Journal of Environmental Management 392 (2025) 126706

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Ecological dynamics and resilience of anabranching rivers: Ecohydraulic insights from fish habitats

Shicheng Li [a], Ruida Wang [b], Qianqian Wang [b], Hao Zheng [b], Yacun Yang [b], Nan Wang [b], Chenyang Cao [b], Weiwei Yao [b,*]

[a] Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Stockholm, 10044, Sweden
[b] State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu, 610065, China

A R T I C L E I N F O

Keywords:
Anabranching river
Channel structure
Ecohydraulic modeling
Habitat assessment
Ecological resilience

A B S T R A C T

Anabranching river systems, characterized by multiple stable channels separated by vegetated islands, play a crucial role in maintaining aquatic biodiversity. Despite their ecological significance, anabranches' influence on ecohydraulic environments and fish habitats remains largely unexplored. This study seeks to address the gap by offering an in-depth investigation into the habitat dynamics and sensitivity of anabranching rivers, aiming to enhance the understanding of anabranches' ecological suitability, resilience, and stability. For this purpose, the study establishes an ecohydraulic framework to assess the habitat status for target species in four anabranching reaches with distinct channel complexity. The main channels provide optimal habitats for species favoring dynamic environments at moderate to high flows. In contrast, the low-energy anabranches provide refuges during extreme flows, supporting species that rely on stable and low-velocity conditions. The study also highlights the critical role of channel complexity in sustaining ecological resilience; reaches with complex anabranching patterns and vegetated islands provide higher habitat stability across a wide range of hydrological scenarios, mitigating the impacts of extreme events on aquatic habitats. Long-term ecological predictions demonstrate that anabranching channels enhance ecological stability, with limited fluctuations in habitat quality. From a management perspective, this study advocates for conservation practices that preserve these multi-channel structures and hydrological connectivity, supporting sustainable habitat conditions under changing environmental pressures. This research offers valuable insights for managing anabranching rivers and contributes a framework for habitat assessment applicable to similar ecosystems.

1. Introduction

The complex interplay among flow, sediment, morphology, and physiographic conditions creates diverse forms of alluvial rivers (Church and Ferguson, 2015; Rhoads, 2020). Based on channel morphology, alluvial rivers are usually classified into three types: straight, meandering, and braided channels (Carling et al., 2014; Latrubesse, 2008). Anabranching rivers are sometimes also recognized as a distinct channel type, characterized by multiple channels separated by relatively stable islands that persist nearly up to the bankfull stage (Guo et al., 2023; Rhoads, 2020). In recent decades, the growing accessibility of remote sensing technologies has led to the identification of more anabranching rivers in diverse physiographic settings worldwide (Latrubesse, 2015; Liu et al., 2016; Mendoza et al., 2016).

Ecologically, anabranching rivers support biodiversity by providing riparian habitats (Henriques et al., 2022). As an integral ecosystem component of anabranching rivers, vegetation accounts for the formation, evolution, and stability of these rivers. Vegetation interacts with rivers passively and actively (Camporeale et al., 2013). The passive way involves riparian vegetation affecting roughness, hydraulic resistance, and bank erodibility. The active way is linked to biotic processes (e.g., plant colonization and life cycles), influencing the hydraulic and morphodynamic processes (Henriques et al., 2022). The floodplain wetlands in anabranching systems create heterogeneous habitats and support distinct riparian vegetation communities, representing biodiversity hotspots (Marchetti et al., 2013). For instance, in the Moravkar River floodplain, the plant species diversity along the anabranches is greater than that of the single-thread channel (Škarpich et al., 2016). The diverse habitat conditions are primarily represented by terrestrial and riparian habitats, which are influenced by periodic inundation and

* Corresponding author.
E-mail address: yaoww@scu.edu.cn (W. Yao).

https://doi.org/10.1016/j.jenvman.2025.126706
Received 26 November 2024; Received in revised form 4 July 2025; Accepted 21 July 2025
Available online 29 July 2025

subsequent dry periods (Hupp and Bornette, 2003). Activities like river capture and regulation disrupt the flow dynamics, vegetation cycles, and the maintenance of aquatic habitats (Thapa et al., 2016) and should, therefore, be avoided. Maintaining habitat heterogeneity in anabranching systems is critical to river management and can be achieved through proper environmental flows and land management practices (Nilsson et al., 2007).

Anabrnching rivers maintain ecological integrity by offering diverse instream habitats. The multiple interconnected channels and stable islands offer a range of aquatic habitats. The channels create distinct flow regimes and substrates (Entwistle et al., 2018), catering to the habitat requirements of different organisms. Anabranches also improve habitat reliance, sustaining fauna and flora even during low- or no-flow periods (Entwistle et al., 2019). The structural complexity supports high levels of biodiversity, including fish and invertebrates. Abrial et al. (2019) revealed the complex dynamics of fish assemblages in lotic environments with extensive anabranching floodplains, highlighting the in-channel characteristics of floodplain river networks and their vital role in fish conservation, especially during shallow water stages. Ecological assessments of the Pike Anabranching system indicated favorable conditions for the increased presence of non-native fish species. Floodplain management interventions (e.g., enhancing connectivity and flowing habitats) could promote native fish diversity and abundance by creating micro- and meso-habitats (Beyer et al., 2010). The complex anabranch systems within the Chowilla-Lindsay-Wallpolla Icon Site are recognized as crucial habitats for supporting diverse flora and fauna. Notably, the anabranches provide essential habitats for native fish, owing to their unique hydrological regimes and the high density and complexity of instream habitats (Tonkin et al., 2017). Leigh et al. (2008) showed that the Chowilla Anabranching system provides a complex of physical and hydraulic habitats that support a range of life-history phases of native and exotic fish species.

Anabranching channels generate complex flow and sediment dynamics, which contribute to the creation of diverse habitats. However, despite their ecological importance, anabranches' influence on ecohydraulic environments and fish habitats remains largely unexplored. Only a few studies have covered this topic (Fernandes et al., 2004; Gualtieri et al., 2017; Nakajima et al., 2017). For example, Entwistle et al. (2019) performed a numerical study to explore the spatial complexity of habitats for locally anabranching channels. The habitat quality was assessed using a simplified metric (Froude number index), which offered limited ecological insights. Wang et al. (2024b) conducted a similar study, but the focus was mainly on multi-thread rivers. While both types of rivers have multiple channels, anabranching rivers are characterized by their stability and separation by vegetated islands. In contrast, multi-thread rivers, particularly braided ones, feature highly dynamic channels constantly shifting and separated by sediment bars.

This study aims to provide an in-depth investigation into the ecological dynamics and habitat resilience of anabranching rivers, which is limited in previous studies. The main objectives are to (a) enhance our understanding of how multi-channel structures promote fish habitat quality, (b) explore how anabranching channels react ecologically to extreme hydrological events, and (c) assess anabranches' long-term ecological stability. These aspects are also the gaps in existing literature, which are to be addressed by the present study. By advancing an integrated ecohydraulic framework, this study is expected to contribute to informed strategies for maintaining habitat quality and sustaining biodiversity in complex river systems.

2. Materials and methods

2.1. Study area and target species

The Yellow River is China's second-longest and sixth-longest globally, spanning ~5464 km. Its basin plays a crucial ecological role, supporting diverse ecosystems, wildlife, and human activities. The river's upper reaches exhibit a dynamic anabranching channel pattern, providing an ideal setting for studying the influence of anabranches on fish habitats.

The study site [Fig. 1(a)], the Maqu Anabranching System (MAS), extends approximately 56 km and is located in the core region of the Zoige Basin, within Maqu County (34.0° N, 102.1° E). The system begins as the Yellow River enters the central part of the Zoige Basin, flowing through a broad valley with a gentle channel gradient. The average channel gradient is 0.5 ‰, and the median grain size of the riverbed is ~4.5 mm (Li et al., 2013). The mean total channel width, including islands, is ~1500 m, while the average active channel width, excluding islands, is ~480 m (Guo et al., 2023). Based on morphological characteristics, the MAS is divided into four reaches [Fig. 1(b)]. The reach boundaries are defined at nodal points where there are no islands.

Reach I, located most upstream, is 11 km long and characterized by rounded islands and a few narrow anabranches likely formed through floodplain incision (Guo et al., 2023). Reach II spans 12 km and exhibits a more complex anabranching pattern, with its lower section encompassing several large islands separated from the floodplain by smaller anabranches. Similarly, Reach III, with a length of 21 km, features multiple large, elongated islands, including the largest island in the MAS. The anabranches of Reach III feature islands of varying sizes and diverse types of asymmetric bifurcations. Reach IV, the most downstream reach, has a length of 12 km and exhibits the lowest degree of channel diversity. The lower section of Reach IV includes a large pseudo-meander. Its meandering pattern is evidenced by the sinuous channel relics and scroll bars visible within the surrounding floodplain.

The Upper Yellow River flows through two ecologically sensitive regions, including the MAS, playing a vital role in maintaining the aquatic ecosystems of the Qinghai-Tibet Plateau. The riverine systems in this region are home to ~44 endemic fish species (Zhao et al., 2020). Two ecologically valuable species in the study area are selected as target species for habitat modeling: *Schizothorax wangchiachii* (*S. wangchiachii*) and *Cyprinus carpio* (*C. carpio*). *S. wangchiachii* is a species of ray-finned fish in the genus *Schizothorax*. *C. carpio* is a widespread freshwater fish of eutrophic waters in lakes and European and Asian rivers. The native wild populations are considered vulnerable to extinction by the International Union for Conservation of Nature (Ford, 2024).

2.2. Ecohydraulic modeling

This study establishes an ecohydraulic code for habitat modeling (Yao, 2021). The computational framework comprises a hydro-morphodynamic and a habitat module (Fig. 2). The hydro-morphodynamic module simulates physical hydrodynamic and sediment conditions, and the habitat module assesses the habitat quality for target species. This section provides the theoretical background of the ecohydraulic model.

2.2.1. Hydro-morphodynamic module

The hydro-morphodynamic model is developed to solve the two-dimensional shallow water equations by incorporating riverbed shear stress and the standard k-ε turbulence model, which is motivated by its satisfactory performance in similar studies (Li et al., 2024; Liu et al., 2024; Wang et al., 2024a). The continuity equation is expressed as

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)=0 \tag{1}$$

The momentum equation for the x- and y-component reads:

$$\begin{cases}\dfrac{\partial u}{\partial t}+u\dfrac{\partial u}{\partial x}+v\dfrac{\partial u}{\partial y}=-g\dfrac{\partial \eta}{\partial x}+\dfrac{1}{h}\left(\dfrac{\partial (h\tau_{xx})}{\partial x}+\dfrac{\partial (h\tau_{xy})}{\partial y}\right)-\dfrac{\tau_{bx}}{\rho h}+f_{cor}v \\ \dfrac{\partial v}{\partial t}+u\dfrac{\partial v}{\partial x}+v\dfrac{\partial v}{\partial y}=-g\dfrac{\partial \eta}{\partial x}+\dfrac{1}{h}\left(\dfrac{\partial (h\tau_{yy})}{\partial y}+\dfrac{\partial (h\tau_{yx})}{\partial x}\right)-\dfrac{\tau_{by}}{\rho h}+f_{cor}u\end{cases} \tag{2}$$

where u, v = depth-integrated velocity components in x and y directions;

