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Assessing River Habitat Impacts of Navigation Channel Regulation in Large Rivers

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Abstract: Multi-scale habitat modelling is key for river management, yet meso-habitat metrics for navigable rivers remain scarce. This study presents a fish-swimming-capacity-based approach for delineating meso-habitat functional units in mountain rivers that can be directly embedded into hydraulic design. Environment DNA (eDNA) metabarcoding was employed to identify the dominant species in the study reach, from which one was selected as the target fish. Based on literature data regarding the relationship between fish body length and its critical swimming speed, a coefficient α was introduced to obtain the relationship equation between the body length and the absolute critical swimming speed. The absolute critical swimming speed of the target fish was calculated to define the ecological indicators for fish habitat. Subsequently, a two-dimensional hydrodynamic model was employed to calculate the flow velocity distribution in the study reach during dry, normal, and flood periods. Combining the absolute critical swimming speed of fish with the hydrodynamic results yields a rule table for fish ecological functional habitat units. Case studies at Wanglongqi and Lianshitan regulation works showed that spur dikes significantly reduce migration-corridor area at low discharge, while medium and high discharge maintain connectivity. The method converts ecological thresholds into engineer-friendly spatial units, striking a balance between navigation development and ecological integrity.
Key words: Meso-habitat; Functional unit; Yangtze River.

1. Introduction

River ecosystems are vital repositories of global biodiversity, with different river types exhibiting distinct geomorphological and hydrological characteristics, leading to variations in fish population structure and distribution [1-3]. However, with global economic development and increasing shipping demands, rivers are often subjected to channel regulation projects, such as the construction of spur dikes and dredging, to enhance navigability [4,5]. While these navigation improvement projects create economic value, they also alter the natural hydrological regime and physical habitat structure, impacting fish survival, reproduction, and migration [6-9]. Therefore, to balance the relationship between navigation development and ecological conservation, habitat assessment techniques based on hydrodynamic models have become an essential tool in river management.

Multi-scale habitat modeling, particularly the identification and evaluation of meso-habitats, is a widely accepted and successfully applied approach [10,11]. However, current meso-habitat methods are primarily applied to small and medium-sized rivers, with limited application in large rivers, and they exhibit significant limitations in assessing engineering impacts. Traditional habitat models often rely on empirical habitat suitability curves, lacking a direct link to fish physiological behavior, which restricts their ecological relevance and predictive accuracy [12,13]. Furthermore, existing models focus on natural rivers. For navigable rivers affected by engineering structures and characterized by highly complex flow conditions, quantitative metrics and assessment methods for meso-habitats remain scarce. This makes it difficult to effectively translate ecological objectives into design parameters that are understandable and operable for engineers, creating a practical gap between ecology and engineering.

Swimming is one of the most fundamental life activities for fish and is crucial for various behaviors such as predator avoidance, foraging, migration, and homing. The inducing flow velocity (IFV) is the minimum flow velocity required to elicit a rheotactic response in a fish [14]. The critical swimming speed (U_{crit}) is defined as the maximum sustained swimming speed of a fish, reflecting its maximum sustained aerobic capacity, typically for durations exceeding 200 min. Brett [15] was the first to employ an incremental velocity test to determine the maximum sustained speed in fish, establishing U_{crit} as a key metric for assessing maximum aerobic endurance. A fish's swimming ability is primarily determined by its species and body length, with key morphological parameters influencing performance, including body length and caudal fin shape [16,17]. Among all hydrodynamic factors, flow velocity is considered the most critical factor influencing fish swimming behavior [18].

Therefore, there is an urgent need to develop a novel habitat assessment method that can directly couple fish eco-physiological demands with complex engineering hydrodynamic environments. This study proposes a meso-habitat unit delineation method based on fish swimming ability. This method aims to use fish swimming ability as an ecological threshold and to output the assessment results as functional units, thereby providing a scientific and intuitive basis for decision-making in the ecological design of navigation regulation projects.

2. Material and method

2.1 Study area

The study area is a river reach in the upper Yangtze River, spanning from Yibin (28°45′46.98″ N, 104°40′47.11″ E) to Jiangjin, Chongqing (29°17′33.11″ N, 106°15′6.93″ E), covering a total length of approximately 314 km (Fig.1). This reach is characterized as a mountainous river, with a riverbed composed predominantly of gravel and cobbles. The channel is interspersed with numerous reefs, while the banks are frequently lined with protruding rock points and bedrock shelves. The longitudinal profile of the channel features an alternating sequence of riffles and deep pools, with maximum pool depths reaching up to 70 m. The study reach is subject to swift and highly variable flow velocities. During the low discharge period, velocities in the deep pools are relatively slow (generally < 2 m/s) due to greater water depths, whereas velocities over the riffles are rapid, often reaching 3–4 m/s in shallower areas.

