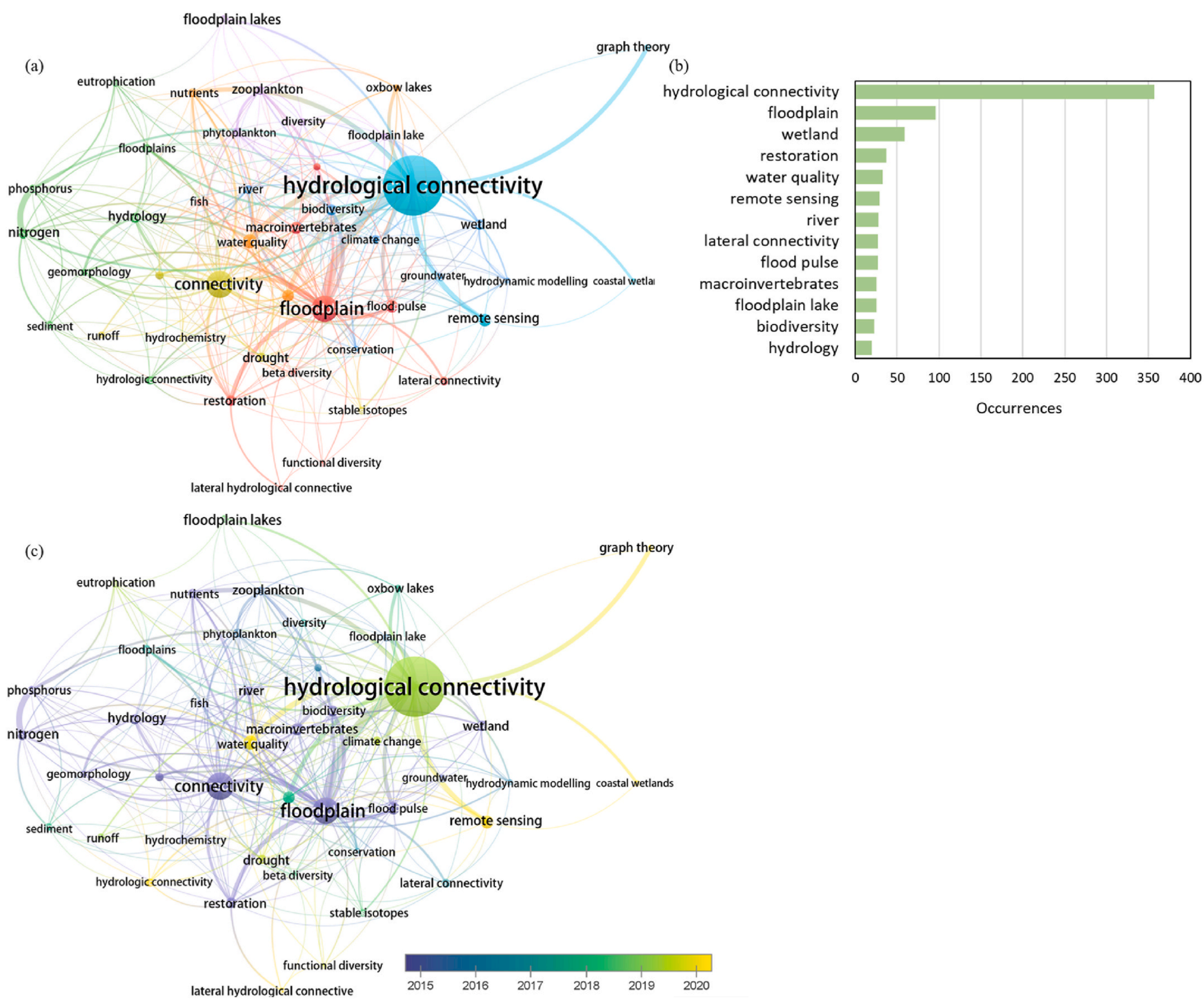

Fig. 1. Analysis of hydrological connectivity research trends. (a) is keyword co-occurrence network map, (b) is ranking chart of keywords occurring more than 20 times, and (c) is keyword co-occurrence overlay map.

frontiers, with higher frequency indicating stronger association with research hotspots (Shao et al., 2021; Liu et al., 2024). The literature analyzed was sourced from the Web of Science Core Collection, covering publications from 1992 to 2025, and a total of 1118 relevant publications were retrieved using the search query: TS=("hydrological connectivity" OR "water connectivity" OR "hydrologic linkage") AND TS = river. Subsequently, we performed keyword cluster analysis using *VOSviewer* (version 1.6.2) to identify key research hotpots on river hydrological connectivity.

2.2. Keyword cluster analysis

From 1992 to 2025, a total of 3379 keywords were identified in river hydrological connectivity research, including 44 keywords (1.3 % of the total) occurred more than 10 times (Fig. 1a). Synonym merging revealed 13 high-frequency keywords (>20 occurrences) representing research hotspots in hydrological connectivity studies. These were: hydrological connectivity (357), floodplain (96), wetland (59), restoration (37), water quality (33), remote sensing (29), river (28), lateral connectivity (27), flood pulse (27), macroinvertebrates (26), floodplain lake (26), biodiversity (23), and hydrology (20) (Fig. 1b). The analytical results demonstrate that floodplains, wetlands, rivers, and floodplain lakes as primary research domains in hydrological connectivity studies, with focus on hydrological connectivity-ecosystem functioning-environmental quality relationships, with remote sensing serving as the predominant methodological approach. Furthermore, the post-2019 period represents a rapid expansion phase in hydrological connectivity research (Fig. 1c).

The analysis demonstrates: (*i*) hydrological connectivity has emerged as a rapidly developing research frontier, yet (*ii*) its critical linkages with fluvial carbon fluxes remain underexplored, necessitating systematic mechanistic investigations.

3. Concept of river hydrological connectivity patterns

3.1. Definitions of hydrological connectivity

In 1980, Vannote et al. (1980) proposed the "river continuum" concept, suggesting that the variation of physical variables within a river system from source to mouth is continuous. Merriam (1984) subsequently introduced connectivity into landscape studies, proposing the concept of "landscape connectivity". Amoros and Roux (1988) pointed out the landscape spatial structure and functional connectivity of river systems from a landscape-scale perspective and introduced the concept of "river connectivity". Due to different research perspectives, there are differences in the definitions of hydrological connectivity among different scholars (Table 1).

Current definitions of hydrological connectivity focus predominantly on longitudinal river-ecosystem connections (e.g., lakes, wetlands) and material and energy fluxes, while overlooking lateral, vertical, and non-channel connectivity dimensions. Moreover, these definitions inadequately address seasonal variability in hydrological connectivity or its non-rhythmic alterations under climate change and anthropogenic disturbances. Therefore, it is imperative to propose an integrative conceptual framework for river hydrological connectivity through a novel perspective to enhance mechanistic understanding.