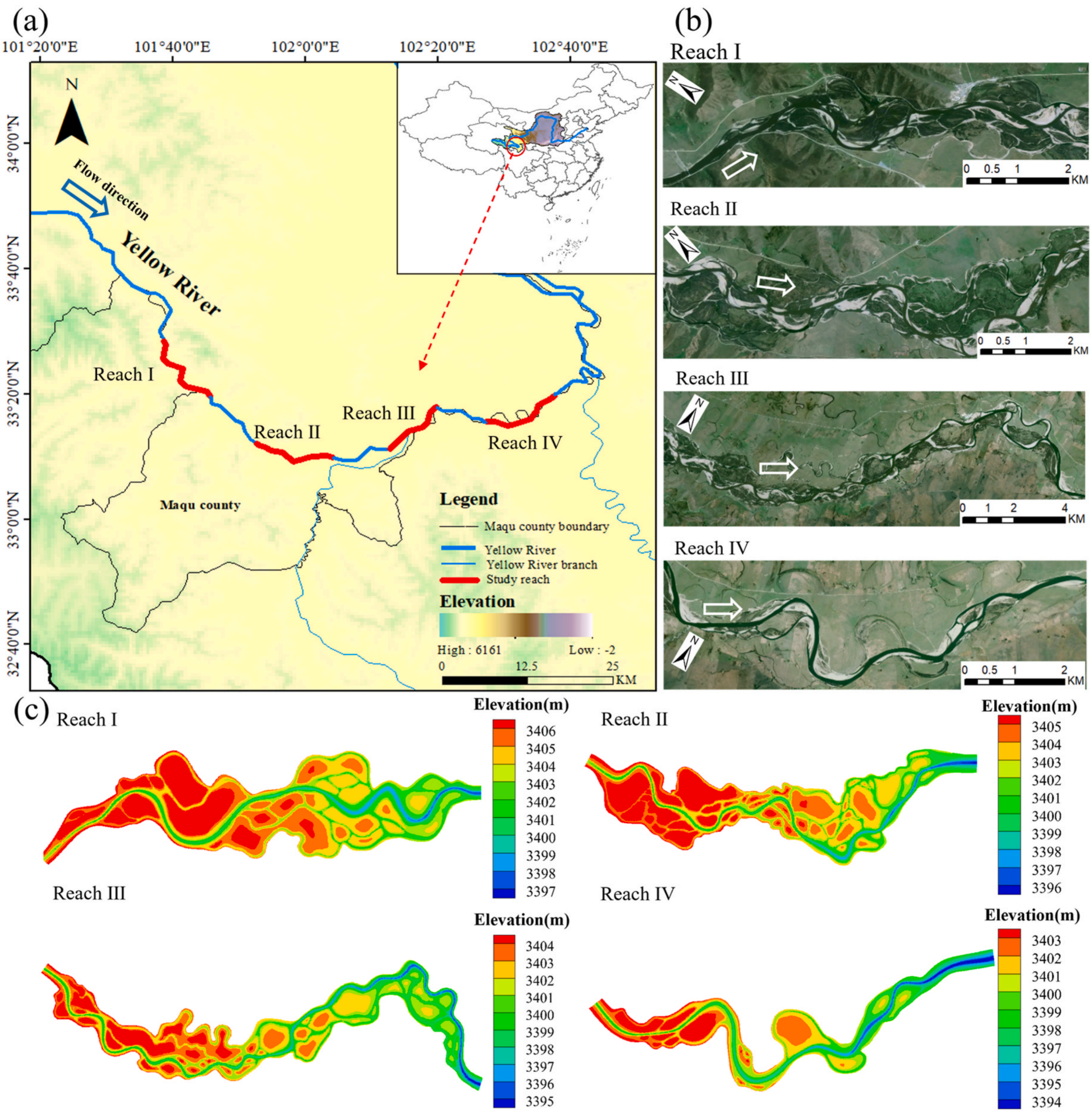

Fig. 1. Overview of the study area: (a) Maqu Anabranching System, (b) satellite images of the anabranching reaches, and (c) bathymetry of the anabranching reaches.

t = time; g = gravitational acceleration; η = water surface elevation; ρ = water density; h = water depth; f_{cor} = Coriolis parameter (neglected in numerical modeling due to its limited influence on the MAS scale); τ_{xx}, τ_{yy}, τ_{xy}, τ_{yx} = depth-averaged Reynolds shear stress; τ_{bx}, τ_{by} = bed shear stress. The shear stresses are computed by

$$\begin{cases} \tau_{xx} = 2\upsilon_t \dfrac{\partial u}{\partial x}, \tau_{yy} = 2\upsilon_t \dfrac{\partial v}{\partial y}, \tau_{xy} = \tau_{yx} = \upsilon_t \left(\dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x} \right) \\ \tau_{bx} = \rho C_f u \left(u^2 + v^2 \right)^{1/2}, \tau_{by} = \rho C_f v \left(u^2 + v^2 \right)^{1/2} \end{cases} \quad (3)$$

where υ_t = eddy viscosity and C_f = bottom friction.

The hydrodynamics are described by the shallow water equations, and the sediment transport involves the movement of sediment particles. A multilayer sediment model is applied to simulate riverbed deformation and dynamic substrate distribution (e.g., sand, gravel, cobble).

The bedload transport equation for the Meyer-Peter and Muller (MPM) function is defined as:

$$Q_b = \begin{cases} 0, \theta \le 0.47 \\ \alpha (\theta - \theta_c)^{3/2}, \theta > 0.47 \end{cases} \quad (4)$$

with $\theta = \frac{\mu \tau_b}{(\rho_s - \rho) g D_{50}}$ and $\theta_c = 0.047$, where Q_b = bedload transport rate, θ = Shields number, θ_c = critical Shields number, α = empirical parameter, μ = coefficient, ρ_s = sediment density, and D_{50} = median sediment diameter.

The suspended load transport equation is given by

$$\frac{\partial (Ch)}{\partial t} + \frac{\partial (Chu)}{\partial x} + \frac{\partial (Chv)}{\partial y} = \frac{\partial}{\partial x} \left(\varepsilon_t h \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(\varepsilon_t h \frac{\partial C}{\partial y} \right) + E - D \quad (5)$$

with $\varepsilon_t = \frac{\upsilon_t}{\sigma_t}$ and $E - D = w_s (C_{eq} - C_{ref})$, where C = suspended sediment concentration, ε_t = turbulent diffusivity, E = suspension rate, D = deposition rate, σ_t = turbulent Schmidt number, C_{eq} = equilibrium concentration of suspended sediment, C_{ref} = reference concentration at the bed, and w_s = settling velocity of sediment particles, calculated by the model of Dey (2014).

The Exner equation is introduced to determine the bed evolution

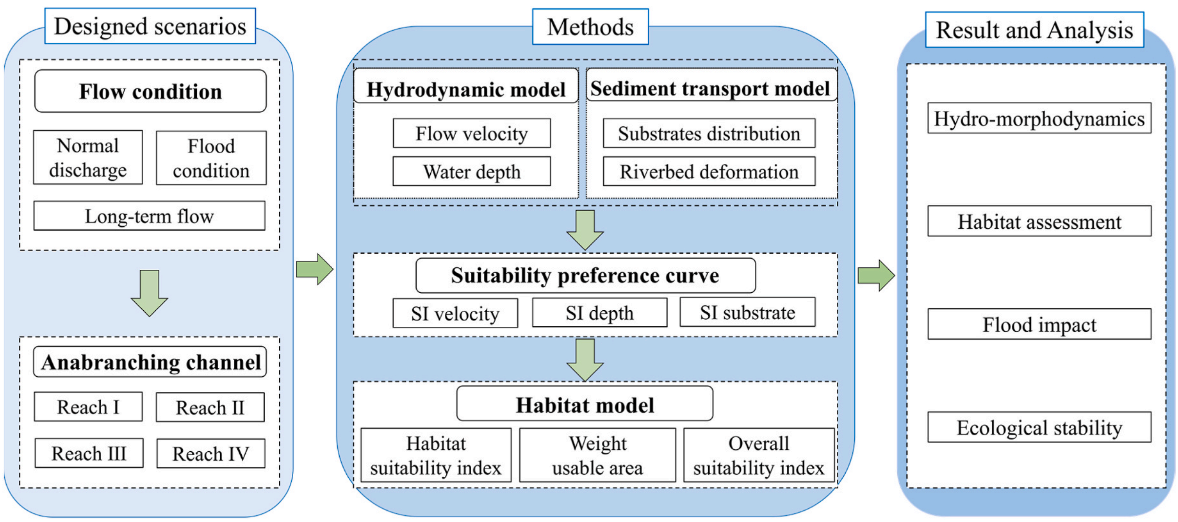

Fig. 2. Ecohydraulic model application for habitat assessment of the anabranching reaches.

influenced by bedload and suspended load:

$$(1-p)\frac{\partial Z_f}{\partial t}+\frac{\partial Q_b}{\partial x}+\frac{\partial Q_b}{\partial y}+(E-D)_{Z=Z_{ref}}=0 \tag{6}$$

where p = non-cohesive bed porosity, Z_f = bed elevation, and $(E-D)_{Z=Z_{ref}}$ = net sediment exchange between the bed and the water column at a reference elevation Z_{ref}.

2.2.2. Habitat module

The habitat module simulates and predicts the quality, availability, and distribution of fish habitats based on environmental factors, such as flow velocity, water depth, and substrate composition. The habitat suitability index (HSI) quantitatively represents habitat characteristics, ranging from zero to one, where zero denotes unsuitable conditions and one represents optimal conditions. The HSI is computed for each cell within the hydro-morphodynamic model:

$$HSI_i=(SI_1+SI_2+SI_3)^{1/3} \tag{7}$$

where HSI_i = HSI value for each computational cell i, and SI_1, SI_2, SI_3 = suitability index curves for fish-preference factors. Flow velocity, water depth, and substrate are the most critical parameters and are used as habitat suitability indices. Biological data are limited in the study area, and no new habitat monitoring is conducted in this study. Consequently, suitability data for the target species (Fig. 3) are obtained from previous ecological studies (Jiang et al., 2010; Li, 2017; Li et al., 2023; Xie et al., 2024). The curves are also reviewed and refined (if needed) through expert evaluation, incorporating input from local river managers.

Habitat quality is categorized into three levels based on HSI values: low (HSI $\leq$ 0.3), medium (0.3 $<$ HSI $<$ 0.7), and high suitability (HSI $\geq$ 0.7) (Yao, 2021). As a result, the low, medium, and high suitability proportions (LSP, MSP, and HSP) are defined as

$$LSP=\frac{\sum_i^m A_{i(HSI_{Ai}\leq 0.3)}}{\sum_i^m A_i},\ MSP=\frac{\sum_i^m A_{i(0.3<HSI_{Ai}<0.7)}}{\sum_i^m A_i},\ HSP=\frac{\sum_i^m A_{i(HSI_{Ai}\geq 0.7)}}{\sum_i^m A_i} \tag{8}$$

where A_i = area of cell i.

Weighted usable area (WUA) is a measure of the total area that is suitable for the species. It takes into account the habitat quality in each computational cell, expressed by

$$WUA=\sum_1^m A_iHSI_i \tag{9}$$

The overall suitability index (OSI) represents the proportion of the WUA relative to the total habitat area. It is a percentage measure of overall habitat suitability, calculated by

$$OSI=\frac{\sum_{i=1}^m A_iHSI_i}{\sum_1^m A_i} \tag{10}$$

The OSI ranges from 0 to 1, representing unsuitable and ideal

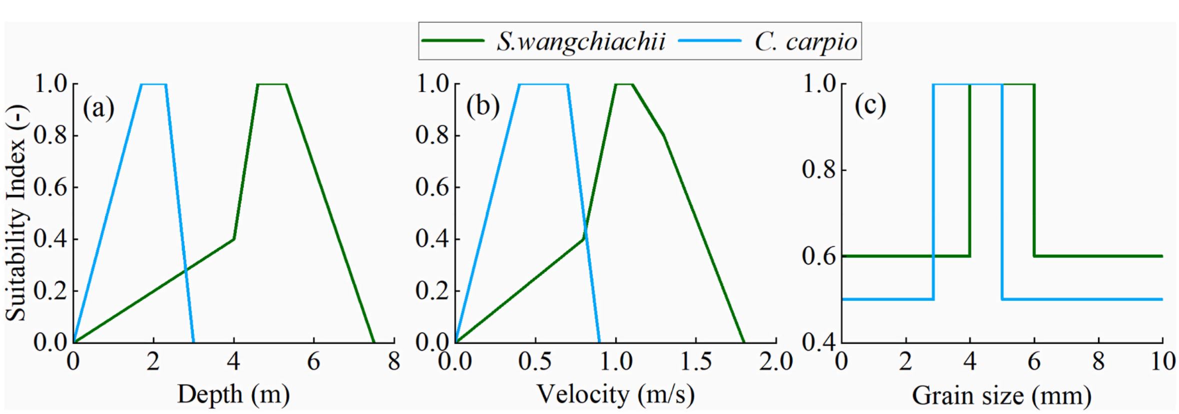

Fig. 3. Habitat suitability curves for target species: (a) flow velocity, (b) water depth, and (c) grain size.

conditions. These indices in the habitat module allow for assessing habitat suitability across complex river systems by integrating spatial and environmental factors into the model.

2.3. Model setup

The ecohydraulic model consists of a hydro-morphodynamic and a habitat module. The hydro-morphodynamic part is adapted from TELEMAC-SISYPHE and updated by the authors. The habitat model, combined with the hydro-morphodynamic model, is solved using the implicit finite volume approach (Yao, 2021). Subsequently, the ecohydraulic model is applied to evaluate the habitat quality for the target species in the anabranching reaches under various flow scenarios (Fig. 1).