To support the development of the Yangtze River Economic Belt, extensive navigation channel training has been implemented in this reach since the 1970s. However, natural morphological evolution combined with unregulated sand and gravel mining has altered the flow patterns and channel geometry. Consequently, the channel dimensions periodically failed to meet required navigation standards, restricting the passage of 1,000-tonne class vessels and compromising navigational safety.

Two representative channel improvement sections, the Wanglongqi (28°53′45.91″ N, 105°44′18.35″ E) and Lianshitan (28°49′45.74″ N, 105°53′56.16″ E) reaches, were selected as case studies for engineering applications. The entire reach from Wanglongqi to Lianshitan is situated within a drifting-egg spawning ground, while the Wanglongqi section also hosts an adhesive-egg spawning ground. The primary engineering measures implemented included dredging and dam construction. Dredging was conducted on shoals and submerged reefs within and adjacent to the navigation channel that failed to meet depth requirements, thereby ensuring navigational safety. At the Wanglongqi reach, a 610 m long combined spur and longitudinal dike was constructed on the left bank, and a 750 m long longitudinal dike on the right bank. At the Lianshitan reach, a system of fish-bone groynes was installed on the right bank to restore the pre-disturbance aquatic habitat.

Furthermore, the reach is notable for its abundant fishery resources. It lies within the National Nature Reserve for Rare and Endemic Fishes in the Upper Yangtze River (hereinafter referred to as the protected area), which was established in April 2000. The reserve hosts a total of 199 fish species, 70 of which are endemic to the Yangtze River. Rare species include *Acipenser dabryanus* and *Myxocyprinus asiaticus*. The order Cypriniformes is the most speciose group [19]. According to its ecological functions, it is divided into the core area, buffer area, and experimental area. The establishment of this reserve aims to minimize the ecological impacts of hydraulic engineering projects, mitigate the ongoing decline in fishery resources, and prevent further reductions in population sizes.