3.2. Concept of hydrological connectivity incorporating fluvial geomorphology

3.2.1. Fluvial geomorphology

River hydrological connectivity comprises two basic elements: the river channel and the flowing water. The river channel serves as the foundation for hydrological connectivity, so the river hydrological connectivity patterns are closely related to fluvial geomorphology. Flowing water drives surface erosion, shaping valley landforms through sediment transport and deposition. A lateral cross-section along the flow direction represents the river valley profile, which includes the riverbed, floodplain, valley slope, terrace, and valley shoulder (Fig. 2a). The lowest central area is the riverbed, with floodplains on either side of the riverbed. The riverbed and floodplains are referred to as the valley bottom, while the valley slopes are the slopes on both sides of the river valley, often with terraces developed. During the dry season, the river's flow rate is minimal, and only the riverbed carries runoff. Conversely, during the wet season, flow increases, water levels rise, and the floodplains are submerged, resulting in the entire river valley remaining water-covered.

Table 1
Definitions of hydrological connectivity.

Research Perspective	Definition	Reference
Landscape	The corridor that promotes or hinders the movement of organisms and biogeochemical elements between different patches.	Malard et al. (2002)
Aquatic Ecology	The ability to transport and transfer materials, energy, and organisms within and between hydrological cycle elements, using water as the medium.	Pringle (2003)
Water System	The connectivity of river channels, tributaries, lakes, and other wetlands, reflecting the continuity of water flow and the connectivity of the water system.	Changjiang Water Resources Commission (2005)
Hydrology	The migration efficiency of runoff carrying materials and energy from the watershed source, through the river network, to the watershed outlet cross-section.	Freeman et al. (2007)
Watershed Ecology	The dynamic property of regional interconnections described by hydrological processes.	Turnbull et al. (2008)
Other	The maintenance, reshaping, or creation of water flow connection channels on natural and artificial river, lake, and reservoir systems, designed to meet certain functional goals, in order to maintain relatively stable flowing water bodies and the associated material cycles.	Xia et al. (2012)

The profile along the flow direction is the longitudinal profile of the riverbed (Fig. 2b). Generally, the riverbed in the upper reaches has a steep "V" shape, with deep and narrow cutting; the middle reaches gradually widen, while the lower reaches transition to a wide, shallow form with a gentler slope. The differences in the riverbed along the longitudinal direction cause flow velocity to decrease downstream. The flow velocity peaks in the upstream, where floods spread easily, then declines toward the mouth, promoting sediment deposition and delta formation. In addition, contrasting upstream and downstream riverbed forms lead to varying water level rise and surface widening across reaches. The upstream section is narrow with a small flow cross-section, causing rapid water level rise and pronounced depth changes during floods. In contrast, the downstream section has a widened valley, resulting in large variations in the water surface area.

3.2.2. Meaning of river hydrological connectivity patterns incorporating fluvial geomorphology

Fluvial geomorphology is a key factor influencing hydrological structural connectivity in river systems. River hydrological connectivity can be defined as a three-dimensional interactive pathway (longitudinal: river source to river mouth; lateral: riverbed to floodplain; vertical: surface water to groundwater) with a temporal dimension (Ward, 1989). Along with the flow, rivers also transport materials, energy, and organisms, representing the functional connectivity (Obolewski et al., 2016; Harvey et al., 2019). Based on this, we redefine river hydrological

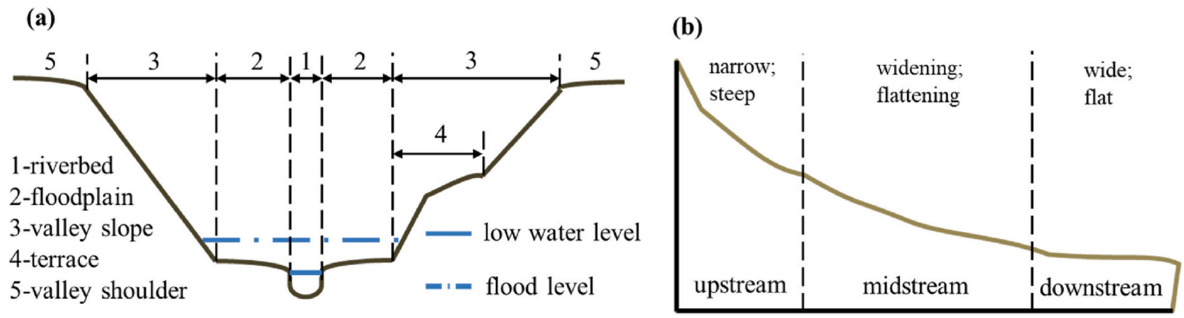

Fig. 2. River valley geomorphic profiles. (a) is the transverse profile of the river valley, and (b) is the longitudinal profile of the riverbed.

connectivity as the average state exhibited during the transport of materials, energy, and organisms by the water in the river channel, characterized by structural connectivity and functional connectivity, with temporal dynamics, spatial dynamics, and relative stability. Distinct from previous definitions, this concept incorporates both spatial dimensions (longitudinal, lateral, vertical) and temporal variability based on fluvial geomorphology, aligning with the theoretical paradigm of rivers as "River Continuum Concept (Vannote et al., 1980)". It significantly enhances the coupling between hydrological and ecological processes, providing a scientific foundation for river health assessment and systematic management.

3.2.2.1. Attributes of river hydrological connectivity patterns incorporating fluvial geomorphology. We posit that river hydrological connectivity patterns incorporating fluvial geomorphology exhibit two key attributes: (*i*) River hydrological connectivity patterns, with fluvial geomorphology as the basic physical framework, possess the attribute of structural connectivity; and (*ii*) river hydrological connectivity patterns, with different modes and degrees of connectivity, have varying impacts on the transport of materials and energy, thus possessing the attribute of functional connectivity.

Structural connectivity describes the spatial connectivity within different river segments and between river ecosystems and other ecosystems. It specifically manifests as physical connections in space between the downstream (longitudinal), riverbed and floodplain (lateral), and surface water and groundwater (vertical), and is a form of static connectivity. Structural connectivity has stability and smoothness. Stability refers to the relative stability of the riverbed and floodplain under certain flow impacts, which forms the basis of structural connectivity. Smoothness refers to the absence of obstacles between the connecting channels, reflecting the essence of structural connectivity. Good structural connectivity features a complete longitudinal riverbed line, reasonable lateral cross-sectional forms, and unobstructed surface water-groundwater discharge channels (Chen et al., 2020a). Dam density, river system closure, and development coefficient can be used to represent the degree of structural connectivity.

Functional connectivity refers to the process of material transport, exchange, and energy flow through water, and is expressed as the degree of exchange of materials and energy in the longitudinal, lateral, vertical, and temporal dimensions, which is a dynamic form of connectivity (Merenlender and Matella, 2013). This connectivity fundamentally depends on the continuity of river flow. Functional connectivity can be characterized by the amount of water and the speed of flow, which respectively affect the quantity and rate of material and energy exchange. Spatially, functional connectivity can be represented by flow rate and velocity differences in the longitudinal direction, water level and inundation extent in the lateral direction, and surface water-groundwater interactions in the vertical direction.