Four anabranching reaches (Reaches I–IV in Fig. 1) are studied using the ecohydraulic model. In each reach, the computational domain consists of an inlet (most upstream), an outlet (most downstream), and solid walls (Fig. S1). Flow and sediment discharges are applied to the inlet, while water level and a zero gradient condition are used as outlet boundary conditions for velocity and turbulent kinetic energy, respectively. A solid wall boundary condition is imposed along the riverbanks. Following recommendations from similar studies (Li et al., 2024; Yao, 2016), the riverbed substrate distribution is modeled by categorizing sediment into ten fractions and dividing it into two distinct layers. This level of discretization allows the model to capture the full range of sediment sizes, from fine sand to coarse gravel, while keeping computational costs manageable. The two-layer structure represents vertical heterogeneity in the riverbed: the upper active layer participates in short-term sediment exchange, while the lower substrate layer represents a more stable foundation. Topographic meshes are generated to discretize the computational domains (Fig. S1). Mesh independence and convergence are evaluated, resulting in an optimal solution of unstructured triangular mesh with an average element number of ~22,000. The convergence criteria are satisfied when the maximum errors are less than 10^{-9}. Model inputs are summarized in Table S1. The numerical model was calibrated against measurements, as reported in our previous paper (Wang et al., 2024b), which demonstrated the reliability of the model.

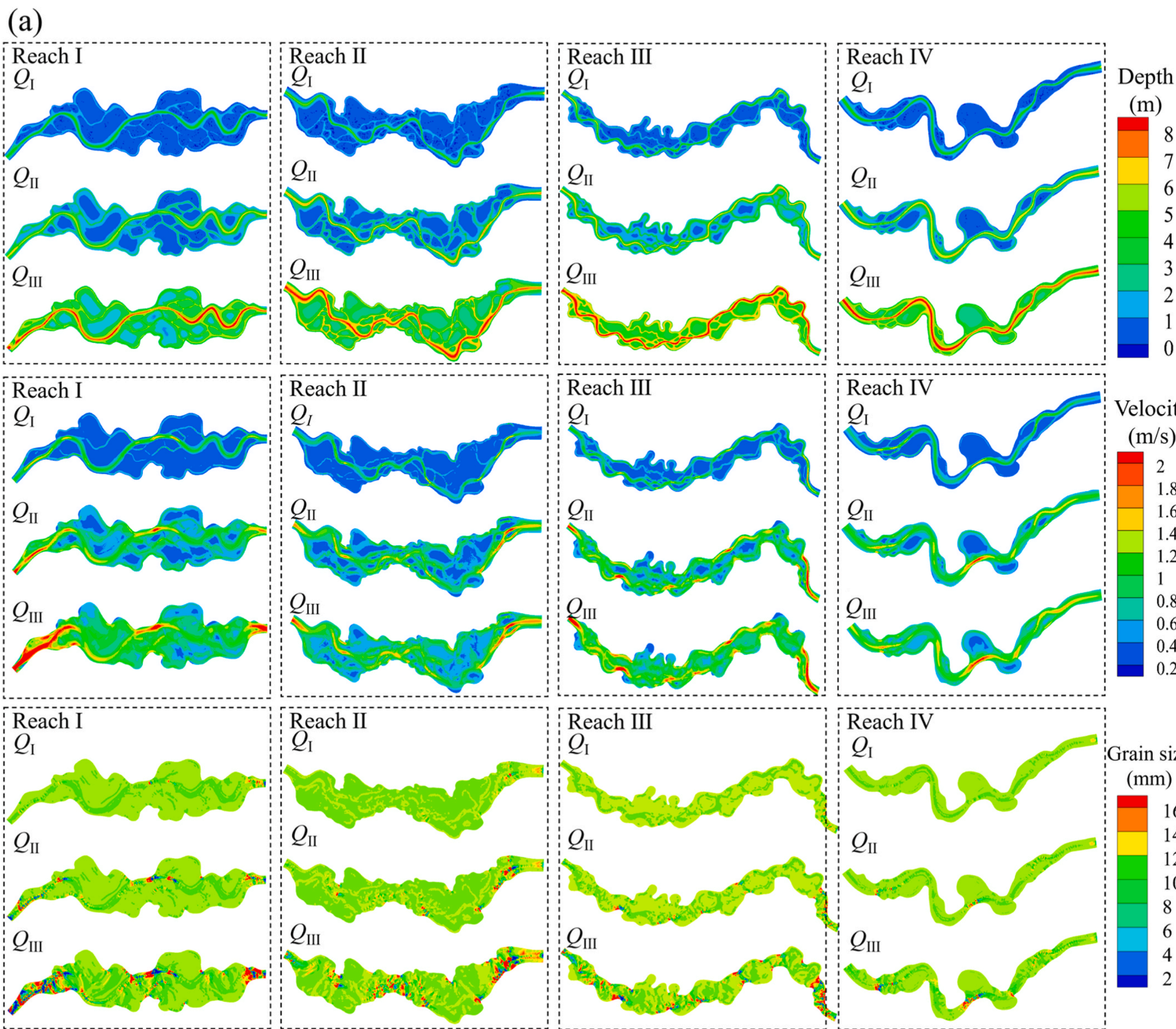

Fig. 4. Hydro-morphodynamics of the anabranching rivers under low, medium, and high discharges for (a) *S. wangchiachii* and (b) *C. carpio*.

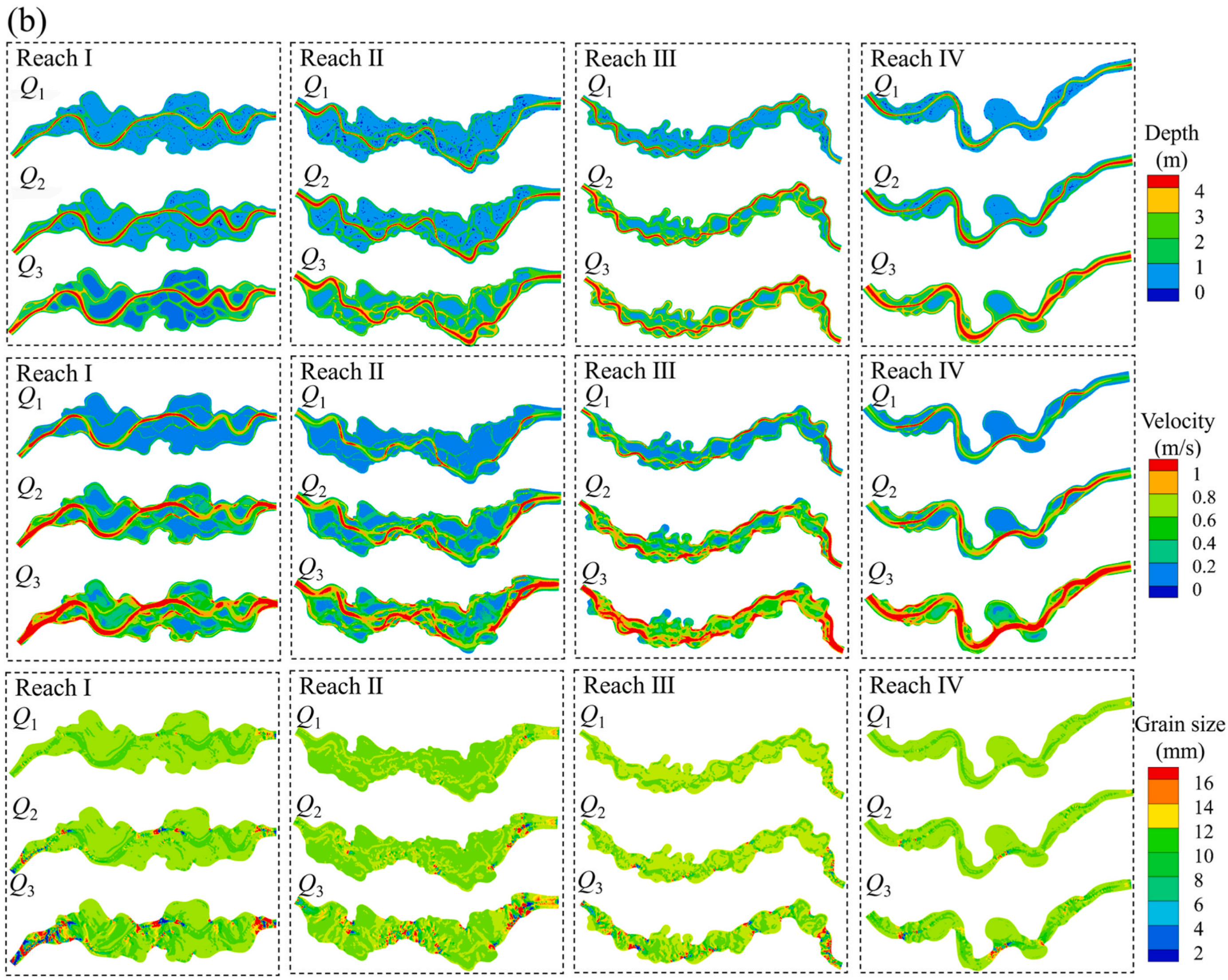

Fig. 4. (*continued*).

3. Results and analysis

3.1. Hydro-morphodynamics

For practical purposes, we define a low, medium, and high flow for each species. The medium flow is the observed optimal discharge for the target fish. The low and high flows are two suboptimal discharges smaller and larger than the medium one, respectively. Consequently, $Q_{I} = 500$ m^3/s, $Q_{II} = 1500$ m^3/s, and $Q_{III} = 2500$ m^3/s are selected as the low to high discharges for *S. wangchiachii*, and $Q_1 = 300$ m^3/s, $Q_2 = 1000$ m^3/s, and $Q_3 = 1500$ m^3/s for *C. carpio*. Fig. 4 presents the hydro-morphodynamics of the anabranching rivers under low, medium, and high discharges for both species. Reaches I and II, characterized by complex channels and large islands (Fig. 1), exhibit the highest depth variability, providing diverse flow conditions through their morphological complexity. With its wide valley and elongated islands, Reach III shows moderate depth variation. Reach IV, with fewer and smaller islands, shows the most uniform depth patterns, corresponding to its more meandering and simpler channel structure.

Reaches I and II stand out at all discharge levels as the most dynamic channels, with the greatest velocity variability, while Reach IV remains the slowest and most uniform. As discharge increases, Reaches I and II channel faster flows through their anabranching structures, creating velocity differences, whereas the simpler reaches, particularly Reach IV, remain relatively slow and stable. These results are related to channel morphological complexity. Diverse multi-threaded pathways facilitate dynamic flow redistribution during varying discharges (e.g., Reaches I and II). In contrast, Reaches III and IV exhibit relatively simplified morphology and limited channel branching, leading to minimal hydraulic complexity.

In all reaches, grain size increases as discharge rises, but the extent of this increase varies. Reaches I and II experience the most significant changes. The enhanced sediment transport is likely attributed to the abundance of fine sediment and the greater energy exerted by the anabranching channels, as evidenced by previous studies (Guo et al., 2023; Stevaux and Souza, 2004). Reach III also sees increases in grain size but to a lesser degree, while Reach IV shows minimal changes in sediment distribution, even at high discharge. The variation in grain size across the reaches is associated with the channel morphology and the resulting flow dynamics. A complex reach structure displays high variability, and a simple reach remains almost uniform in sediment distribution.

3.2. Habitat assessment

General knowledge of fish distributions in the study area, sourced from local river authorities and practitioners, suggests that *S. wangchiachii* predominantly occupies main channels, while *C. carpio* is more common in anabranching zones. However, the influence of flow conditions and channel anabranches on the habitat suitability for both species remains underexplored. Therefore, we design a wide range of flow scenarios for ecological assessment. Fig. 5 exemplifies the spatial distribution of the HSI for the anabranching rivers under low, medium, and high flows. For *S. wangchiachii*, the high-HSI areas at low discharge appear mainly in the main channel (HSI = 0.4–1), particularly for the single-thread channel (Reach IV). Under this flow condition, most water is concentrated in the main channel, maintaining sufficient depth and flow velocity. In highly anabranching channels like Reaches I and II, tributaries create flow convergence or divergence, leading to various hydraulic conditions such as eddies, backwaters, and zones of differing velocity and depth, providing a wide range of microhabitats. Consequently, some tributaries in Reaches I and II also show higher HSI. At medium flow, the main channels in all reaches maintain high habitat quality (HSI = 0.8–1). Compared with low flow, more tributaries become ecologically suitable (HSI = 0.3–0.7) due to increased discharge. At high flow, the anabranching structures help create refuges where the flow is less intense, but many areas in the main channels exhibit lower suitability. Therefore, the tributaries in all reaches contribute significantly to habitat availability.

For *C. carpio*, the main channels in all reaches generally show a lower HSI than the tributaries (especially at medium and high flows), which confirms *C. carpio*'s preference for the tributaries. The suitability curves for *C. carpio* show that they prefer moderate depths (1–2 m), moderate flow velocities (0.4–0.8 m/s), and gravel-sized substrates (4–6 mm) (Fig. 3). Tributaries, particularly in anabranching systems, often provide these conditions by contributing moderate flow, ideal sediment, and suitable depth in confluence zones (Fig. 4). As a result, tributaries usually show higher HSI values. In fact, confluence zones play a critical role in shaping fish distribution by creating diverse hydraulic and thermal conditionsdue. For example, due to food availability and habitat complexity, confluence zones are hotspots for fish productivity and diversity, featuring high spatial heterogeneity of fish density, size, and species (Gualtieri et al., 2020; Yuan et al., 2023).