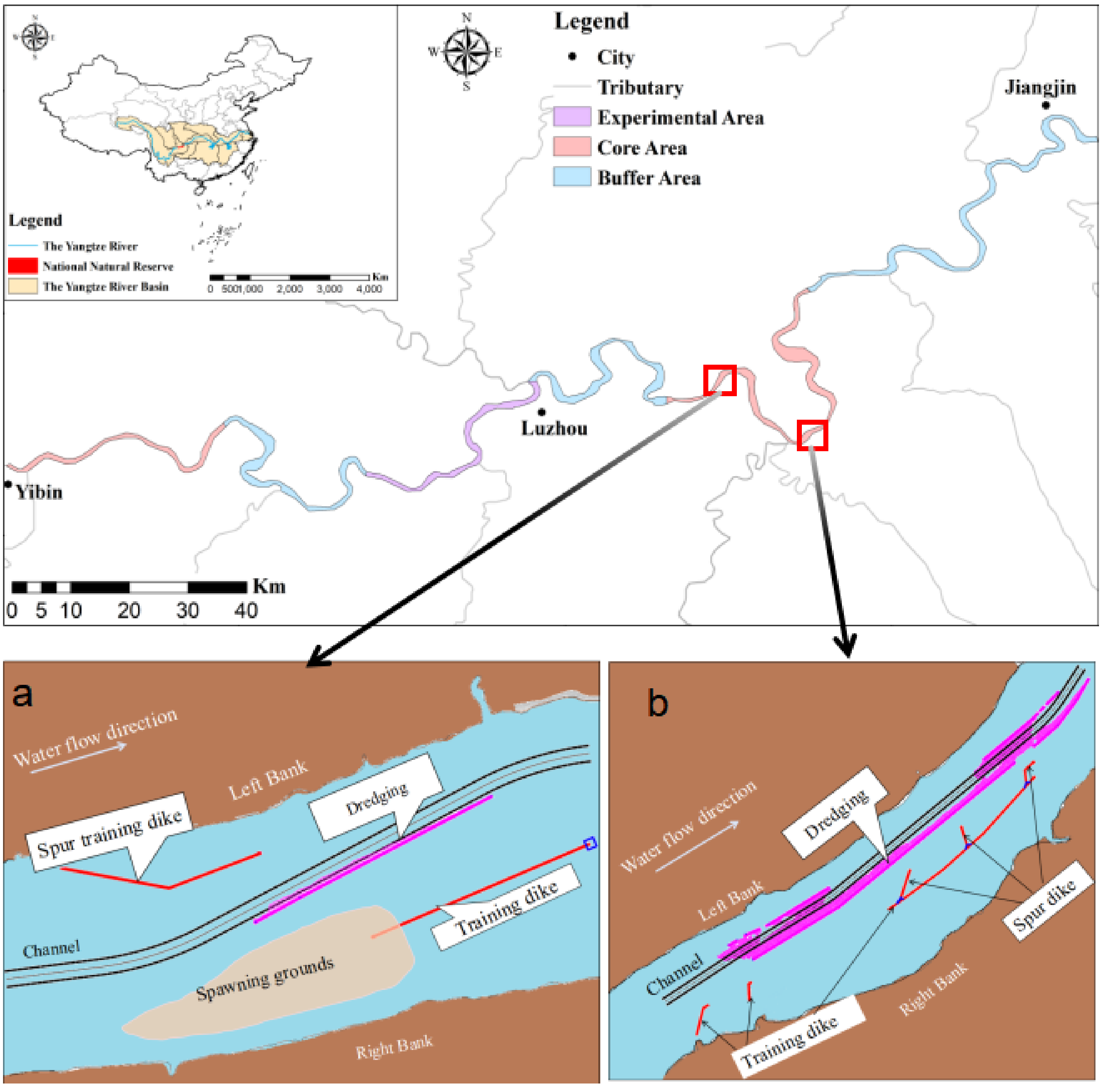


Fig 1. The study area is located in the Yangtze River Upper Reaches protected area. The case of channel improvement section a is the channel improvement section of Wanglong Qi, and b is the channel improvement section of Lianshitan.

2.2 Meso-habitat function unit method

The delineation of functional habitat units in this study is primarily based on river typology. The river type fundamentally shapes the structure and distribution of fish communities by mediating the hydrodynamic conditions, creating a mosaic of habitats that dictate species-specific adaptations and survival. The detailed classification flowchart is illustrated in Figure 2.