Structural and functional connectivity are interdependent components of an integrated system. Structural connectivity forms the basis of functional connectivity and directly affects the continuity and flow of river water. Functional connectivity, as a manifestation of structural connectivity, is the primary driver of water circulation, material exchange, and energy flow. Therefore, at any given time or space, different states of structural and functional connectivity exist within a watershed, representing the hydrological connectivity pattern of that period.

3.2.2.2. Characteristics of river hydrological connectivity patterns incorporating fluvial geomorphology. River hydrological connectivity patterns incorporating fluvial geomorphology are characterized by temporal dynamics, spatial dynamics, and relative stability. Temporal dynamics are reflected in variations in material and energy transport volume and transfer rates in the same space over time. Influenced by precipitation, the river's hydrological connectivity pattern varies seasonally at the same water-crossing section. During the wet season, increased precipitation raises river discharge, causing water to spill over the riverbed and inundate the floodplain. This opens lateral exchange channels between the riverbed and floodplain, thereby intensifying material exchange. During the dry season, when water levels fall, the lateral connection is severed, limiting materials exchange (Nat et al., 2002; Thompson et al., 2023). However, baseflow recharge enhances the vertical connectivity between surface water and groundwater (Chen and Teegavarapu, 2020; Chen et al., 2023). Overall, river flow and velocity increase during the wet season, enhancing longitudinal hydrological connectivity. As water levels rise, the water surface expands, increasing the connectivity between river ecosystems and terrestrial ecosystems, resulting in stronger material exchange. Seasonal fluctuations in water levels are reflected in the expansion and contraction of the river surface, with differences in the intensity of material and energy exchange in the lateral, longitudinal, and vertical dimensions. These variations represent different hydrological connectivity states and are an important manifestation of the variation in river hydrological connectivity patterns over time.

The spatial dynamics of hydrological connectivity patterns are reflected in differences in material and energy transport volumes and transfer rates across different spaces during the same period. These are primarily manifested in the differences in water volume and flow velocity from upstream to downstream. At the river source, water volume is low and flow velocity is slow, resulting in weak longitudinal hydrological connectivity (Bracken and Croke, 2007). In the upstream reaches, although water volume remains low, the narrow cross-section leads to higher flow velocity and, consequently, more efficient material transport. As confluence increases, the downstream reaches experience increased water volume and material transport, but the enlarger cross-sectional area reduces flow velocity, thereby decreasing transport efficiency (Feng and Gleason, 2024). At the river mouth, where the water volume is highest, the flat terrain causes water to spread, slowing flow velocity, and promoting materials such as sediment easily accumulate, resulting in the lowest material transport capacity. These varying connectivity modes and intensities between upstream and downstream reaches illustrate the spatial variation of the river's hydrological connectivity patterns.

From a long-term scale and across the entire watershed, hydrological connectivity patterns exhibit relative stability. In a natural watershed, the longitudinal riverbed profile and valley morphology do not experience abrupt changes. Minor variations in longitudinal, lateral, and vertical connectivity can be disregarded over extended time scales. Therefore, the structural connectivity pattern of the river remains relatively stable. Under the natural rhythm of the climate, meteorological and environmental conditions tend to remain consistent throughout the year, supporting the conditions for the dynamic equilibrium of runoff generation and confluence. At the same time, the material and energy reserves of the watershed are relatively fixed, with functional connectivity in relative balance. Thus, in a natural watershed unaffected by extreme climate events or human activities, hydrological connectivity patterns remain relatively stable over multi-year timescales. This stable state of hydrological connectivity can be represented by multi-year averages.

4. Variation characteristics of river hydrological connectivity patterns and their impact on carbon emissions

4.1. Impact of non-natural rhythms on river hydrological connectivity patterns

Under natural rhythms, the river hydrological connectivity pattern remains relatively stable. However, under the influence of climate change and intensive human activities, which represent non-natural rhythms, river hydrological processes experience abnormal changes, resulting in non-natural changes in the river's hydrological connectivity pattern.

4.1.1. Impact of climate change on river hydrological connectivity patterns

Climate change, especially extreme droughts, reduces river runoff, thereby diminishing the river's lateral and vertical hydrological connectivity (Fig. 3). During non-drought periods, high runoff levels connect the riverbed and floodplain, resulting in strong lateral connectivity. However, under meteorological drought, river runoff decreases, leading the floodplain be exposed, and reducing lateral hydrological connectivity. Baseflow, a relatively stable component of river runoff that links groundwater recharge with surface water, also declines under extreme drought conditions (Lapworth et al., 2021; Wang et al., 2023). This reduces interactions between groundwater and surface water, leading to weakened vertical connectivity. Therefore, meteorological drought leads to a reduction in streamflow and baseflow, which is an important reflection of changes in lateral and vertical hydrological connectivity.

Moreover, changes in lateral and vertical hydrological connectivity can, in turn, influence the generation and transformation of streamflow and baseflow, further affecting the river hydrological connectivity pattern. Lateral and vertical hydrological connectivity control flow pathways and are therefore critical to runoff formation and transformation (Jencso and McGlynn, 2011). Lateral hydrological connectivity affects the timing, rate, and magnitude of hillslope runoff, thereby influencing the development of runoff, particularly in regions with high infiltration capacity (Shen and Liu, 2021). Runoff changes are particularly significant in waterlogged catchments, where hydrological connectivity is highly responsive. River vertical hydrological connectivity is a necessary condition for streamflow (Jencso et al., 2010). Somers and McKenzie (2020) indicated that groundwater significantly contributes to runoff and plays a stronger regulatory role during drought periods. High levels of lateral and vertical hydrological connectivity, supplying water to the river from the hillslopes and underground, are conducive to the generation of runoff and accelerate the response of hydrological processes. Thus, changes in streamflow and baseflow are manifestations of hydrological connectivity, which in turn affect the streamflow and baseflow processes.

4.1.2. Impact of human activities on river hydrological connectivity patterns

Under intensive human activities, especially dam construction, the natural structural connectivity is disrupted. The flow and connection of water bodies along the longitudinal direction are restricted, leading to reduced or interrupted runoff, and significantly altering hydrological connectivity patterns (Fig. 4). Before dam construction, water flowed freely along the riverbed, facilitating material exchange and energy flow between upstream and downstream. After dam construction, however, the flow path is obstructed, and downstream flow volume, timing, and duration are all regulated by the dam (Palmer and Ruhi, 2019).

At the same time, dams significantly influence the spatial distribution of water bodies and the centroid of water storage, profoundly altering the spatial structure of watershed hydrology. By intercepting upstream runoff and storing it in reservoirs, dams control downstream flows through flood releases, resulting in a reduction in downstream river, lakes, and reservoirs flows, and a lack of ecological flow in the riverbed, leading to a drop in water levels and a shrinking of the water surface (Fang et al., 2018; Yuan et al., 2024). Therefore, the changes in watershed water distribution and the shift in the centroid of water storage caused by dam construction are important reflections of changes in river hydrological connectivity patterns.