Fig. 6 quantifies the percentage of low, medium, and high-quality habitat (LSP, MSP, and HSP) under varying flow rates. Across different reaches, the MSP and HSP exhibit a consistent pattern, characterized by an initial increase followed by a decrease as river discharge rises. However, the flow rates at which the MSP and HSP peak differ, with HSP's optimal discharge higher than that of the MSP. For *S. wangchiachii*, the HSP values for Reach I−IV at low flow are 3.9 %, 4.1 %, 9.4 %, and 9.6 %, respectively. These numbers are 13.0 %, 14.1 %, 24.7 %, and 21.0 % at medium discharge, and they are 26.5 %, 26.5 %, 0.7 %, and 9.6 % at high flow. For *C. carpio*, low-quality habitats dominate the four reaches under most discharges. At low flow, the HSP values for Reach I−IV are 28.3 %, 30.7 %, 35.8 %, and 31.1 %. These numbers are 43.4 %, 41.5 %, 19.9 %, and 37.4 % at medium discharge, and they are 36.4 %, 39.1 %, 4.3 %, and 32.6 % at high flow. Generally, Reaches I and II offer the most suitable (MSP + HSP) habitats for both species.

Fig. 7 shows the variation of WUA and OSI under different flow rates. As flow increases, both habitat indices rise before declining, regardless of fish species or channel diversity. For *S. wangchiachii* [Fig. 7(a)], in a moderately anabranching system like Reach I, the variety of channels, flow patterns, and habitat structures likely create a wide range of suitable habitats as flow increases. However, after a certain point (2100 m^3/s), the complexity may lead to excessive flows that cause habitat loss (e.g., through higher velocities or scouring) and reduce habitat suitability. Reach II (highly complex) provides a variety of habitats and is more diverse than Reach I. The flow complexity (e.g., flow direction, velocity gradients, velocity shelters, and transverse flows (Crowder and Diplas, 2000)) supports habitat up to a similar discharge (1600 m^3/s), but the less pronounced decline suggests that the habitat in this reach is more resilient to higher discharges. In Reaches III and IV (fewer anabranches), the optimal conditions occur at lower discharges (900 m^3/s and 1100 m^3/s), and the habitats become unsuitable more quickly as discharge increases beyond the peak, presumably due to limited structural

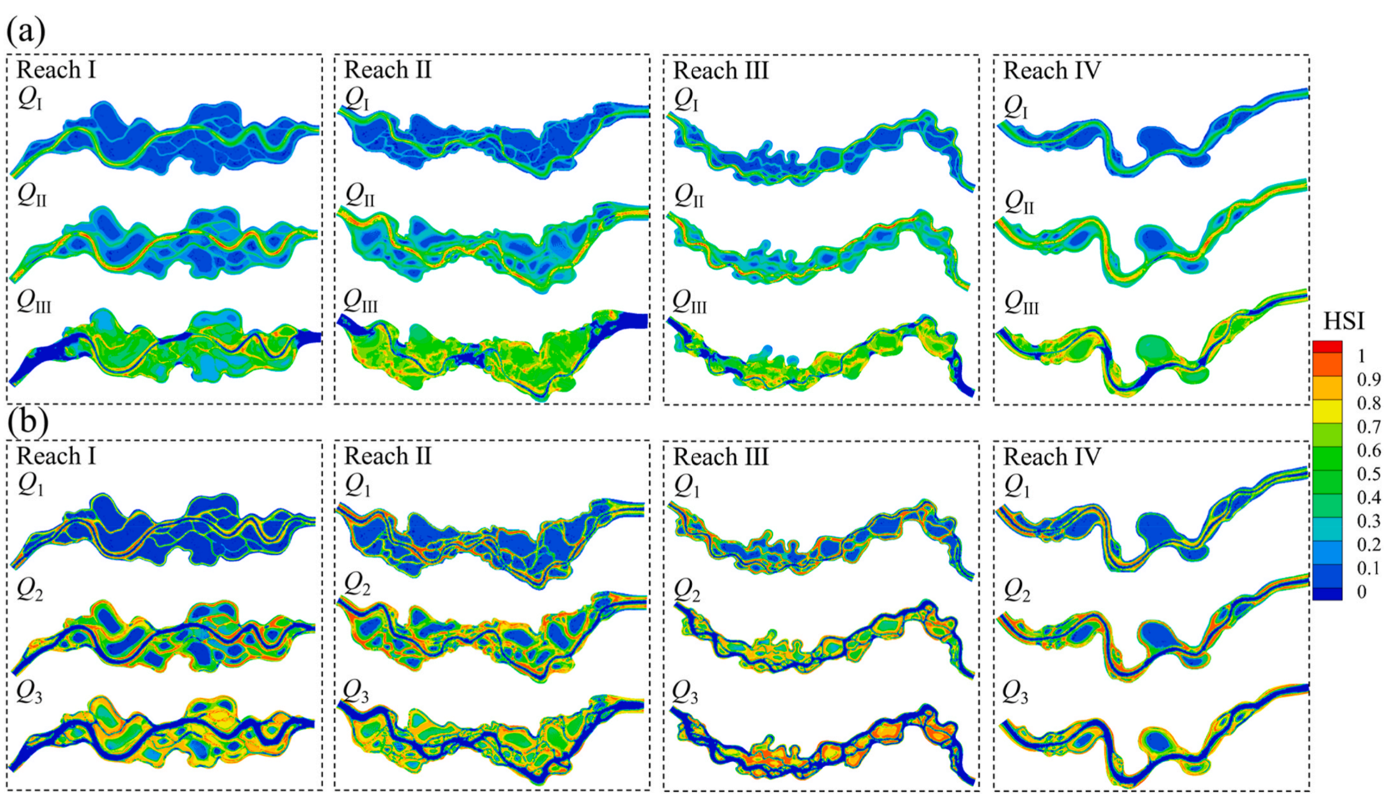

Fig. 5. Habitat suitability index for the anabranching rivers under low, medium, and high flows for (a) *S. wangchiachii* and (b) *C. carpio*.

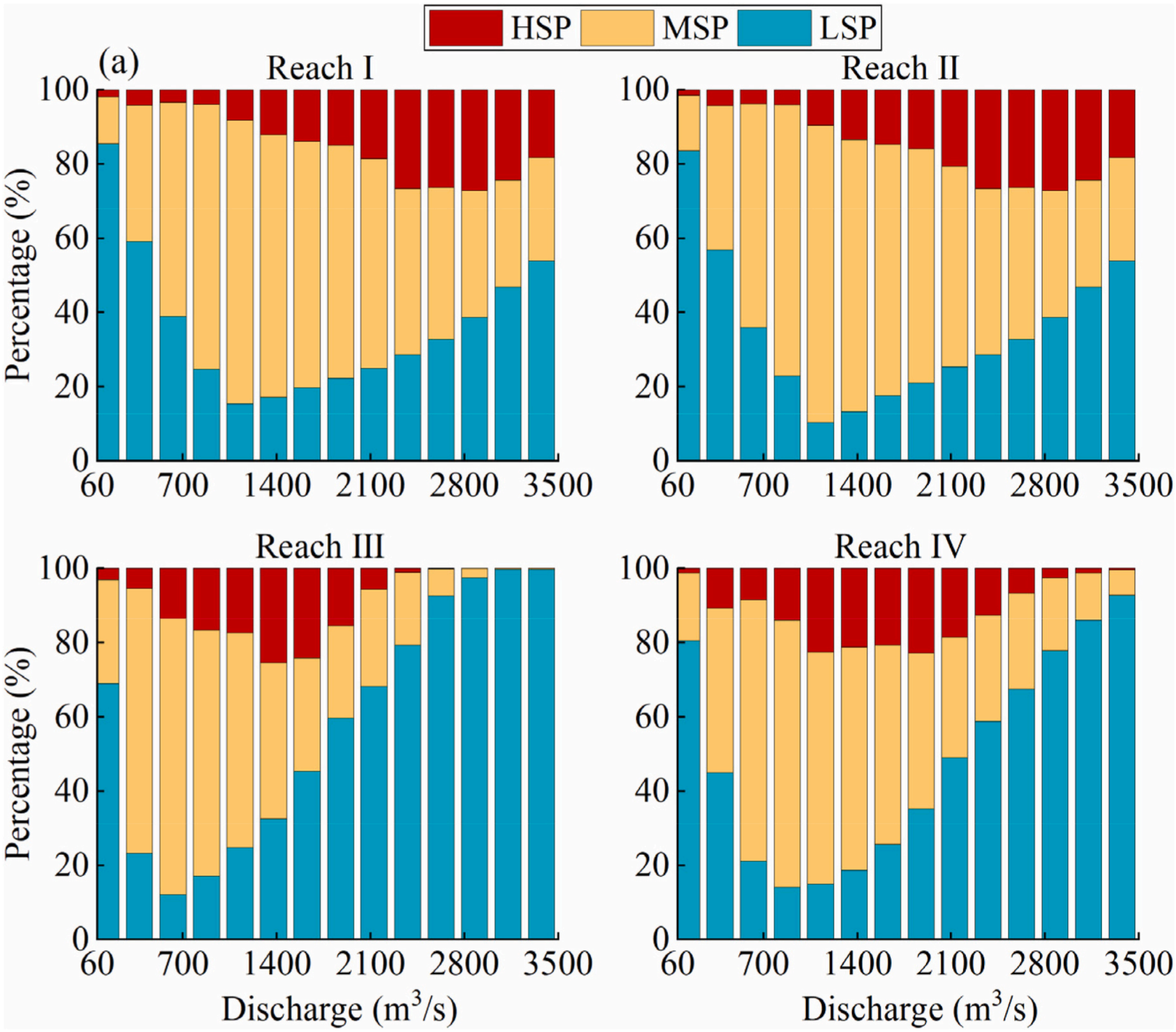

Fig. 6. Percentage of low, medium, and high suitability index (LSP, MSP, and HSP) for (a) *S. wangchiachii* and (b) *C. carpio*.

complexity to buffer against higher flows.

The WUA and OSI for *C. carpio* [Fig. 7(b)] show a similar pattern to those of *S. wangchiachii*. However, *S. wangchiachii* reaches its peak WUA at higher discharges, indicating it is better adapted to higher flows. These results are consistent with the observations by the river managers, where *S. wangchiachii* prefers the main channel (higher discharges), while *C. carpio* inhabits primarily in the anabranches (lower discharges). The river reaches maintain a suitable habitat over a broad range of flows, particularly in more complex reaches. In contrast, the WUA for *C. carpio* reaches its peak at lower discharges (600 m^3/s across all reaches) and experiences a sharp decline in habitat suitability beyond this, suggesting *C. carpio* is more sensitive to higher flows. Both species benefit from the complexity of Reaches I and II, which provide the highest habitat suitability. Still, *S. wangchiachii* is more resilient to changes in discharge, while *C. carpio* has a narrower range of optimal flow conditions, particularly in simpler reaches (III and IV). Thus, *S. wangchiachii* thrives in higher and more variable discharges, and *C. carpio* is limited to lower flows. A comparison of the OSI results yields a similar conclusion.

3.3. Flood impact

Floods are a natural part of an aquatic ecosystem and play a critical role in the dynamic balance of river and wetland environments. This study adopts two representative historical flood events in the study area to assess their impact on fish habitats. Each scenario is considered separately for a specific species, as both species exhibit distinct habitat preferences (*S. wangchiachii*: peak flow $Q_{PF1} = 3500$ m^3/s; *C. carpio*: peak flow $Q_{PF2} = 2000$ m^3/s). Fig. 8 compares the HSI distribution for the anabranching rivers before and after flood events. As expected, under high flows, the main channels show low suitability, and the tributaries provide the majority of the high-HSI habitats, particularly for complex reaches. For example, for *S. wangchiachii*, the main channel in Reach I is mostly unsuitable (HSI $\approx$ 0), while the tributaries exhibit an HSI = 0.5–1. However, most areas in Reaches III and IV are ecologically unsuitable, with low HSI values. This is likely related to their simplistic channel structures that create limited hydraulic diversity. For *C. carpio*, tributaries become even ecologically more important. During peak flows, the main channels may experience turbulent, high-energy flows, creating unsuitable habitats for *C. carpio*, which prefers low velocities. Flow splitting by islands creates hydraulically diverse areas where water flow may be more stable than the main river. After floods, the reaches exhibit limited habitat loss, indicating their flood-resilient capability.

Fig. 9 presents the percentage of low, medium, and high-quality habitats under flood conditions. For *S. wangchiachii*, low-quality habitats dominate across all reaches during peak flows, while high-quality habitats are absent. This is particularly evident in Reaches III and IV, where LSP = 94.0 % and 89.4 % and HSP = 0 for both reaches.