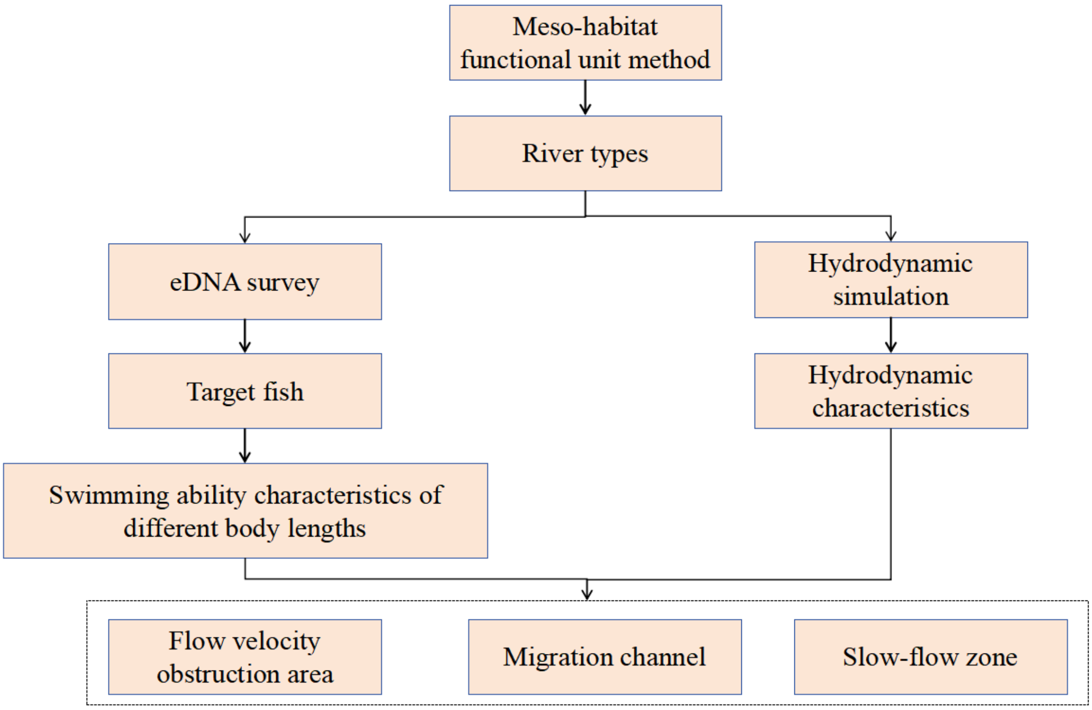


Fig 2. Flowchart

2.3 Fishery resources survey

The eDNA monitoring data were derived from three surveys in the upper Yangtze River, representing snapshots of fish diversity under three distinct hydrological regimes: the high discharge period (August 2021; [20]), the low discharge period (January 2022), and the moderate discharge period (May 2022). The protocols for sampling and eDNA extraction were adopted from Wang et al. [20]. Results from three eDNA surveys revealed a total of 166 fish species, belonging to 8 orders, 25 families, and 99 genera. Among them were 10 species listed as National Class-II Protected Animals in China and 26 endemic species to the Yangtze River. Based on the distribution patterns and ecological habits of these fish, the 17 representative species were selected, encompassing 4 orders and 17 families. These species were chosen to represent the full spectrum of key ecological traits, including flow preference, vertical position in the water column, and migratory behavior. A detailed list of these representative species is provided in Appendix A1.

2.4 Fish swimming ability

U_{crit} is commonly used to characterize the swimming ability of the fish. The body length is positively correlated with U_{crit} [21-23]. The relationship between U_{crit} and body length is generally described using statistical calculation methods. The functions commonly used the linear function $U^{a}_{crit}=aL+b$ [14] and quadratic function $U^{a}_{crit}=aL^2+b$ [24] to describe it. In the function, coefficients a and b have dimensions. Therefore, Xu [25] derived the absolute critical swimming speed of juvenile fish by adding a coefficient α to determine the correlation coefficient R^2. The calculation formula is

$$R^2=\left[\frac{\sum_{i=1}^{N}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i-\bar{X})^2\sum_{i=1}^{N}(Y_i-\bar{Y})^2}}\right]^2 \tag{1}$$

Among them, X is the body length, with the unit of m. Y is U_{crit}, with the unit of m/s. N is the number of the data.

When α=0.8, R^2 is at its maximum, thus the formula for the absolute critical swimming speed of grass carp is

$$U^{'}_{crit}=0.8(gL)^{0.5} \tag{2}$$

Among them, $U^{'}_{crit}$ is the absolute critical speed, with the unit of m/s. L is the body length, with the unit of m.

And g is gravitational acceleration, g=9.8 m/s^2.

2.5 Hydrodynamic simulation

To simulate flow variations in the project reach, a two-dimensional hydrodynamic model was established for three representative discharge scenarios: dry, normal, and flood seasons (Table 1). The study reach for the numerical model extends 32.3 km from Wanglongqi to Lianshitan, encompassing two channel improvement sections to ensure all engineering boundaries are adequately resolved. In accordance with the regulation scheme, the computational mesh was generated with 244,627 elements and 492,498 nodes. To accurately simulate the hydraulic performance of the regulation structures, the mesh was locally refined in the vicinity of the project areas. The model's inlet discharge and output water level were prescribed using data from the nearby Zhutuo Hydrological Station, which provides measurements of water level, discharge, sediment, and precipitation with Class I accuracy for discharge. This data is proprietary to the research collaboration and is not publicly available. The model was based on the solution of the de Saint-Venant equations, including the continuity and momentum equations [26]. The topographic and validation data were provided by the Chongqing Shipping Engineering Survey and Design Institute of the Yangtze River, a government-affiliated institution. The data are shared exclusively with collaborating organizations for using in engineering and scientific research and are not publicly available.

Table 1. Model and simulation design of operating conditions

Number	Input discharge (m^3/s)	Input tributary discharge (m^3/s)	Output water level (m)	Note
1	5920	270	204.64	Low discharge
2	11500	380	207.47	Middle discharge
3	26000	810	213.17	High discharge

3. Results

3.1 Meso-habitat function unit method application

The study reach was classified into functional meso-habitat units (Table 2) based on the relationship between fish body length and swimming ability. Meso-habitat function unit represent flow characteristics. The flow velocity ranges are determined by the interval between the fish's IFV and its absolute critical swimming speed. Ecology function is defined as the qualitative description of the significance of each unit, achieved through the integration of ecology and hydraulics.