4.2. Impact of changes in river hydrological connectivity patterns on river carbon emissions

4.2.1. Basic theory of river carbon emissions

River carbon emissions refer to the release of CO_2 and CH_4 from the river surface into the atmosphere (Battin et al., 2023), typically represented by two indicators: emission rate and total emissions. Total carbon emissions at a given time can be expressed as the product of emission rate, emission area, and emission duration. However, because water surface area is a dynamic characteristic of rivers, defining the carbon emission region based solely on the instantaneous area of flowing water can be inaccurate. Moreover, river carbon emission rates exhibit temporal and spatial variability influenced by factors such as temperature, flow, and flow velocity. Temperature affects microbial activity, thereby influencing decomposition rates; flow, as the carrier of material

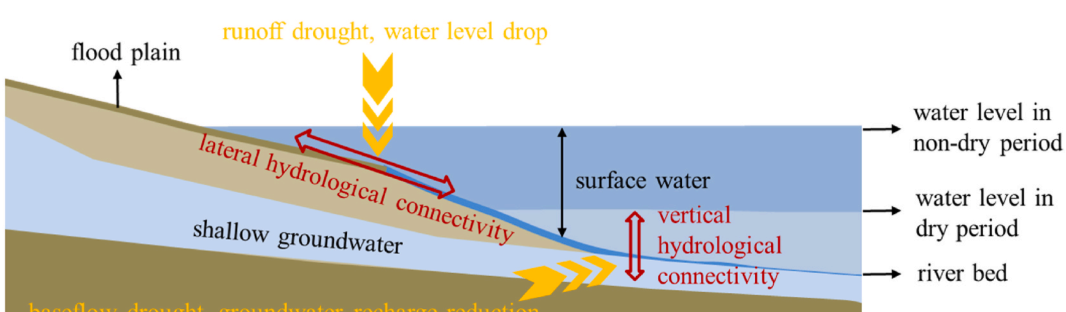

Fig. 3. Changes of lateral and vertical hydrological connectivity patterns under drought events.

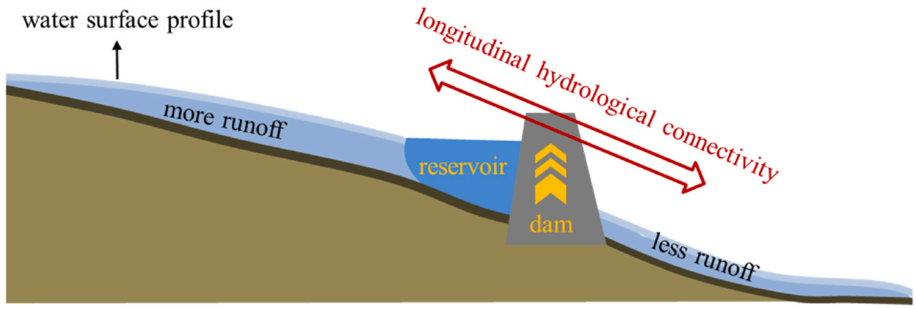

Fig. 4. Changes of longitudinal hydrological connectivity pattern under reservoir construction.

exchange, reflects the amount of carbon substrate in the river; and flow velocity impacts the speed of material transport and the rate of gas diffusion, collectively affecting carbon emission rates (Liu et al., 2022; Battin et al., 2023).

Therefore, based on the concept of river hydrological connectivity patterns that incorporate fluvial geomorphology, we propose that the region of river carbon emissions should encompass the entire river valley, including both the riverbed and riverbanks, while the water surface area should be considered separately for different seasons or the multi-year average state.

4.2.2. *Impact of changes in river hydrological connectivity patterns on carbon emissions*

River hydrological connectivity ensures the transport,

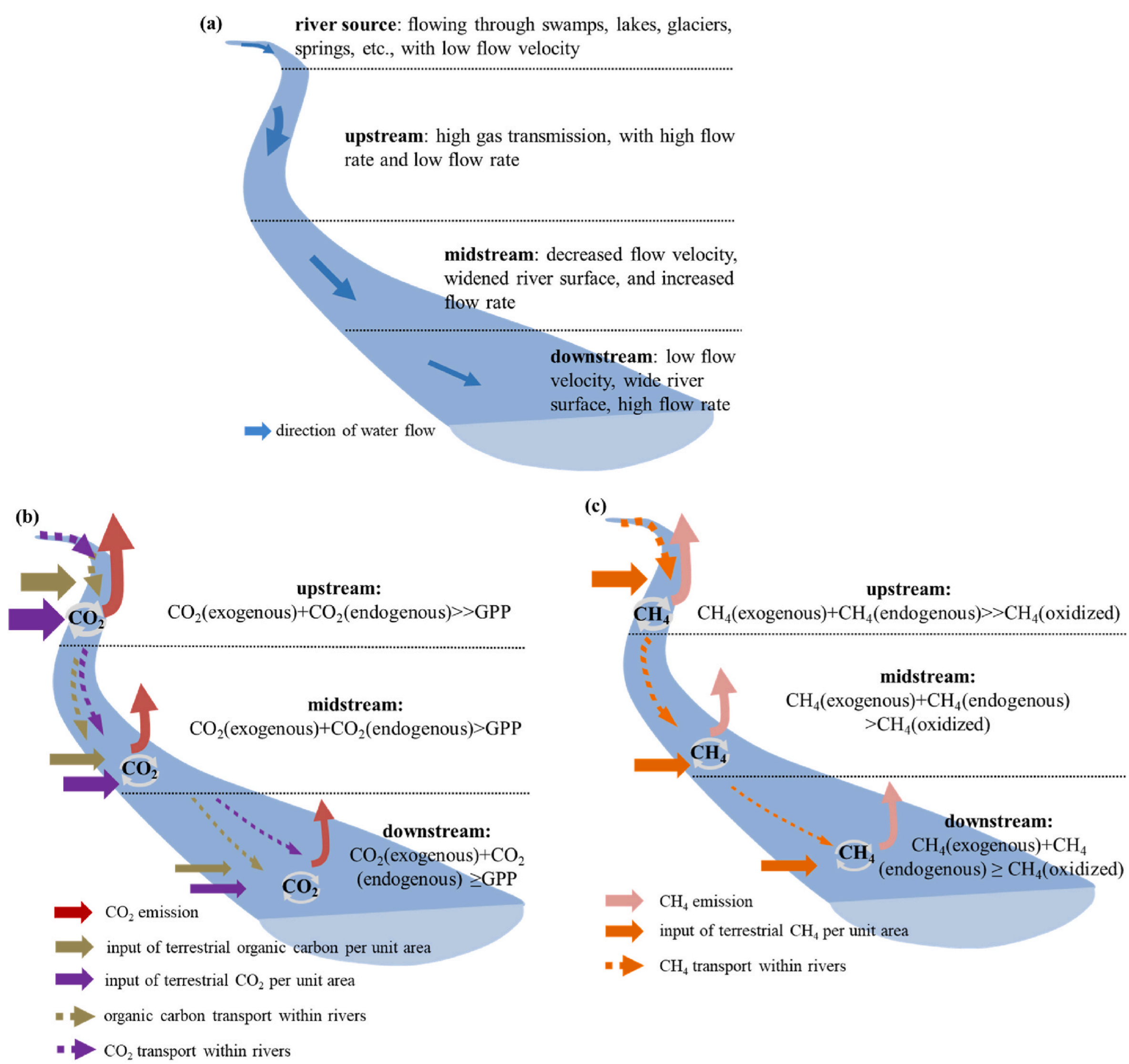

Fig. 5. Impact of changes in longitudinal hydrological connectivity patterns on river carbon emissions. (a) is the longitudinal hydrological change of the river; (b) refers to the longitudinal CO_2 emissions of the river, with GPP representing gross primary productivity; and (c) is CH_4 emissions along the longitudinal direction of the river. The change in flow rate is the key factor affecting carbon emissions. Arrow thickness indicates the magnitude of the quantity.