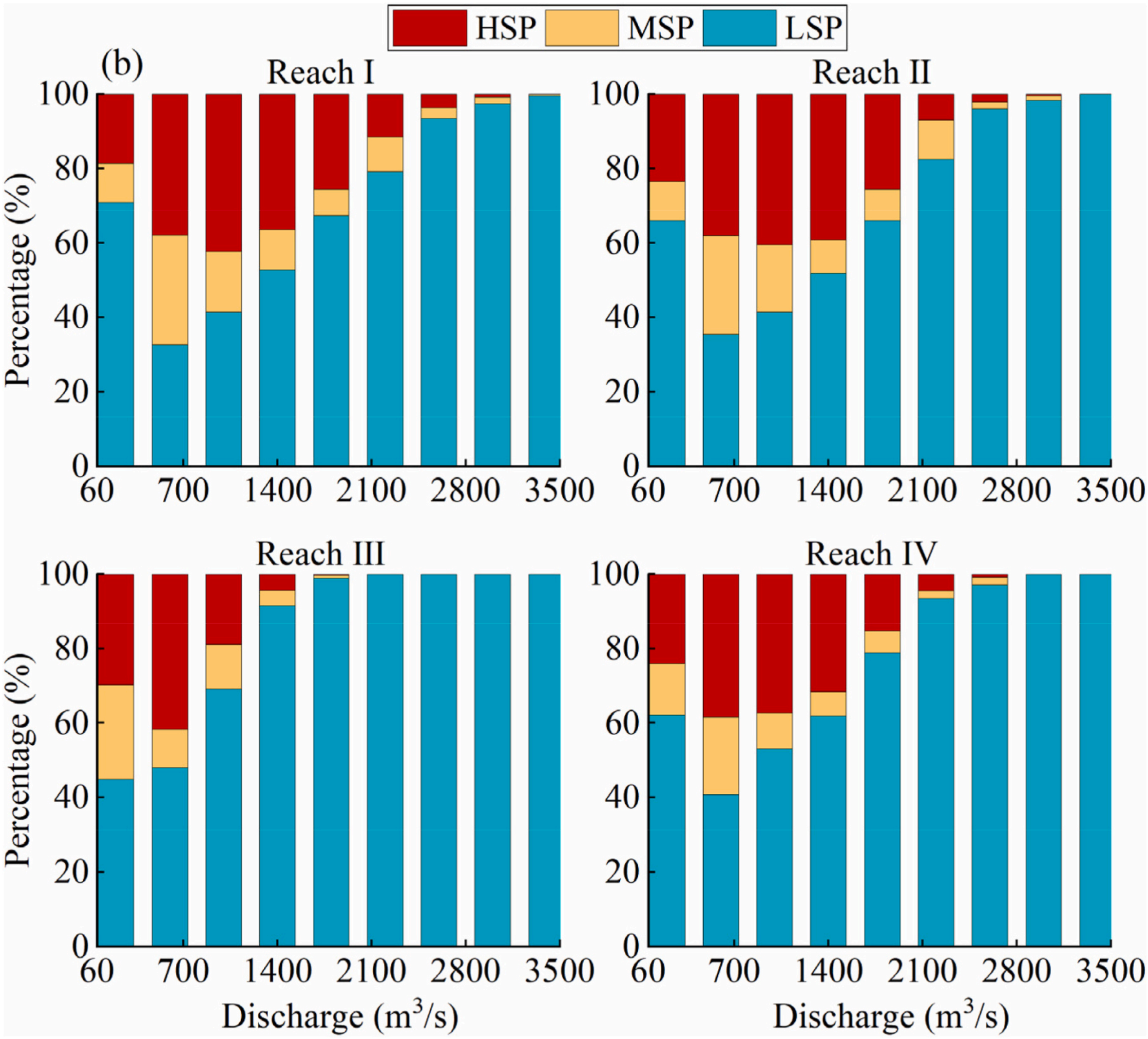

Fig. 6. (*continued*).

Following flood events, medium- and high-quality habitats show only a slight decline. In more complex reaches (Reaches I and II), the proportion of medium-quality habitats increases moderately (13.7 % and 12.7 %), likely due to enhanced connectivity among channels and backwaters areas. For *C. carpio*, high flows negatively impact habitat quality, with low-quality habitats prevailing across all reaches, and peak flows further degrading habitat suitability. Similar to *S. wangchiachii*'s habitat conditions, the percentage of high-quality habitats for *C. carpio* generally decreases, with a moderate increase (25.1 %) in medium-quality habitats in Reach II. Overall, the habitats demonstrate high resilience to flooding.

Fig. 10 displays the WUA and OSI results for both species under flood conditions. At peak flows, all reaches experience habitat loss due to excessive water depth, increased flow velocity, and sediment disturbance. For *S. wangchiachii*, Reach II provides high-quality habitats (even under peak flows) and is most resilient to floods, with WUA = 4.5×10^6 m^2 and OSI = 0.31. Reach III exhibits the least habitat suitability, with both indices the lowest (WUA = 1.3×10^6 m^2 and OSI = 0.11, mean of pre- and post-floods). For *C. carpio*, Reaches I and II show the highest suitability. The mean values for Reach I are WUA = 4.4×10^6 m^2 and OSI = 0.37, and WUA = 5.0×10^6 m^2 and OSI = 0.35 for Reach II. The habitats in Reach IV are most sensitive to floods, experiencing a sharp decline in WUA and OSI (both by 45 %).

3.4. Ecological stability

Ecological stability is critical for the health and resilience of fish populations and aquatic ecosystems. Therefore, long-term simulations of up to five years are conducted for habitat evaluation. The flow scenarios are typical normal discharges: $Q_{e1} = 1200$ m^3/s and $Q_{e2} = 800$ m^3/s (Wang et al., 2024b). Fig. 11 shows the temporal variation of habitat quality. The HSI for both species exhibits minimal difference over time, suggesting that the habitat conditions in each reach are stable without substantial changes. This may be attributed to the river system achieving a dynamic equilibrium in flow regime, sediment transport, and morphological changes, resulting in relatively stable physical habitat conditions. An analysis of bed deformation and grain size distribution confirms this conclusion (Fig. S2). Consequently, the percentages of low, medium, and high-quality habitats also remain almost constant (Fig. 12).

Table 1 compares the WUA and OSI over the simulated time. Both parameters remain stable across all years, showing steady habitat quality with no noticeable improvement or degradation. For example, in Reach I, the WUA drops marginally from 5.37×10^6 m^2 to 5.35×10^6 m^2 for *S. wangchiachii* and from 5.61×10^6 m^2 to 5.59×10^6 m^2 for *C. carpio*, while the OSI for both species remains constant. Again, the stability in WUA and OSI across the years is presumably related to the physical stability of the rivers. The anabranching channel structures allow flow to

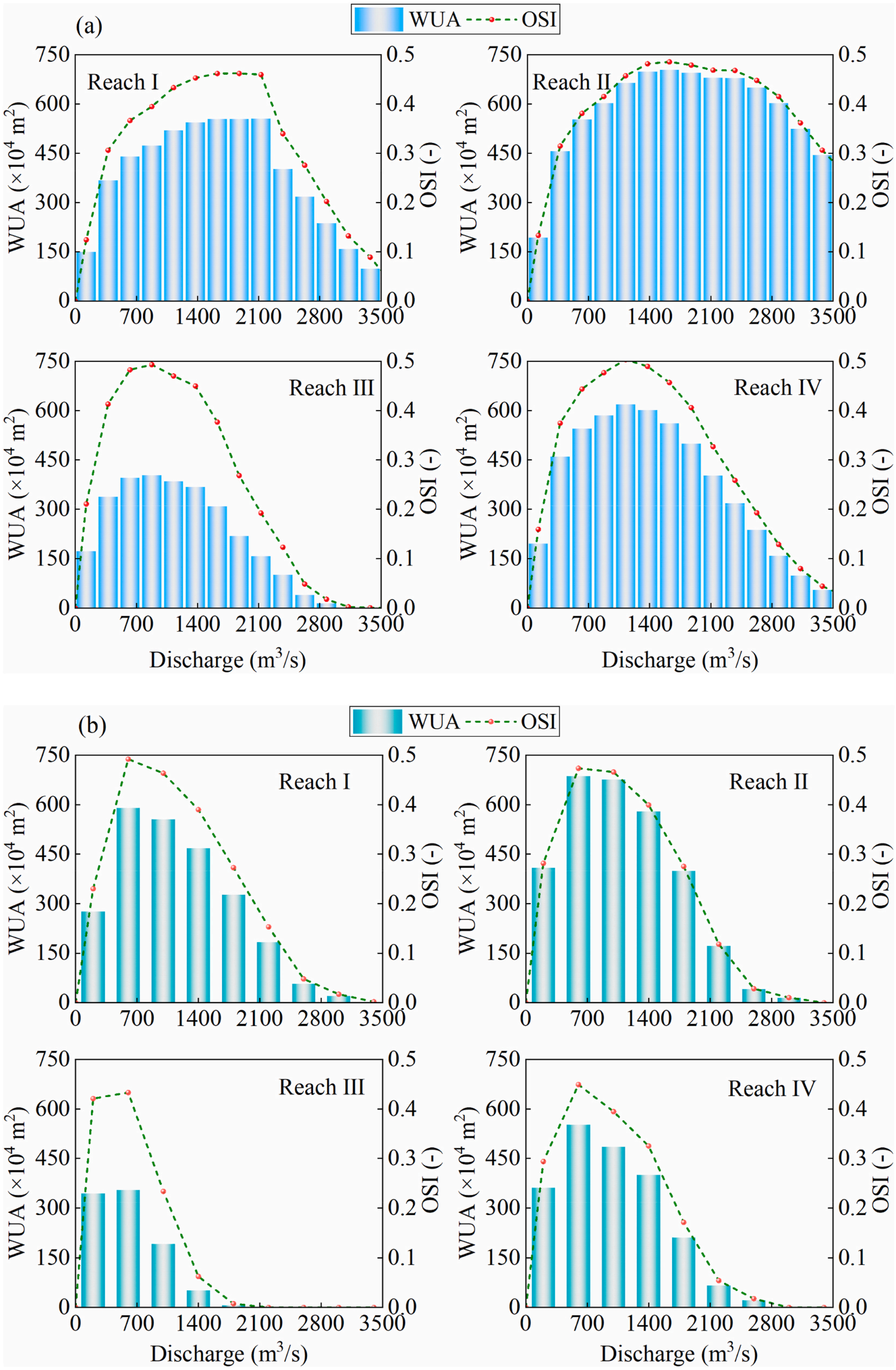

Fig. 7. Variation of WUA and OSI under different flow rates for (a) *S. wangchiachii* and (b) *C. carpio*.

be distributed across multiple channels rather than confined to a single main channel. This results in a diverse flow regime where different channels carry varying flow velocities and depths. Moreover, excessive scouring or deposition is minimized, as the flow is spread across several channels. All these factors play a crucial role in maintaining stable physical and habitat conditions. This is consistent with the findings by Nanson and Knighton (1996): anabranching rivers are relatively stable compared with single-channel systems due to their ability to distribute flow and sediment across multiple channels, coupled with mechanisms like cohesive bank materials and stabilizing vegetation.