Table 2. Meso-habitat function unit method

Meso-habitat function unit	Flow velocity range	Ecology function
Slow-flow zone	U <IFV	Foraging and spawning habitat
Migration channel	IFV≤ $U \le U'_{crit}$	Habitat for shelter, foraging, and migration
Flow velocity obstruction area	$U > U'_{crit}$	Unsuitable river channel habitat

In this study, eDNA survey detected 17 target fish species, most of which are rheophilic benthic fish. Therefore, *Spinibarbus sinensis* was selected as the target fish. Yu [27] fitted the relationship between body length of 6-10 cm and U_{crit} for *Spinibarbus sinensis* was $U_{\text{crit}} = 2.971L^{0.51}$. According to the formula (2), the coefficient α of the *Spinibarbus sinensis* is 0.9. The IFV of the *Spinibarbus sinensis* is 0.3 m/s [28]. In this study, the target fish was chosen to be the *Spinibarbus sinensis* with a body length of 0.3 m [29]. Thus, the calculated U'_{crit} of this fish was 1.6 m/s. Based on the operating conditions, the habitat units of the study river reach were divided as shown in Table 3.

Table 3. Meso-habitat function unit classification and operating conditions

Discharge	U <0.3 m/s	0.3 m/s < U < 1.6 m/s	U > 1.6 m/s
Low-discharge	Slow-flow zone	Migration channel	Flow velocity obstruction area

($Q=5920m^3/s$)			
Middle-discharge ($Q=11500m^3/s$)	Slow-flow zone	Migration channel	Flow velocity obstruction area
High-discharge ($Q=26000m^3/s$)	Slow-flow zone	Migration channel	Flow velocity obstruction area

3.2 Hydrodynamic analysis

Under the low discharge condition (Q = 5920 m^3/s), the flow velocity in the study reach was generally greater than 1.5 m/s, with localized velocities exceeding 1.98 m/s. Specifically, the velocity in the main navigation channel was 1.5 m/s at Wanglongqi and exceeded 1.9 m/s at Lianshitan. At the medium discharge (Q = 11500 m^3/s), velocities were generally above 2.0 m/s, with peak local velocities surpassing 2.4 m/s. The main channel velocities were 2.0 m/s at Wanglongqi and greater than 2.4 m/s at Lianshitan. For the high discharge scenario (Q = 26000 m^3/s), the reach experienced predominantly over 2.9 m/s, with some areas exceeding 3.1 m/s. The corresponding main channel velocities were 2.9 m/s at Wanglongqi and above 3.1 m/s at Lianshitan.

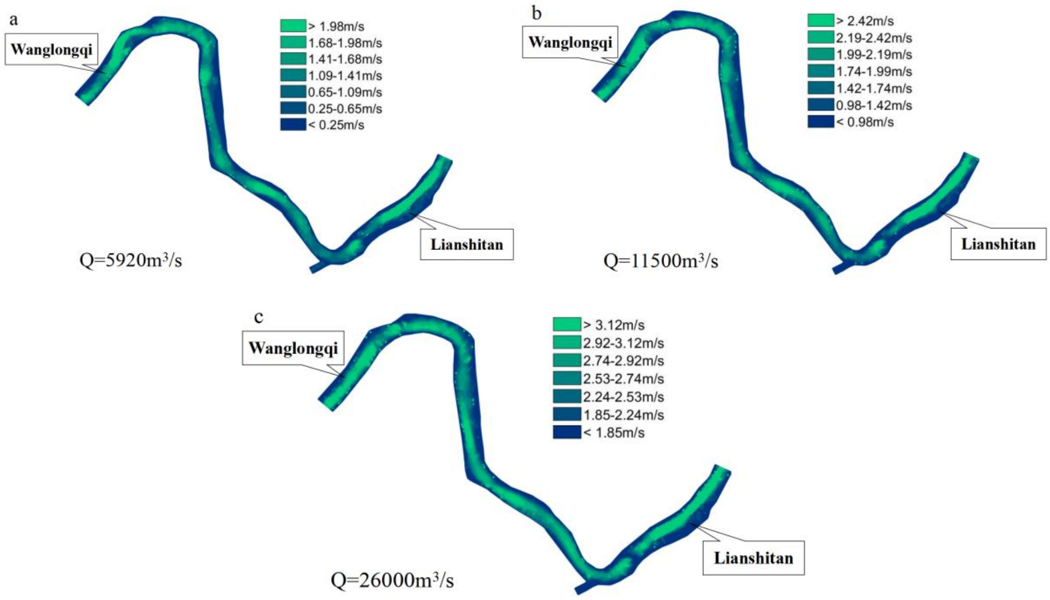


Fig 3. Flow velocity distribution in the study reach under different discharges (a. Q=5920 m^3/s; b. Q=11500 m^3/s; c. Q=26000 m^3/s)