transformation, and cycling of materials and energy, serving as a primary driver of the river carbon cycle (Cui et al., 2016). Changes in hydrological connectivity patterns affect river carbon emissions by influencing both the input of exogenous carbon and the transmission and transformation of internal carbon. Exogenous carbon enters the river via the water body and is transferred and diffused under the influence of flow and velocity. Variations in flow and velocity along the longitudinal direction, changes in water levels and inundation areas along the lateral direction, and the strength of surface water-groundwater interactions along the vertical direction are key factors influencing river carbon emissions.

4.2.2.1. Impact of longitudinal hydrological connectivity on river carbon emissions. Flow and flow velocity are key elements through which changes in longitudinal hydrological connectivity patterns affect carbon emissions by influencing the input of CO_2, CH_4, and organic carbon into the river, as well as the gas transfer rate at the water-air interface, thereby driving river carbon emissions (Fig. 5). In the river source region, groundwater provides a substantial supply of carbon. Additionally, many river source areas pass through wetlands, lakes, and other carbon-rich zones, where large amounts of dissolved CO_2 and CH_4 in nearby soils enter the river, making this a high carbon emission zone. Gases that cannot be discharged in time are carried upstream through runoff, and the CH_4 input from wetlands, floodplains, soil, and groundwater surrounding the river further increases CH_4 concentration in the upstream river (Wang et al., 2017). As the slope of the riverbed decreases in the midstream and downstream, river width expands, flow velocity decreases, and carbon emission rates decline.

When longitudinal hydrological connectivity is impaired, the connection between upstream and downstream is restricted or blocked, limiting or halting the flow of biota, materials, and energy, creating "isolated" sections and altering the river carbon emission pattern (Stanley et al., 2016). For example, reservoir construction intercepts runoff and stores water, creating anaerobic conditions that promotes the production and emission of CH_4. Meanwhile, reduced or completely dried downstream runoff increases oxygen flux, leading to higher CO_2 emissions. These upstream-downstream differences in carbon emissions affect the spatial pattern of carbon emissions (Gómez-Gener et al., 2016).

4.2.2.2. Impact of lateral hydrological connectivity on river carbon emissions. Changes in water levels are a key factor influencing how lateral hydrological connectivity patterns affect carbon emissions (Fig. 6). As water level rise, the riverbed and floodplain become hydrologically integrated, increasing the intensity and frequency of connectivity and material exchange between them, which in turn impacts river carbon emissions.

Root respiration of floodplain plants and decomposition of soil organic carbon produce CO_2, which is transported into the river through slope surface runoff (Sawakuchi et al., 2016), constituting a primary source of CO_2 in the river. As lateral hydrological connectivity increases, the excess partial pressure of CO_2 in the floodplain decreases. Under disconnected conditions, the excess partial pressure of CO_2 is significantly higher than under connected conditions, indicating substantial CO_2 input into the river via water flow. Concurrently, water flow carries large amounts of dissolved organic carbon from the floodplain into the river, providing a material basis for carbon emissions (Osburn et al., 2018; Senar et al., 2018). Studies have shown that in organic-rich watersheds, river ecosystem respiration increases during peak flow events and continues to rise for several weeks (Demars, 2019). Moreover, river ecosystem respiration exceeds gross primary productivity (Bernhardt et al., 2022), highlighting the significant contribution of terrestrial carbon inputs to river carbon emissions.

Changes in water level induce periodic transitions between terrestrial and aquatic conditions in the floodplain, altering anaerobic conditions, soil moisture, soil organic matter, carbon-nitrogen ratios, and microbial activity and community structure, which in turn affects CO_2 and CH_4 emissions from the floodplain (Jiang et al., 2017; Poblador

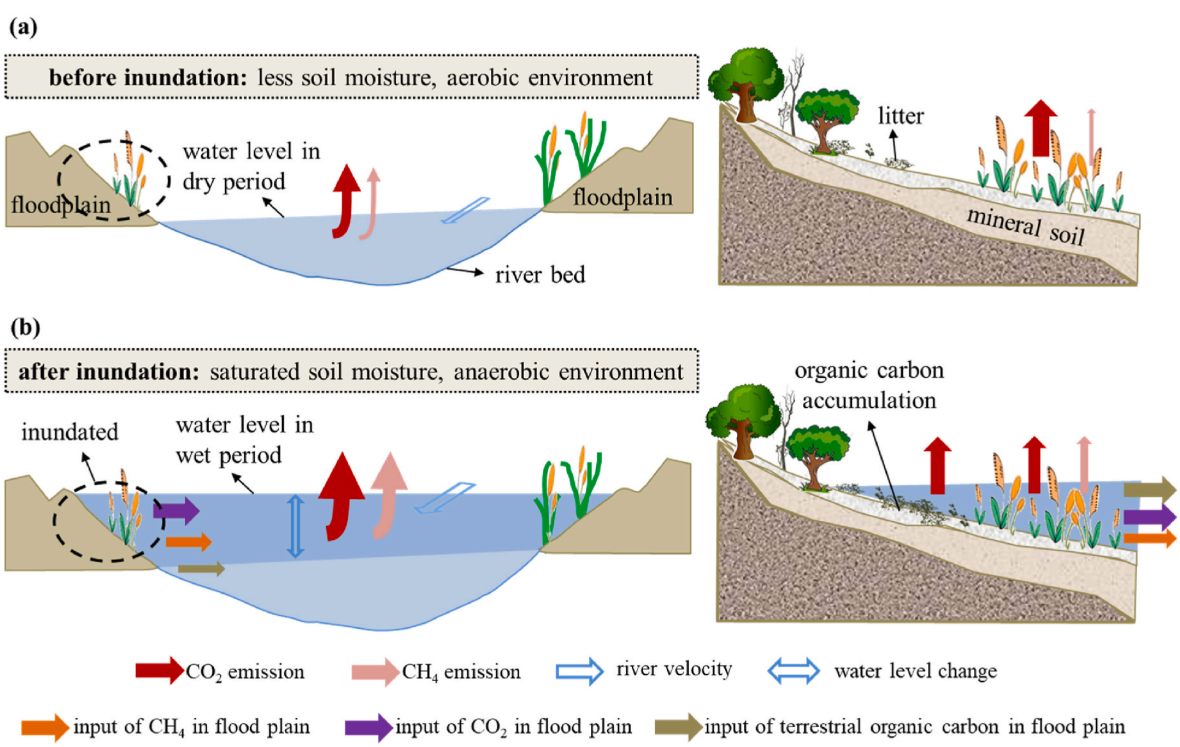

Fig. 6. Impact of changes in lateral hydrological connectivity pattern on river carbon emissions. Water level changes are the key factor affecting carbon emissions. (a) and (b) show the changing floodplain environment due to the change of lateral hydrological connectivity under the change of water level, respectively. Arrow thickness indicates the magnitude of the quantity.