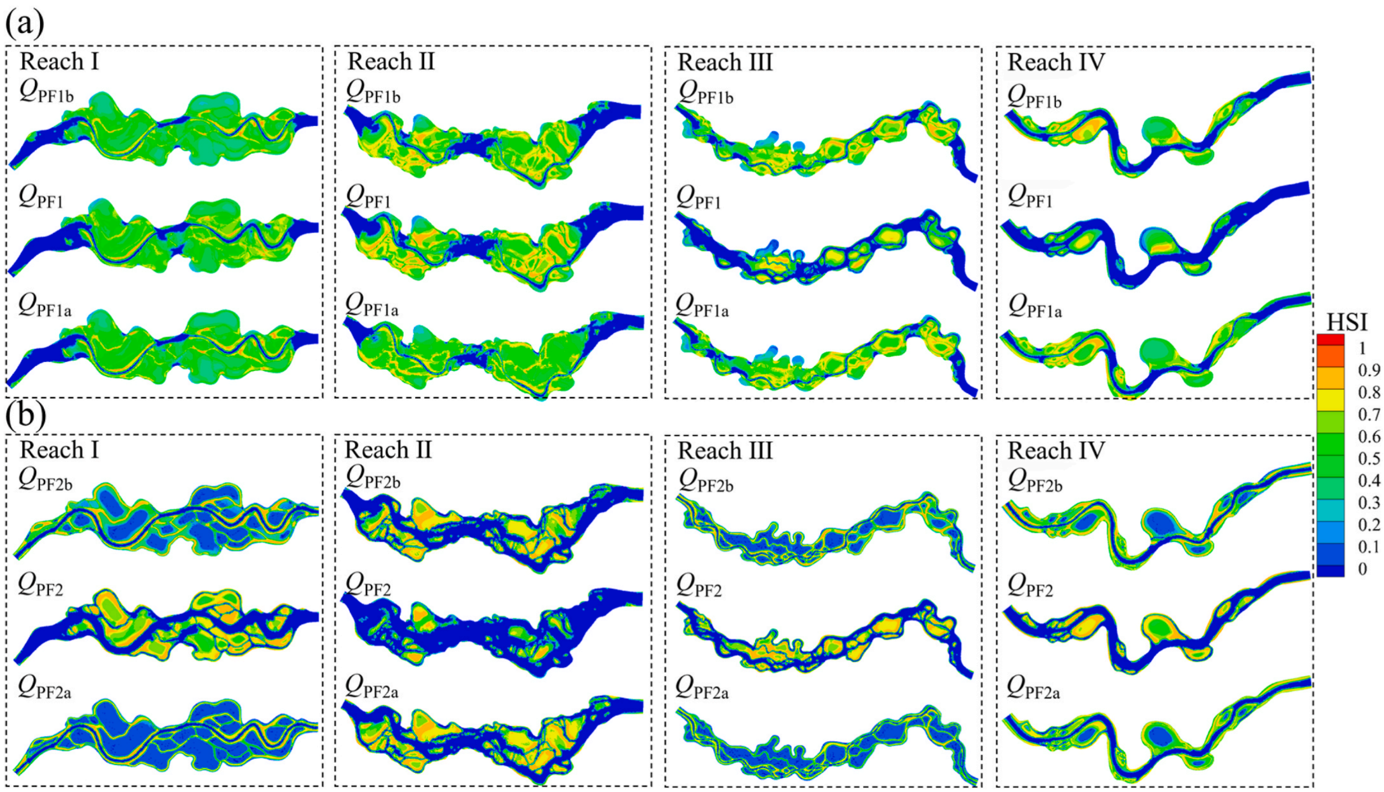

Fig. 8. Habitat suitability index for the anabranching rivers before and after flood events for (a) *S. wangchiachii* and (b) *C. carpio*. Peak flows $Q_{PF1} = 3500$ m^3/s and $Q_{PF2} = 2000$ m^3/s. Q_{PF1b}, Q_{PF2b} = discharges before floods, and Q_{PF1a}, Q_{PF2a} = discharges after floods.

4. Discussion

4.1. Ecological benefits of anabranches

Anabranching rivers, such as the MAS, provide numerous ecological benefits to the health and resilience of aquatic ecosystems. Anabranching rivers consist of multiple channels separated by vegetated and semi-permanent alluvial islands, eroded from the existing floodplain or formed through accretion (Nanson and Knighton, 1996). Channel division and joining contribute positively to fish habitats by creating a heterogeneous flow environment. As a result, anabranching structures offer a range of microhabitats suited to different species' needs, including varying flow velocities, depths, and substrate types. In the MAS case, *S. wangchiachii*, which favors the main channel, benefits from the diverse flow patterns in highly anabranching reaches. The increased flow velocity and the variety of available habitats support its preference for dynamic environments [Fig. 5(a)]. On the other hand, *C. carpio* finds suitable habitats in calmer areas, such as tributaries and anabranches with moderate depths and lower flow velocities. These areas are critical in providing refuge from high-energy conditions in the main channels [Fig. 5(b)]. This is similar to braided rivers that offer various types of refugia, including shore areas and hypogeic and hyporheic habitats, which are crucial for maintaining biodiversity under frequent disturbances (Tockner et al., 2006).

Vegetated islands and multiple branches within an anabranching system create a natural buffer during flood events (Nanson, 2013). These features reduce the energy and flow velocity in individual branches, mitigating the impact of floods on aquatic habitats. This characteristic reduces scouring and sediment displacement, preventing habitat degradation and maintaining stability. The resilience of habitats in Reaches I and II of the MAS in high-flow scenarios further illustrates the value of channel complexity in buffering against extreme hydrological events (Fig. 8). This is analogous to rivers with highly sinuous bend sequences, where diverse hydrodynamic and geomorphic conditions provide suitable fish habitats under various flow conditions, including high flows (Zhang et al., 2024).

The structural complexity of anabranches promotes biodiversity by providing enhanced feeding and nursery conditions. First, the interaction of branches and frequent shifts of flow paths is beneficial for sediment deposition and nutrient cycling. This process, in return, facilitates the growth of aquatic vegetation and invertebrates (Henriques et al., 2022), offering food sources for many species. Second, at confluence zones, where tributaries join together, flow turbulence and mixing are enhanced, which can concentrate food resources like drifting insects and organic matter (Boddy et al., 2019). Therefore, these zones may become prime feeding areas with high prey density. Third, aquatic vegetation and diverse flow conditions in the anabranches (Guo et al., 2023) create favorable nursery grounds for juvenile fish. The vegetated environment and shallow side channels offer shelters to improve the survival of young fish.

4.2. Implications for river management and conservation

The ecohydraulic model presented in this study provides crucial insights into the ecological assessment of anabranching rivers, highlighting essential implications for managing and conserving aquatic systems. The complex interaction of anabranching structure, flow, and sediment dynamics requires careful management to sustain fish habitats. Management practices that prevent channel simplification, such as avoiding channelization, are essential for conserving the diverse ecological functions.

Beyond its site-specific implication, the established ecohydraulic model contributes to a versatile tool for informed restoration and conservation efforts. It can be easily adapted to assess the effectiveness of different measures, such as creating new anabranches, reconnecting side channels, or removing barriers that limit flow and species movement. The model also applies to assessing the potential effects of climate change on river ecosystems. Climate change is altering hydrological

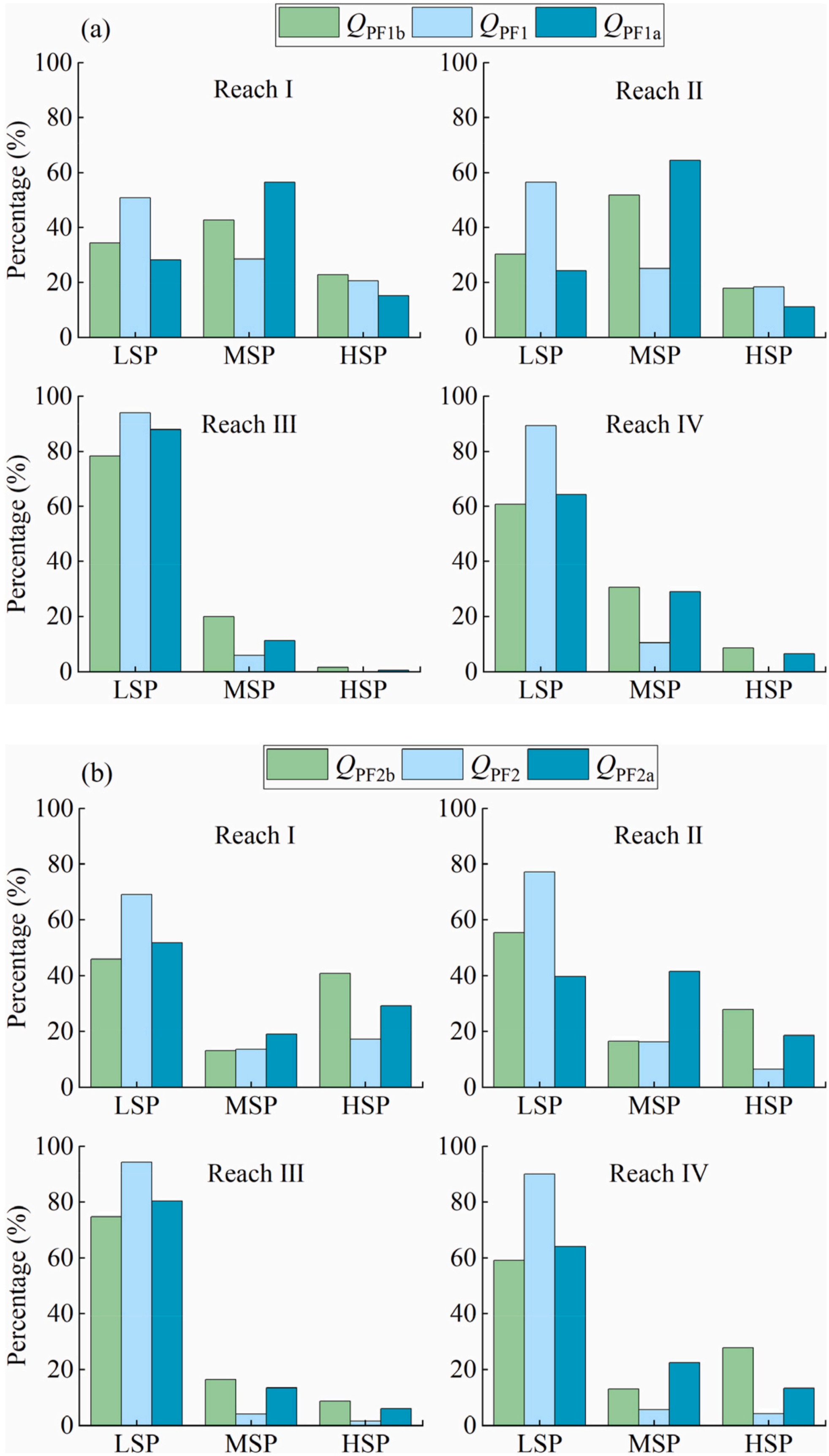

Fig. 9. Percentage of low, medium, and high suitability index (LSP, MSP, and HSP) under ecological flood conditions for (a) *S. wangchiachii* and (b) *C. carpio*.

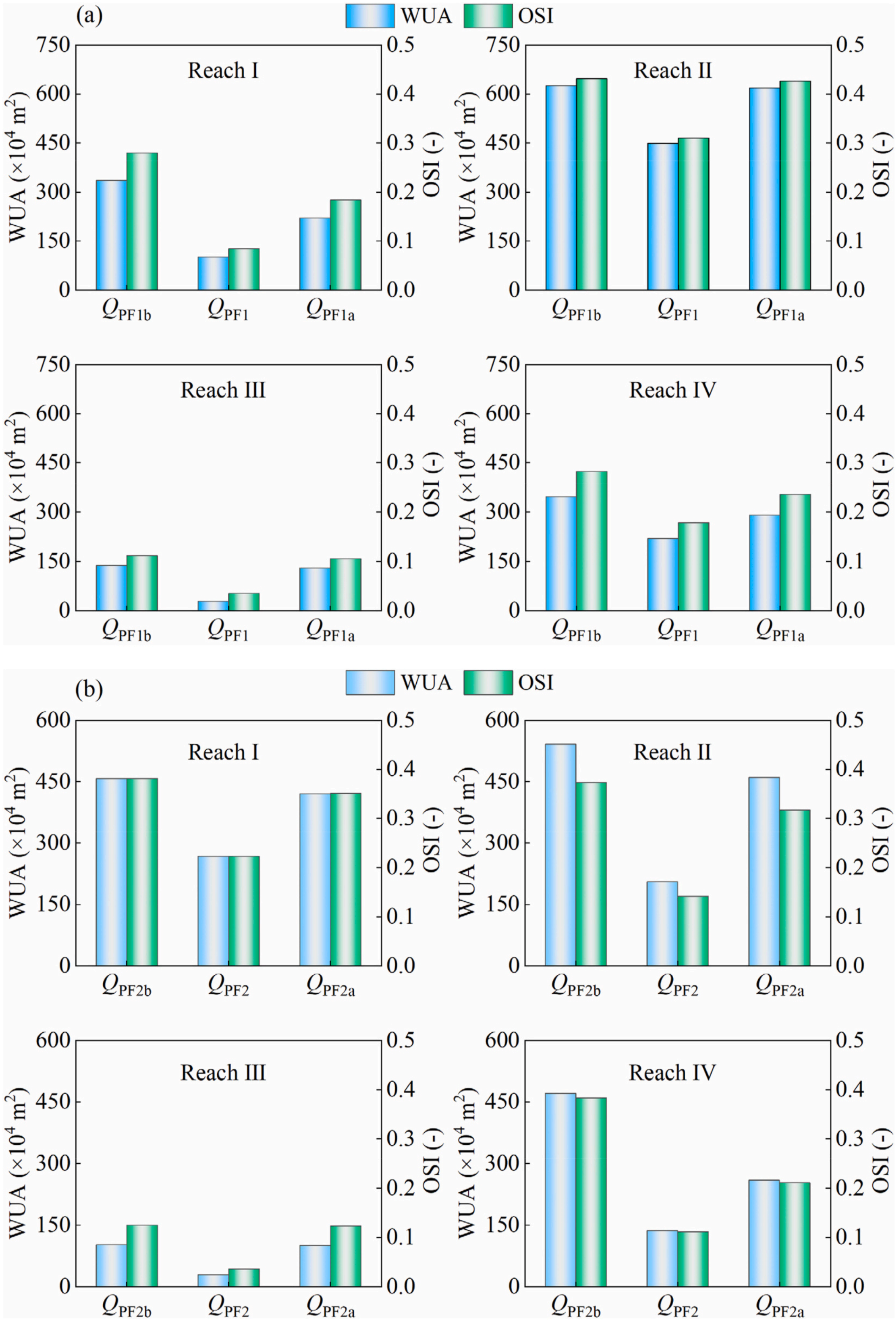

Fig. 10. Variation of WUA and OSI under flood conditions for (a) *S. wangchiachii* and (b) *C. carpio*.

regimes in terms of the magnitude and frequency of extreme events. By considering future climate scenarios, the model can identify vulnerable habitats and guide the development of adaptive management strategies to enhance the resilience of aquatic ecosystems in a changing climate. Furthermore, the model provides a framework for studying the effects of habitat fragmentation and connectivity on riverine species, contributing to ecological studies by exploring the interaction between physical processes and biological responses.