3.3 Analysis of the impact of channel improvement project on fish habitat

According to Figure 4, the main channel dredging project for the Wanglongqi Beach section falls entirely within the hydraulic barrier zone, regardless of the flow rate. The two groyne structures, however, partially occupy the migration corridor under low discharge conditions but are fully contained within the hydraulic barrier zone at medium to high flows. Consequently, the dredging operations are unlikely to affect fish habitats under any discharge condition. In contrast, caution is advised for groyne construction, as performing this work during low discharge periods may pose a risk to fish habitats.

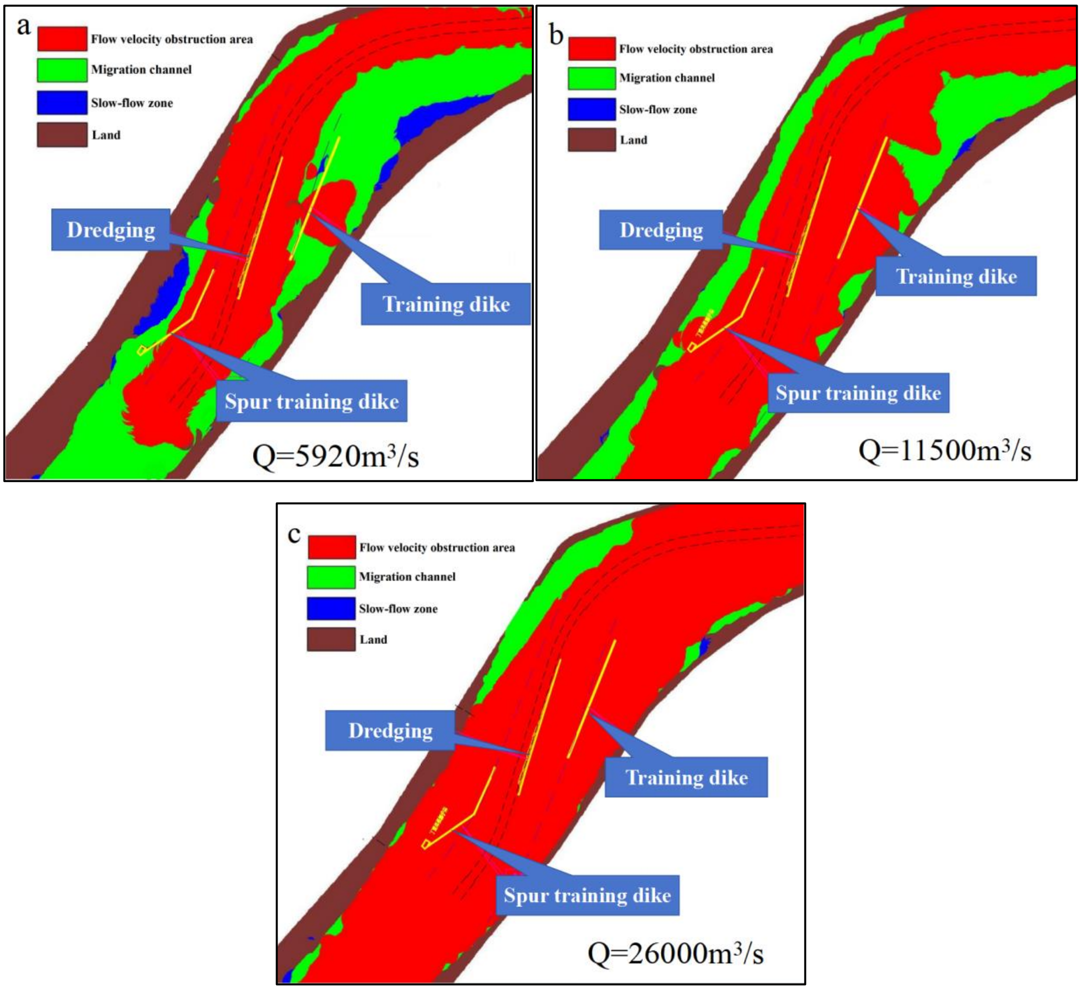
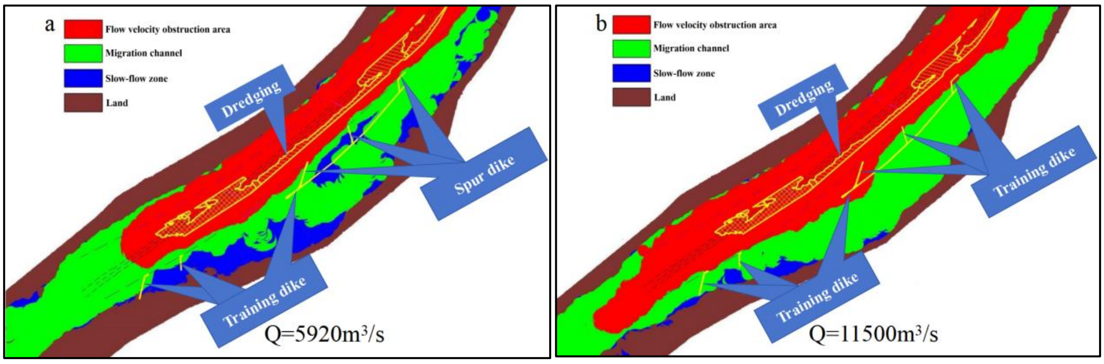