et al., 2017). On the one hand, before flooding, floodplain soils are relatively dry and aerobic, promoting respiration from vegetation and microbes, and thus increasing CO_2 emissions. After flooding, soil moisture becomes saturated, and the increase in anaerobic conditions reduces microbial decomposition activity and ecosystem respiration while promoting the growth of methanogens, leading to reduced CO_2 emissions and increased CH_4 emissions (Hatala et al., 2012; Jansson and Hofmockel, 2020; Shi et al., 2021). On the other hand, prolonged flooding decreases microbial activity, limiting microbial decomposition. Consequently, material deposition rates exceed decomposition rates, causing accumulation of laterally input organic matter in the floodplain, which increases organic carbon storage and contributes to higher river carbon emissions over time.

4.2.2.3. Impact of vertical hydrological connectivity on river carbon emissions. River vertical connectivity refers to the interaction between groundwater and surface water, serving as a crucial pathway for groundwater recharge to the river. The strength of the interaction between groundwater and surface water is a key factor determining how changes in vertical hydrological connectivity patterns affect river carbon emissions (Fig. 7).

Firstly, groundwater contains a substantial amount of carbonates, which significantly contribute to river carbon emissions. Studies have shown that the CO_2 emission flux in rivers primarily fed by groundwater is 60 times higher than that of rivers of the same level (Humborg et al., 2010). Rock weathering is an important pathway for CO_2 production in rivers (Sun et al., 2017), providing the material foundation for CO_2 generation and emission. Groundwater, rich in CO_2, is directly transported into the river. Deep groundwater contains high concentrations of dissolved inorganic carbon produced by the weathering of carbon-rich rocks (Amiotte-Suchet et al., 2003), while shallow groundwater has a stronger hydrological connectivity with surrounding soils and contains significant amounts of CO_2 produced by soil processes (Peter et al., 2014). Because groundwater is typically colder, the temperature difference between the groundwater and the atmosphere reduces CO_2 solubility upon entry into the river, thereby promoting its release.

Secondly, groundwater carries methanogens, providing the driving force for river carbon emissions. Due to its low oxygen content, groundwater supports the activity of anaerobic microorganisms, such as methanogens, whose metabolic processes produce substantial amounts of CH_4 (Kulongoski and McMahon, 2019). When groundwater recharge occurs over a broad area and at a higher flow rate, more CH_4 retained in the aquifer is released into the river (Schout et al., 2020). In addition, methanogens in the hyporheic zone sediments will enter the river as groundwater is replenished, contributing to CH_4 production in the river. Therefore, groundwater recharge can lead to spatial heterogeneity in river CH_4 production (Hope et al., 2001), and the relative contribution of groundwater increases, resulting in large-scale variability in river CH_4 emissions (Jones and Mulholland, 1998).

4.2.2.4. Changes in carbon emissions from static water bodies (reservoirs) and their impact on basin carbon emissions. Rivers are dynamic continuous systems, and dams alter the flow characteristics by intercepting water and storing it in reservoirs (Chang et al., 2024). As flow approaches the reservoir, river velocity slows down, and the flow rate within the reservoir approaches zero, turning the dynamic river water into a static water body. Compared to rivers, reservoirs exhibit lower hydrological connectivity, and their carbon emission patterns change with the internal material and nutrient cycling. Thus, the shift from dynamic to static conditions, characterized by low flow velocity and high water levels, is a key driver for the unique carbon emission patterns in reservoirs (Keller et al., 2021). This transformation profoundly impacts the carbon emission patterns of downstream river reaches and the entire basin, increasing the uncertainty in carbon accounting for river systems.

Damming alters flow dynamics, with the flow rate slowing down and the water depth increasing, resulting in a change in the hydrological connectivity pattern, which directly affects carbon emissions (Fig. 8). Firstly, reservoirs have slower flow rates, which reduces the rate of gas exchange with the atmosphere. However, as a static artificial lake, the slower flow rate causes large amounts of terrestrial sediment particles to accumulate at the bottom of the reservoir. Additionally, submerged vegetation and biomass act as a significant carbon sink, providing substantial raw materials for carbon emissions from reservoirs (Li et al., 2017; Prairie et al., 2018; Chen et al., 2020b). A study showed that reservoirs store 13 % of the total organic carbon transported from land to the ocean, and this figure could increase to 19 % by 2030 due to growing reservoir construction (Maavara et al., 2017). Stagnant water impedes the cycling and transport of nutrients such as carbon, nitrogen, phosphorus, and silica, leading to eutrophication in the reservoir. During summer, high primary productivity may temporarily turn eutrophic reservoirs into carbon sinks (Zhao et al., 2013; Shi et al., 2017).

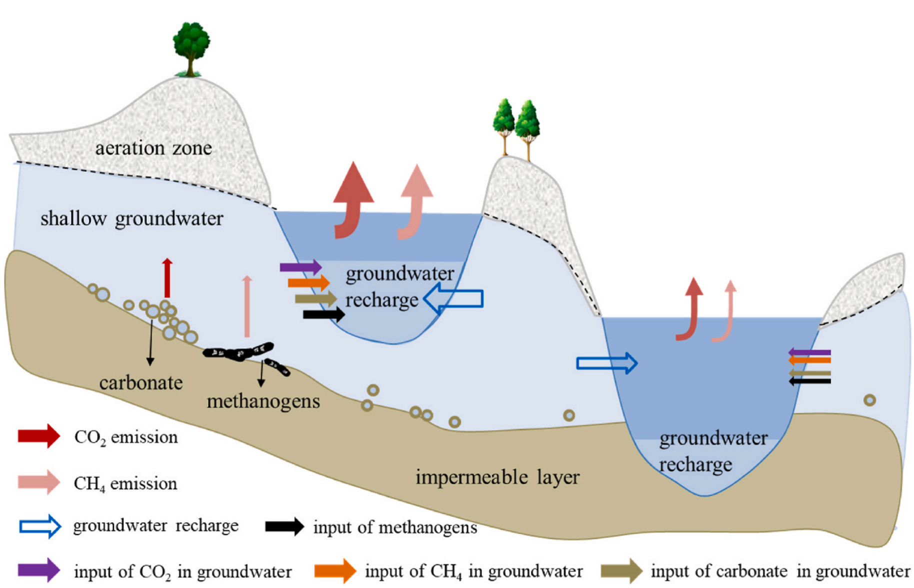

Fig. 7. Impact of changes in vertical hydrological connectivity patterns on river carbon emissions. The intensity of interaction between groundwater and surface water is the key factor affecting river carbon emissions. Arrow thickness indicates the magnitude of the quantity.