4.3. Limitations and future work

While applying the ecohydraulic model to assess fish habitat quality within the anabranching rivers provides valuable insights, several limitations in this study need to be noted. First, habitat suitability

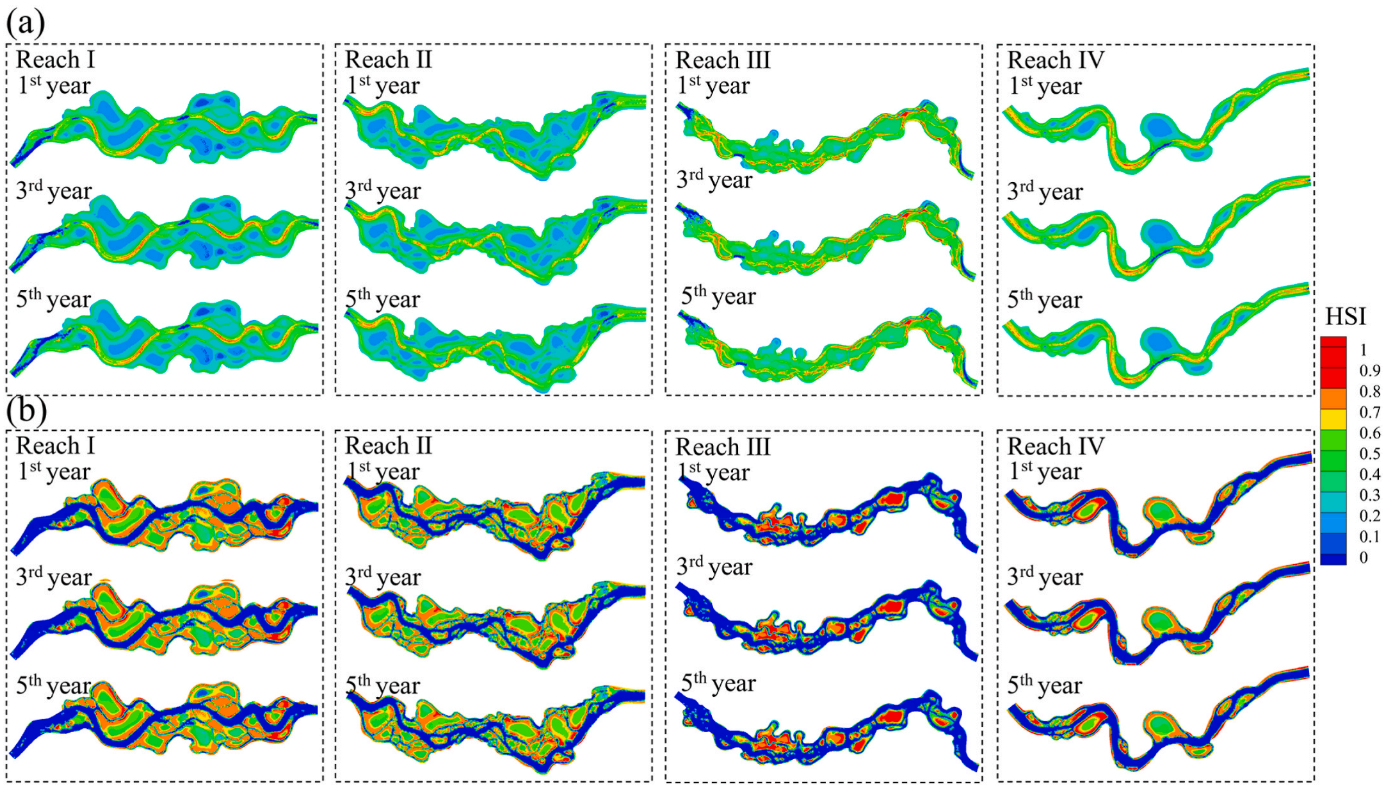

Fig. 11. Temporal variation of habitat quality for (a) *S. wangchiachii* ($Q_{e1} = 1200$ m^3/s) and (b) *C. carpio* ($Q_{e2} = 800$ m^3/s).

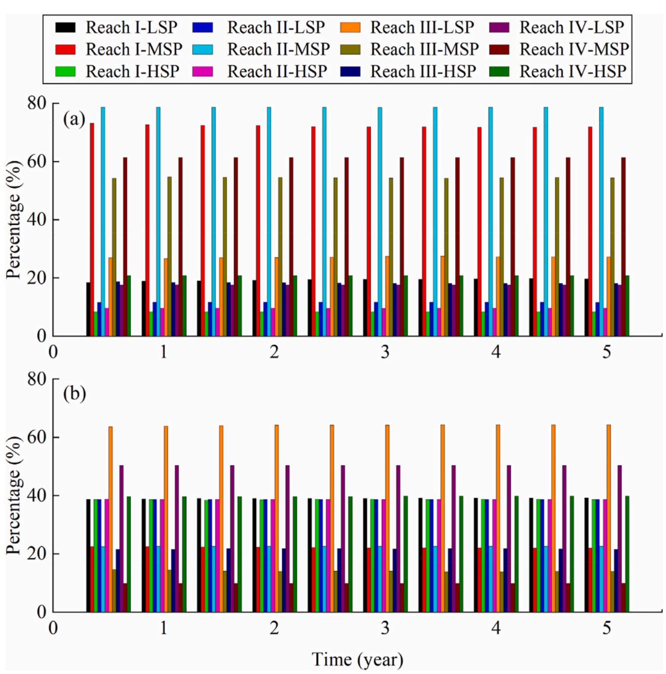

Fig. 12. Percentage of low, medium, and high suitability index (LSP, MSP, and HSP) under long-term flow scenarios for (a) *S. wangchiachii* and (b) *C. carpio*.

thresholds are simplistic approaches. This approach is commonly used to establish the connection between hydraulic conditions and ecological responses (Li et al., 2024; Wang et al., 2024a), but the availability of suitable habitat may not be a strong predictor of population status (Garshelis, 2000; Railsback et al., 2003). Observed relationships between habitat suitability and population dynamics are uncertain when used to predict responses to novel conditions (Railsback et al., 2023). To address this issue, future work may be devoted to individual-based models (IBMs). IBMs can capture the essential mechanisms through which populations respond to time-varying habitat conditions and management actions. The population responses can be predicted by representing the mechanisms by which these variables influence individual fitness, e.g., growth, survival, and reproduction (Railsback et al., 2023). In addition, although the suitability curves developed based on previous ecological studies and expert judgment reflect regionally relevant ecological preferences, the generalizability of the curves may be constrained, particularly under flow or habitat conditions not well represented in the source data. As a result, the sensitivity of habitat modeling results may contain a degree of uncertainty that could influence ecological interpretations. Future studies may incorporate field observations of fish presence and habitat use, conducting uncertainty analyses to quantify the influence of suitability assumptions on habitat predictions.

Second, although the hydrodynamic model produces physically consistent outputs, the uncertainty associated with model parameters is not explicitly studied. This choice is consistent with common practices in many ecohydraulic studies (Burman et al., 2021; Harris et al., 2024; Yang et al., 2025; Yao, 2016). However, it is important to recognize that parameter uncertainty can influence model predictions. Therefore, incorporating uncertainty quantification methods, e.g., Monte Carlo simulations or parameter perturbation, would provide a rigorous understanding of the robustness of model outputs. Moreover, vegetation effects are represented indirectly through increased roughness values assigned to vegetated areas, e.g., mid-channel islands. This approach simplifies the complex interactions between vegetation structure (e.g., stem density, flexibility) and flow dynamics, limiting the accuracy of flow predictions. Future work may incorporate more detailed representations of vegetation structure, e.g., drag-force-based resistance formulations, to improve realism in ecohydraulic simulations. This study focuses on two representative fish species with contrasting habitat preferences. It does not capture the full range of habitat responses of the

Table 1
Temporal variation of WUA and OSI for *S. wangchiachii* and *C. carpio*.

River Reach	*S. wangchiachii*						*C. carpio*					
	WUA ($\times 10^4$ m^2)			OSI			WUA ($\times 10^4$ m^2)			OSI		
	1st yr	3rd yr	5th yr	1st yr	3rd yr	5th yr	1st yr	3rd yr	5th yr	1st yr	3rd yr	5th yr
Reach I	537	536	535	0.45	0.45	0.45	561	560	559	0.47	0.47	0.47
Reach II	674	675	674	0.46	0.46	0.46	652	652	652	0.45	0.45	0.45
Reach III	385	384	383	0.47	0.47	0.47	358	354	355	0.44	0.43	0.43
Reach IV	598	598	598	0.49	0.49	0.49	481	481	481	0.39	0.39	0.39

broader fish community. Therefore, the findings should be interpreted as potential ecological functions of anabranching channels, rather than a comprehensive biodiversity assessment. Future work should include additional species to better represent community-level responses to hydromorphological dynamics.

Last, like many studies (Liu et al., 2024; Yi et al., 2014), model validation against biological data is challenging, which may limit confidence in model applications. This is partly due to the adaptation strategies of the species. Fish species often adjust their behavior unpredictably in response to changing environmental conditions, such as flow and habitat structure. Consequently, the collected biological data under specific conditions may not adequately represent species responses modeled by ecohydraulic tools, thus complicating the validation. One way to address the challenge is to establish long-term monitoring programs that collect biological data over extended periods and at different spatial scales, aiming to capture seasonal and inter-annual variations in species behavior and habitat use.

5. Conclusion

Anabranching channels are ecologically crucial in enhancing habitat diversity and promoting ecosystem functions. This study examines the ecological dynamics and habitat resilience of anabranching river systems, aiming to address critical gaps in understanding anabranches' habitat suitability, resilience, and stability. For this purpose, ecological assessments of four anabranching river reaches with varying structural complexity are performed for two valuable fish species *S. wangchiachii* and *C. carpio*. This study arrives at the following conclusions.

- The main channels in all reaches are more ecologically suitable for *S. wangchiachii*, particularly under low to medium flows, while the tributaries are more critical to *C. carpio*. This is consistent with local ecological knowledge reported by river managers, where *S. wangchiachii* predominantly inhabit fast-flowing main channels, while *C. carpio* are more commonly found in slower, anabranching zones. Generally, highly anabranching channels (Reaches I and II) provide more suitable (medium to high-quality) habitats for both species.
- As flow discharge increases, habitat suitability for both species rises before declining, regardless of channel diversity. *S. wangchiachii* thrives in higher and more variable discharges, and *C. carpio* is limited to lower flows. The rivers maintain a suitable habitat over a broad range of flows, particularly in more complex reaches (I and II). High flows lead to a drastic drop in habitat suitability, particularly for simple reaches (III and IV).
- Under flood conditions, the main channels exhibit low habitat quality, while the tributaries serve as the primary habitats for both species. Pre- and post-flood habitat quality indices demonstrate insignificant differences. Channel diversity shows a positive correlation with habitat resilience.
- Long-term ecological predictions suggest that the MAS experiences limited flow and morphological changes, contributing to ecosystem stability. Consequently, the habitat conditions in all reaches exhibit minimal improvement or degradation.

This study advances the understanding of anabranching river systems' ecohydraulic dynamics and contributions to habitat diversity. From a management perspective, these results highlight the importance of preserving channel complexity and hydrological connectivity to foster habitat stability and ecological resilience. Specifically, maintaining multiple interconnected channels can help buffer against extreme flow events, supporting species diversity and long-term ecosystem health. Future research may build on this by exploring the interactions between biotic and abiotic factors within these ecosystems, offering further insights into conservation strategies under changing environmental conditions.