Fig 4. Delineation of Habitat Units in the Wanglongqi Reach (a. Q=5920 m^3/s; b. Q=11500 m^3/s; c. Q=26000 m^3/s)

Figure 5 illustrates the habitat unit zonation for the Lianshi Beach section. The dredging project falls entirely within the hydraulic barrier zone regardless of flow rate. In contrast, the groyne field partially overlaps with critical fish habitat under low to medium discharge conditions, but is wholly contained within the hydraulic barrier zone at high discharge. Consequently, dredging operations pose no risk to fish habitats under any discharge condition. However, caution is advised for the groyne construction, as activities during low to medium discharges may impact fish habitats.



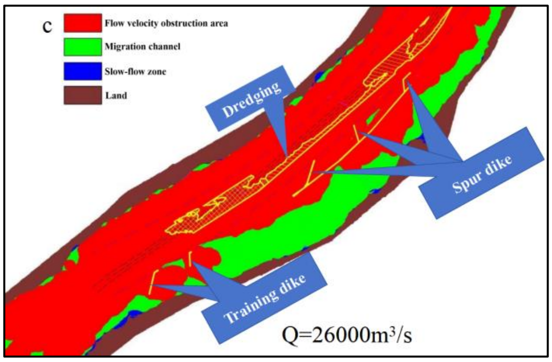


Fig 5. Delineation of Habitat Units in the Lianshitan Reach (a. Q=5920 m^3/s; b. Q=11500 m^3/s; c. Q=26000 m^3/s)

4. Discussion

4.1 The ecological significance of habitat function classification

For large rivers, the mesohabitat units can divide them into small patch-like areas, thereby better distinguishing each habitat [30]. Fish are very sensitive to changes in water, so choosing fish as the basis for classification is a very good idea. Fish swimming ability is represented by their U_{crit}. When river velocity is significantly lower than a fish's U_{crit}, the fish can access any desired location. However, when the velocity approaches or exceeds U_{crit}, remaining in the area requires a substantial energetic effort. The significance of dividing the river into functional habitat units lies in its ability to clearly and quantitatively delineate low-velocity zones, migration corridors, and high-velocity barrier zones.

In contrast, the mesohabitat approach defines river units based on hydraulic forms such as runs, riffles, and pools to investigate the relationships among fish habitat, hydrological patterns, and fish population distribution [10,31,32]. The basis for the classification, however, is an integration of the target species' U_{crit} with the velocity distribution of the study reach, which differs from the mesohabitat approach that relies solely on hydraulic parameters as classification criteria. U_{crit} is not merely a physiological parameter; it is the critical bridge linking river hydraulics and fish ecology. Consequently, such a classification approach is more applicable to practical management and conservation efforts [33].

4.2 Habitat pattern of fish in high-velocity conditions

Flow velocity is one of the key factors influencing fish communities, as it can not only directly affect fish behavioral patterns but also indirectly determine their spatial distribution and habitat quality by altering substrate and food distribution [34-36]. Throughout the study reach, even under low discharge conditions, the average velocity exceeded 1.5 m/s, with local peaks approaching 2 m/s. Such high surface velocities are likely to approach or even exceed the U_{crit} of many native fish species, particularly juveniles or those with lower swimming capabilities [37,38]. Consequently, most of the reach restricts the movement space for fish and limits their access to suitable habitats. Therefore, this reach is more suitable for rheophilic benthic fish, which is consistent with the eDNA detection results.