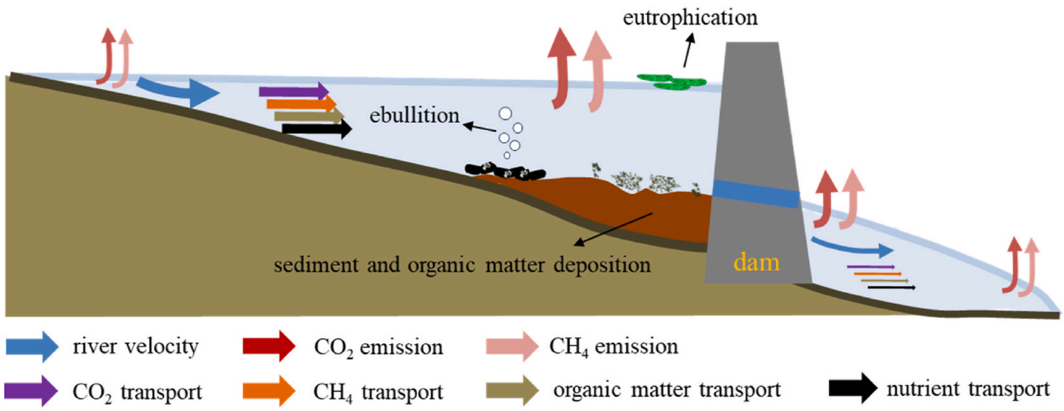

Fig. 8. Impact of damming on river carbon emissions. Key factors influencing carbon emissions in reservoirs include changes in flow velocity, water depth, and the transformation of dynamic river water into static water following dam construction. Arrow thickness indicates the magnitude of the quantity.

However, due to their large carbon storage capacity, these water bodies are often saturated with CO_2 year-round (Yan et al., 2021). Secondly, the water depth of the reservoir far exceeds that of the river, suppressing vertical oxygen mixing (McClure et al., 2018). Combined with microbial oxygen consumption during decomposition processes, reservoirs typically experience long-term, deep, low-oxygen conditions (Deemer et al., 2016; Deemer and Holgerson, 2021), providing an ideal environment for CH_4 production, which is often released into the atmosphere in the form of bubbling (Maeck et al., 2014; Harrison et al., 2017). This bubbling phenomenon reduces methane oxidation, leading to a greater greenhouse gas effect.

Reservoirs regulate the longitudinal hydrological connectivity of rivers, affecting the transport and cycling of materials between upstream and downstream, which makes the carbon cycle and carbon emissions processes and mechanisms more complex, profoundly altering the carbon emission patterns (Raymond et al., 2013; Maavara et al., 2020). On the one hand, dams control the flow of materials and energy between upstream and downstream, altering the carbon emission mechanisms of downstream reaches. While reservoirs block organic matter, they also serve as carbon sources that transport carbon to downstream, making these reaches important contributors to CO_2 emissions (Bevelhimer et al., 2016), with the emission flux tends to decrease with distance from the reservoir. A study reported that CO_2 discharged from reservoirs to downstream rivers accounts for approximately 70 % of the total annual CO_2 emissions from reservoirs (Yan et al., 2021). Although CH_4 emissions decrease from upstream to downstream, emissions from downstream reaches may increase, sometimes even exceeding emissions from the reservoir itself (Yang et al., 2013; Yang, 2019). On the other hand, water releases from reservoirs changes the longitudinal and lateral hydrological connectivity of downstream rivers, which in turn alters the carbon emission patterns. For example, during the dry season, reservoir water releases increase downstream flow, submerging floodplains and bringing large amounts of terrestrial carbon, nutrients, and organic matter into the river, further promoting carbon emissions (Beaulieu et al., 2012; Maavara et al., 2020). However, Ran et al. (2021) observed that the carbon emission flux from inland rivers in China decreased from 128.6 ± 31.3 Tg·a^{-1} in 1980 to 85.8 ± 19.4 Tg·a^{-1} in 2010, with reservoirs being the main factor contributing to the reduction of carbon emissions from inland waters.

5. A framework for assessing carbon emissions under changing hydrological connectivity patterns

Changes in river hydrological connectivity directly affect carbon emission patterns in the watershed. Accurately accounting for river carbon emissions is essential for quantitatively assessing the impact of hydrological connectivity changes on carbon emissions. However, previous methods relying on remote sensing to interpret river areas involve substantial uncertainty. For instance, due to the sensitivity of remote sensing signals to discharge variations, different river reaches exhibit distinct hydraulic visibility, resulting in significant discrepancies in the accuracy of river surface area estimations across reaches (Huang et al., 2024). Furthermore, monitoring surface areas of small-to-medium rivers remains challenging due to limitations in remote sensing data resolution and the spatial coverage of altimetry satellites (Pavelsky et al., 2014). These uncertainties in river surface area estimation propagate errors in carbon emission calculations. To address these challenges, we propose a framework for assessing carbon emissions under changing hydrological connectivity patterns, which can provide a deeper understanding of how hydrological connectivity changes influence carbon emissions (Fig. 9).

River carbon emissions are influenced by the river's surface area, which varies seasonally with changes in water volume. Therefore, when accounting for river carbon emissions, it is necessary to consider the water surface area during different seasons or to aggregate it based on the multi-year average, with a particular focus on the variation in water surface width. However, under the interference of climate change and human activities, the hydrological connectivity pattern undergoes unnatural changes. In such cases, it is necessary to separately account for changes in both the water surface area and the dry river channel area caused by changes in hydrological connectivity patterns. Additionally, river carbon emissions follow different patterns under different hydrological connectivity conditions. Thus, when estimating river carbon emissions under changes in hydrological connectivity patterns, it is necessary to comprehensively consider the transformations of the areas of flowing water, static water bodies, and dry river channels, as well as the differences in their carbon emission patterns, to minimize errors in the total carbon accounting.

5.1. Estimation of river carbon emission area

In the actual scenario, the river experiences dry stretches due to the interception of flow by climate change or human activities, and the carbon emissions come from the flowing river reaches, dry river reaches, and reservoirs, and the areas of these three components need to be calculated separately.

Since the width of the flowing river reaches is affected by the discharge, the width of the flowing river reaches can be estimated using an empirical formula relating discharge to river width (Raymond et al., 2013). River discharge data can be obtained from hydrological yearbooks.