CRediT authorship contribution statement

Shicheng Li: Writing – original draft, Methodology, Conceptualization. **Ruida Wang:** Validation, Software, Investigation, Formal analysis. **Qianqian Wang:** Methodology, Investigation. **Hao Zheng:** Software, Methodology, Investigation. **Yacun Yang:** Visualization, Validation, Software. **Nan Wang:** Visualization, Validation, Investigation. **Chenyang Cao:** Software, Methodology. **Weiwei Yao:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI in writing

The authors used ChatGPT to enhance the readability and language of this manuscript. Following its use, the authors carefully reviewed and revised the content as necessary, taking full responsibility for the final version.

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.

Acknowledgment

We acknowledge financial support from the National Key Research and Development Program of China (2022YFC3202002), the Project of Xinjiang Ecological Water Conservancy Research Center (2024B002), the Science and Technology Project of Guizhou Province ([2024]116), and the Science and Technology Project of Bijie City through the open competition mechanism for selecting the best candidates (BKHZDZX (2023)1). The first author only receives financial support from the Swedish Center for Sustainable Hydropower.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126706.

Data availability

Data will be made available on request.

References

Abrial, E., Espínola, L.A., Amsler, M.L., Rabuffetti, A.P., Latosinski, F.G., Szupiany, R.N., Eurich, M.F., Blettler, M.C.M., 2019. Fish structure in channel networks of a large anabranching floodplain: effect of isolation/connection processes. Water Resour. Res. 55 (12), 10993–11006.

Beyer, K., Marsland, K.B., Sharpe, C., Wallace, T., Zampatti, B.P., Nicol, J.M., 2010. Fish and Fish Habitats of the Pike River Anabranch and Floodplain Complex.

Boddy, N.C., Booker, D.J., McIntosh, A.R., 2019. Confluence configuration of river networks controls spatial patterns in fish communities. Landsc. Ecol. 34, 187–201.

Burman, A.J., Hedger, R.D., Hellström, J.G.I., Andersson, A.G., Sundt-Hansen, L.E., 2021. Modelling the downstream longitudinal effects of frequent hydropeaking on the spawning potential and stranding susceptibility of salmonids. Sci. Total Environ. 796, 148999.

Camporeale, C., Perucca, E., Ridolfi, L., Gurnell, A., 2013. Modeling the interactions between river morphodynamics and riparian vegetation. Rev. Geophys. 51 (3), 379–414.

Carling, P., Jansen, J., Meshkova, L., 2014. Multichannel rivers: their definition and classification. Earth Surf. Process. Landf. 39 (1), 26–37.

Church, M., Ferguson, R., 2015. Morphodynamics: rivers beyond steady state. Water Resour. Res. 51 (4), 1883–1897.

Crowder, D.W., Diplas, P., 2000. Evaluating spatially explicit metrics of stream energy gradients using hydrodynamic model simulations. Can. J. Fish. Aquat. Sci. 57 (7), 1497–1507.

Dey, S., 2014. Fluvial Hydrodynamics: Hydrodynamic and Sediment Transport Phenomena. Springer, Berlin.

Entwistle, N., Heritage, G., Milan, D., 2018. Flood energy dissipation in anabranching channels. River Res. Appl. 34 (7), 709–720.

Entwistle, N., Heritage, G., Milan, D., 2019. Ecohydraulic modelling of anabranching rivers. River Res. Appl. 35 (4), 353–364.

Fernandes, C.C., Podos, J., Lundberg, J.G., 2004. Amazonian ecology: tributaries enhance the diversity of electric fishes. Science 305 (5692), 1960–1962.

Ford, M., 2024. Cyprinus carpio. The IUCN Red List of Threatened Species, 2024.

Garshelis, D.L., 2000. Delusions in habitat evaluation: measuring use, selection, and importance. Research Techniques in Animal Ecology: Controversies and Consequences 2, 111–164.

Gualtieri, C., Abdi, R., Ianniruberto, M., Filizola, N., Endreny, T.A., 2020. A 3D analysis of spatial habitat metrics about the confluence of negro and solimões rivers, Brazil. Ecohydrology 13 (1), e2166.

Gualtieri, C., Ianniruberto, M., Filizola, N., Santos, R., Endreny, T., 2017. Hydraulic complexity at a large river confluence in the amazon basin. Ecohydrology 10 (7), e1863.

Guo, X., Gao, P., Li, Z., 2023. Morphodynamic characteristics of a complex anabranching system in the qinghai-tibet Plateau and the implications for anabranching stability. J. Geophys. Res.: Earth Surf. 128 (2), e2022JF006788.

Harris, A., Porter, M., McKay, S.K., Mulchandani, A., Stone, M., 2024. Hydraulic analysis for assessing environmental flow selection and ecological model formulation. Ecohydrology 17 (4), e2681.

Henriques, M., McVicar, T.R., Holland, K.L., Daly, E., 2022. Riparian vegetation and geomorphological interactions in anabranching rivers: a global review. Ecohydrology 15 (2), e2370.

Hupp, C.R., Bornette, G., 2003. Vegetation as a tool in the interpretation of fluvial geomorphic processes and landforms in humid temperate areas. Tools in Fluvial Geomorphology 269–288.

Jiang, X., Zhao, W., Zhang, W., 2010. The impact of Xiaolangdi Dam operation on the habitat of Yellow River Carp (Cyprinus (Cyprinus) carpio haematopterus Temminck et Schlegel). Acta Ecol. Sin. 30 (18), 4940–4947.

Latrubesse, E.M., 2008. Patterns of anabranching channels: the ultimate end-member adjustment of mega rivers. Geomorphology 101 (1–2), 130–145.

Latrubesse, E.M., 2015. Large rivers, megafans and other Quaternary avulsive fluvial systems: a potential "who's who" in the geological record. Earth Sci. Rev. 146, 1–30.

Leigh, S., Zampatti, B., Nicol, J., 2008. Spatial and temporal variation in larval fish assemblage structure in the Chowilla anabranch system: with reference to water physico-chemistry and stream hydrology. SARDI Aquatic Sciences Publication 1. South Australian Research and Development Institute (SARDI) Aquatic Sciences F2008/000051.

Li, P., Li, Y., Yang, Y., Wang, Q., Yao, W., 2024. Enhancing ecological success in yangtze river channel construction: a numerical modelling approach. Ecohydrology 17 (6), 1–16.

Li, S., 2017. Fisheries of the Yellow River. China Ocean University Press, Shandong, China.

Li, Y., Bao, M., Wang, Q., Wang, Y., Xi, Y., Yao, W., 2023. Habitat simulation and evaluation of Chinese carp in different braided sections in the middle and lower reaches of the yangtze river. Journal of Water Resources and Architectural Engineering 213 (3), 241–247.

Li, Z., Wang, Z., Pan, B., Du, J., Brierley, G., Yu, G.-a., Blue, B., 2013. Analysis of controls upon channel planform at the first great Bend of the upper yellow river, Qinghai-Tibet Plateau. J. Geogr. Sci. 23, 833–848.

Liu, S., Xi, Y., Zhang, C., Zhang, W., Ouyang, L., Giet, W.B.Y., Pan, D., Yao, W., 2024. Determining the fish migration patterns based on fish habitat assessment at a river confluence. Ecohydrology e2724.

Liu, X., Huang, H.Q., Nanson, G.C., 2016. The morphometric variation of islands in the middle and lower yangtze river: a variational analytical explanation. Geomorphology 261, 273–281.

Marchetti, Z.Y., Latrubesse, E.M., Pereira, M.S., Ramonell, C.G., 2013. Vegetation and its relationship with geomorphologic units in the parana river floodplain, Argentina. J. S. Am. Earth Sci. 46, 122–136.

Mendoza, A., Abad, J.D., Frias, C.E., Ortals, C., Paredes, J., Montoro, H., Vizcarra, J., Simon, C., Soto-Cortés, G., 2016. Planform dynamics of the iquitos anabranching structure in the Peruvian upper amazon river. Earth Surf. Process. Landf. 41 (7), 961–970.

Nakajima, R., Rimachi, E.V., Santos-Silva, E.N., Calixto, L.S., Leite, R.G., Khen, A., Yamane, T., Mazeroll, A.I., Inuma, J.C., Utumi, E.Y., 2017. The density and biomass of mesozooplankton and ichthyoplankton in the negro and the amazon Rivers during the rainy season: the ecological importance of the confluence boundary. PeerJ 5, e3308.

Nanson, G.C., 2013. Anabranching and anastomosing Rivers. Treatise on Geomorphology 9, 330–345.

Nanson, G.C., Knighton, A.D., 1996. Anabranching rivers: their cause, character and classification. Earth Surf. Process. Landf. 21 (3), 217–239.

Nilsson, C., Jansson, R., Malmqvist, B., Naiman, R.J., 2007. Restoring riverine landscapes: the challenge of identifying priorities, reference states, and techniques. Ecol. Soc. 12 (1).

Railsback, S.F., Harvey, B.C., Ayllón, D., 2023. Instream 7 User Manual: Model Description, Software Guide, and Application Guide. US Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Railsback, S.F., Stauffer, H.B., Harvey, B.C., 2003. What can habitat preference models tell us? Tests using a virtual trout population. Ecol. Appl. 13 (6), 1580–1594.

Rhoads, B.L., 2020. River Dynamics: Geomorphology to Support Management. Cambridge University Press.

Škarpich, V., Horáček, M., Galia, T., Kapustová, V., Šala, V., 2016. The effects of river patterns on riparian vegetation: a comparison of anabranching and single-thread incised channels. Morav. Geogr. Rep. 24 (3), 24–31.

Stevaux, J., Souza, I., 2004. Floodplain construction in an anastomosed river. Quat. Int. 114 (1), 55–65.

Thapa, R., Thoms, M.C., Parsons, M., 2016. The response of dryland floodplain vegetation productivity to flooding and drying. J. Arid Environ. 129, 42–55.

Tockner, K., Paetzold, A., Karaus, U., Claret, C., Zettel, J., 2006. Ecology of Braided Rivers, vol. 36. Special Publication-International Association of Sedimentologists, p. 339.

Tonkin, Z., O'Mahony, J., Raymond, S., Moloney, P., Lyon, J., 2017. Fish Movement in the Lindsay and Mulcra Island Anabranch Systems: 2017 Progress Report. Arthur Rylah Institute for Environmental Research. Department of Environment, Energy, Environment and Climate Change Group, Heidelberg, Victoria.

Wang, Q., Han, Y., Bao, M., Li, P., Li, Y., Zhang, W., Yao, W., 2024a. Fish entrainment model for decision support in ecosystem management: a case study from China's maling reservoir. Ecohydrol. Hydrobiol. 24 (1), 226–239.

Wang, Y., Guo, X., Wang, N., Li, Z., Ouyang, L., Bao, M., Zhang, W., Yao, W., 2024b. Distinctive hydrodynamic properties and ecological responses of multi-thread rivers under different degrees of multiplicity in the upper yellow river. Sci. Total Environ., 173874

Xie, W., Deng, H., Tian, H., Cheng, B., Tang, X., Pu, Y., Wang, D., Tian, P., Cheng, D., Duan, X., 2024. Habitat suitability of Schizothorax wangchiachii in the heishui river of the lower jinsha river tributary, China. J. Appl. Ecol. 35 (11), 3183–3189.

Yang, L., Hou, J., Wang, X., Wang, P., Wang, Y., 2025. Application of the 2D high-resolution eco-hydraulics model based on GPU acceleration technology in the upper yellow river. Environ. Model. Software, 106393.

Yao, W., 2016. Application of the Ecohydraulic Model on Hydraulic and Water Resources Engineering. Technische Universität München.

Yao, W., 2021. Ecohydraulic tools for aquatic fauna habitat and population status assessment, analysis and monitoring aimed at promoting integrated river management. Ecol. Model. 456, 109682.

Yi, Y., Cheng, X., Wieprecht, S., Tang, C., 2014. Comparison of habitat suitability models using different habitat suitability evaluation methods. Ecol. Eng. 71, 335–345.

Yuan, S., Qiu, J., Tang, H., Xu, L., Xiao, Y., Liu, M., Rennie, C., Gualtieri, C., 2023. Fish community traits near a large confluence: implications for its nodal effects in the river ecosystem. J. Hydrol. 626, 130335.

Zhang, Y., Yaak, W.B., Wang, N., Li, Z., Wu, X., Wang, Q., Wang, Y., Yao, W., 2024. Evaluation of the highly sinuous Bend sequences using an ecohydraulic model to ascertain the suitability of fish habitats for river ecological conservation. J. Nat. Conserv., 126750

Zhao, Y., Xing, Y., Lü, B., Zhou, C., Yang, W., Zhao, K., 2020. Species diversity and conservation of freshwater fishes in the yellow river basin. Biodivers. Sci. 28 (12), 1496.