As discharge increases, velocities remain above 2 m/s. The entire reach is located within a spawning ground for fish with pelagic eggs. High-intensity discharge events can disrupt the drift of these eggs, leading to mortality and thereby affecting fish population recruitment throughout the section [39,40]. On the other hand, fish distribution within the reach exhibits a patchy pattern. Fish actively seek and utilize flow refugia, such as areas behind large boulders or within deep pools. Velocities in these areas are significantly lower than in the main channel, reducing the energetic cost of swimming and providing locations for rest and energy conservation [41,42].

4.3 Engineering ecological management strategy

The primary navigational obstructions in the upper Yangtze River include high flow variability, numerous sharp bends, central bars, shoals, and insufficient channel dimensions [43,44]. Traditional waterway improvement projects tend to employ methods such as reef blasting, dredging, and the construction of groins to enlarge channel dimensions and stabilize flow patterns. However, the implementation of these practices often reduces fish refugia, leading to an uneven distribution of fish communities [45,46]. The functional habitat unit classification method proposed in this study provides a clearer understanding of the relationship between waterway improvement engineering and fish habitats under varying flow conditions. As the study reach is a critical spawning ground, it is recommended that during the breeding season of target fish species, the release of sustained high-velocity flood pulses should be avoided to ensure the normal drift and incubation of fish eggs [47,48].

This classification method can aid in ecological flow management. The velocity at Lianshitan was consistently higher than at the Wanglongqi section. The presence of localized high-velocity zones highlights the complex interaction between flow and riverbed topography, conditions that ultimately determine the distribution patterns of fish [49-51]. These extreme hydraulic constraints must be considered in the management and engineering activities within this reach, as they are the key factors determining the spatial use and survival of the local fish community.

This method can be adopted as a standardized tool for the Environmental Impact Assessment and scheme comparison of all future engineering projects in this river section. At the same time, this method can also be applied to other engineering river sections. Quantitatively assessing the changes in available fish habitat area before and after a project, it can provide a more scientific and intuitive basis for decision-making.

5. Conclusion

This study proposes a method for classifying functional habitat units based on the coupling relationship between target fish species and the flow velocity of the study reach. This is a novel approach that integrates traditional hydraulics with fish biology. It qualitatively describes the significance of functional habitat units and quantitatively evaluates the feasibility of engineering implementation, thereby providing a more scientific and robust basis for future waterway improvement projects.

6. Appendix A1

Order	Family	Category	Habit
Cypriniformes	Cobitidae	*Paracobitis potanini*	Rheophilic,Benthic fish,Resident fish
	Homalopteridae	*Sinogastromyzon szechuanensis*	Rheophilic,Benthic fish,Resident fish
	Cyprinidae	*Ctenopharyngodon idella*	Limnophilic,Lower-middle fish,Half-migratory fish
		Culter alburnus	Rheophilic,Upper-middle fish,Half-migratory fish
		Spinibarbus sinensis	Rheophilic,Benthic fish,Resident fish
		Schizothorax davidi	Limnophilic,Benthic fish,Resident fish
		Gnathopogon herzensteini	Rheophilic,Lower-middle fish,Resident fish
		Xenophysogobio nudicorpa	Rheophilic,Benthic fish,Resident fish
		Acrossocheilus monticola	Rheophilic,Benthic fish,Resident fish
		Procypris rabaudi	Limnophilic,Benthic fish,Migratory fish
	Catostomidae	*Myxocyprinus asiaticus*	Limnophilic,Lower-middle fish,Migratory fish
Perciformes	Gobiidae	*Rhinogobius cliffordpopei*	Limnophilic,Benthic fish,Resident fish
	Serranidae	*Siniperca knerii*	Rheophilic,Benthic fish,Resident fish

	Percidae	*Sander lucioperca*	Rheophilic,Lower-middle fish,Resident fish
Siluriformes	Bagridae	*Tachysurus fulvidraco*	Limnophilic,Benthic fish,Resident fish
	Sisoridae	*Glyptothorax sinensis*	Rheophilic,Benthic fish,Resident fish
Acipenseriformes	Acipenseridae	*Acipenser dabryanus*	Limnophilic,Benthic fish,Migratory fish

7. Acknowledgements

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