$$W = 0.423 \times Q + 2.56 \tag{1}$$

Q represents the long-term average discharge of the river (m^3/s), and W

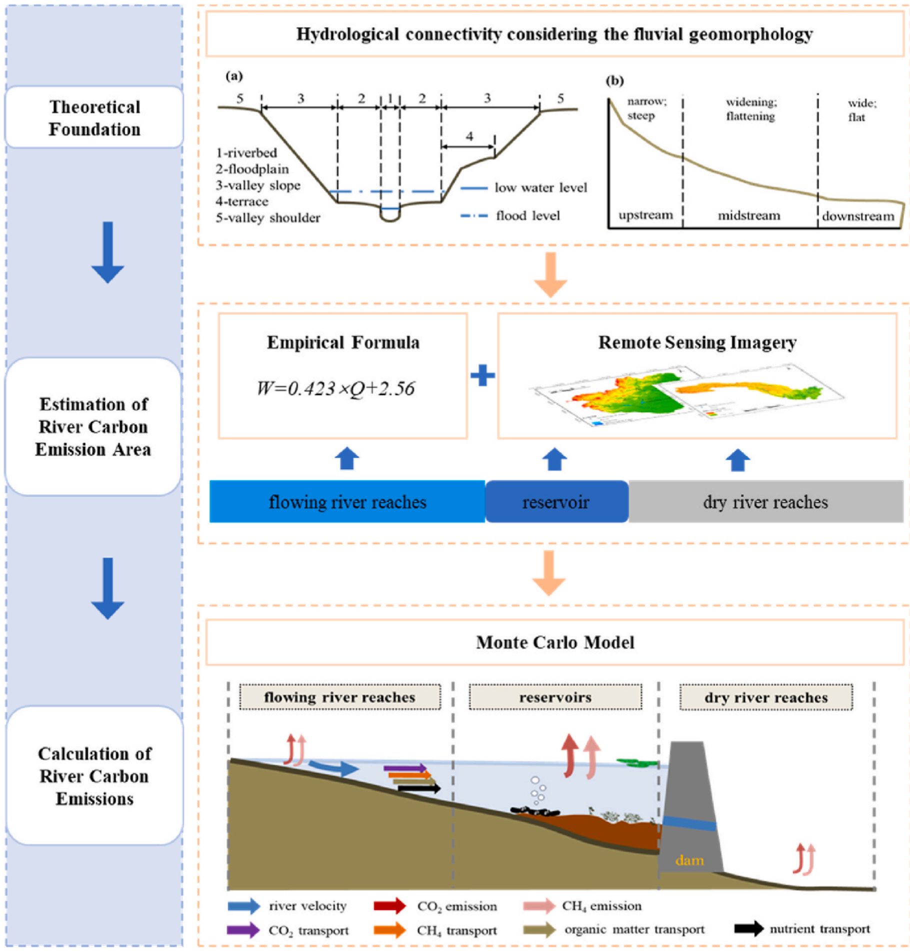

Fig. 9. Framework for assessing river carbon emissions under changing hydrological connectivity patterns.

represents the average river width (m).

We propose a systematic methodology for the efficient and accurate estimation of the surface area of dry river reaches (Table S1), comprising the following four-step procedures: (*i*) Assess the temporal patterns and spatial distribution of dry river reaches through comprehensive literature reviews and field surveys; (*ii*) acquire remote sensing imagery of dry river reaches to measure the total length of disconnected sections; (*iii*) establish a stratified sampling network with at least 50 sampling points using *ArcGIS*, where channel width measurements are collected at each location and averaged to determine the mean width of dry river reaches; and (*iv*) calculate the total surface area of dry river reaches by multiplying the measured river length by the estimated mean width.

When a reservoir is constructed on the river, it is essential to incorporate it into the carbon emission accounting process. The surface area of reservoir can be determined through the following methodology: Obtaining the boundary file of the reservoir from remote sensing imagery and calculating its area using *ArcGIS*.

5.2. Calculation of river carbon emissions

The Monte Carlo model has demonstrated excellent efficacy in previous studies on carbon emission estimation (Raymond et al., 2013; Kharab and Guenther, 2018; Zhang et al., 2020; Dean et al., 2025). Therefore, we recommend employing the Monte Carlo model for riverine carbon flux quantification, with the following specific procedures.

First, select at least 10 sampling sites in flowing river reaches, dry river reaches, and reservoirs respectively. Collect and measure carbon emission gases using the floating chamber method, with a minimum of 3 replicate samplings per site (Zhang et al., 2020; Gao et al., 2022; Yuan et al., 2023). The Monte Carlo model (by *MATLAB*) is used to calculate the average carbon emission flux of CO_2 and CH_4 for flowing reaches, dry river reaches, and reservoirs that consisted of 1000 runs for each sampling sites. Data from seven sampling sites are used for construction of Monte Carlo model, while the remaining data of three sampling sites are employed for validation of the simulation results. Each iterative run randomly resampled a CO_2 or CH_4 flux measurement, and simultaneously selected a surface area on the basis of a normal distribution model around the mean and standard deviation. Randomly resampled flux values were multiplied by randomly selected surface area for each run to generate total gas fluxes. Finally, multiplying the total gas flux per unit of time by the time duration gives the total carbon emissions for the river. Finally, the remaining data of three sampling sites were used to constrain the estimates and reduce the total uncertainty.

6. Conclusions and future perspectives

Under the influence of climate change and human activities that disrupt natural rhythms, the original river hydrological connectivity pattern is disrupted, leading to changes in carbon emission patterns. These disruptions also affect habitat adaptability and cause significant disturbances to the ecological environment of the watershed. Based on previous research, the present study redefines the river hydrological connectivity pattern according to fluvial geomorphology. The river hydrological connectivity pattern represents the average state exhibited during the transport of materials, energy, and organisms by the water in the river channel, characterized by structural connectivity and functional connectivity, with temporal dynamics, spatial dynamics, and relative stability. Differences in flow and velocity in the longitudinal hydrological connectivity, changes in water level and inundation extent in the lateral hydrological connectivity, and the intensity of surface water-groundwater interactions in the vertical hydrological connectivity are the key elements of the hydrological connectivity pattern that influence river carbon emissions.

Future research should focus on the following aspects: (*i*) The present study redefines river hydrological connectivity patterns incorporating fluvial geomorphology, and examines its impacts on riverine carbon emissions. However, given that water bodies also function as carbon sinks (Mendonça et al., 2017; Battin et al., 2023), future research should further investigate and expand upon the more specific implications of hydrological connectivity for carbon sequestration processes. (*ii*) River hydrological connectivity exhibits temporal dynamics, spatial heterogeneity, and relative stability. The present study primarily investigates hydrological connectivity variations and their impacts on river carbon emissions, without extending the analysis to the entire watershed or regional scale. Future research should integrate small-scale studies (focused on small regions and short timeframes) with large-scale studies (encompassing large watersheds and long timeframes), considering the transition processes between different scales to more accurately assess changes in river hydrological connectivity patterns. (*iii*) Advanced technologies such as artificial intelligence, big data, and cloud computing should be integrated to develop a more intelligent system for monitoring, assessing, and predicting the river hydrological connectivity, which will provide reliable data to support effective river management. And (*iv*) river hydrological processes are subject to alterations due to anthropogenic activities such as ecological water diversion projects, dam and reservoir construction, river channel restoration, and land-use changes (Zuo and Cui, 2020; Chang et al., 2024; Ou et al., 2024). These activities can impact river hydrological connectivity, ultimately leading to uncertainties in river carbon emissions. Therefore, comprehensive river carbon accounting should incorporate socio-economic impacts of hydrological connectivity changes, including human activities, land-use changes, and policy interventions, to achieve a holistic watershed-scale carbon emission assessment.

CRediT authorship contribution statement

Jifa Qin: Writing – original draft. **Qiang Liu:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Liqiao Liang:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126626.

Data availability

Data will be made available on request.

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