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Simulating Ecological Effects of a Waterway Project in the Middle Reaches of the Yangtze River Based on Hydraulic Indicators on the Spawning Habitats of Four Major Chinese Carp Species

Shuran Yin [1], Yunpig Yang [2,*], Jianjun Wang [3], Jie Zhang [2,*], Qinghua Cai [1], Yude Zhu [2] and Chenyang Wang [2]

[1] Institute of Hydrobiology, Chinese Academy Sciences, Wuhan 430064, China; yinshuran@163.com (S.Y.); qhcai@ihb.ac.cn (Q.C.)
[2] Tianjin Research Institute for Water Transport Engineering, Ministry of Transport, Tianjin 300456, China; zhuyd@tiwte.ac.cn (Y.Z.); chenyang3623@163.com (C.W.)
[3] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China; wangjianjunb@126.com
* Correspondence: yangsan520_521@163.com (Y.Y.); zhangjie@tiwte.ac.cn (J.Z.)

Abstract: The adaptability of fish to their habitats is closely related to river hydraulics. While navigation channel projects aim to improve the navigation conditions by adjusting the hydrodynamic force of local river sections, the impacts of these projects on the hydraulic indicators of habitats of the four major Chinese carp species (FMCCs) remain unclear. Taking the Daijiazhou reach in the middle reaches of the Yangtze River as a case study, a mathematical model for spawning suitability was established to simulate changes in these hydraulic indicators before and after the implementation of a navigation channel project. The optimal flow rate interval for the spawning of the FMCCs was 17,500–22,000 $m^3 \cdot s^{-1}$. After the navigation channel project was implemented, the habitat suitability index (HSI) and weighted useable area (WUA) increased across the spawning habitats of all FMCCs, indicating that the project implementation created more habitat space. The central bar (Chihugang central bar) became exposed during the dry season, with the HSI and WUA decreasing under low water flow but increasing under medium-low or higher water flow levels. At the Daijiazhou bar head floodplain, which remained unexposed during the dry season, the HSI and WUA increased after project implementation, providing more space for spawning and habitation for the FMCCs. For the low point bar with bank gullies (Lejiawan point bar), the implementation of the bar protection zone project restricted gully development, with the HSI and WUA decreasing for all FMCCs. Based on the above impacts of navigation channel projects on the hydrodynamic environment of fish habitats, this paper provides a reference for the optimization of navigation channel arrangement as well as for the restoration of fish habitats.

Keywords: ecological hydraulics; suitability model; Chinese carp; navigation channel regulation project; Yangtze River

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1. Introduction

As of December 2021, more than 400 waterway improvement projects have been implemented in the middle and lower reaches of the Yangtze River, including systematic, long river reach improvement projects such as the Phase I Jingjiang reach Project, the Phase I and II 12.5 m deep waterway project located in and downstream from Nanjing, and the 6 m deep waterway improvement project currently under construction in the Wuhan-Anqing section. Some of these projects are located near or in the germplasm reserves of the four major Chinese carp species (FMCCs). Traditionally, these waterway improvement projects have focused on improving navigation conditions. However, the increasing requirements for ecological protection in the Yangtze River basin mean that the ecological impacts of the ongoing 6 m deep waterway improvement project from Wuhan to Anqing reach must be considered.

The Yangtze River is the primary natural origin of the FMCCs (black carp, grass carp, silver carp, and bighead carp), which represent China's major freshwater aquaculture and fishing products; they also constitute a valuable natural germplasm resource pool. However, the habitats and spawning environments of these carp species have been destroyed by human activities, such as river and lake barriers [1], flow processes [2], spring and summer water-temperature stagnation effects [3], and overfishing [1,4]. These activities have thus decreased fish stocks [5,6]. Previous studies have focused on characterizing the resources of the FMCCs [7], defining their habitats' hydraulic index suitability curves [8–13], revealing the distribution and variations in their spawning sites [14], and determining their spawning times [2,15–20]. Since the operation of the Three Gorges Project, long-distance cumulative scouring has occurred in the middle and lower reaches of the Yangtze River, which has provided favorable conditions for enhancing the waterway depth [21–23]. Since 2003, many projects have been implemented to improve the navigation conditions of the main channel of the Yangtze River, covering a variety of categories such as dams, bar protection zones, bottom protection zones, and bank protection. Following the strengthening of ecological protection requirements in the river basin, permeable structures have been adopted in such waterway projects to reduce their ecological impacts. Such structures can increase the areas of habitats such as boulders, spur dikes, and riffles by 2, 7, and 131%, respectively, relative to projects in which they are not used [24]. The construction of spur dikes has been shown to increase the weighted available habitat area by 23.9–31.9% [25] while also improving the habitat suitability of inter-dam waters. The recommended spacing of spur dikes should be at least 2.5 times the length of the dike [26], and double dikes have been shown to have a better weighted useable area (WUA) than single dikes [27]. Conceptual flume experiments have shown that the flow velocity around permeable artificial reefs should be maintained at 0.84–1.00 $m \cdot s^{-1}$; this range falls within the most suitable flow velocity range for spawning of the FMCCs [28]. Generally, constructing waterway projects can impact phytoplankton, zooplankton, benthic biomass, and the number of eggs and fry of the FMCCs [29–31]. However, these impacts have been shown to gradually disappear following project completion [30,32,33]. Ecological monitoring conducted during the Phase I Jingjiang Reach Waterway Project showed that a complex biome structure and increased benthic diversity were observed in areas where tetrahedral permeable frames were installed [34,35]; this attracted and gathered fish nearby [36,37]. Permeable, submerged spur dikes that were installed in the Zhoutian reach acted as artificial reefs, provided a sheltered habitat and foraging environment for fish, and facilitated the fertilization and normal hatching of eggs [38]. Moreover, it has been revealed that the Daijiazhou reach Phase II Project will not change the suitable spawning flow rate of the FMCCs, as it will basically maintain the existing hydrological conditions required for the spawning of these fish [39]. The Dongliu Waterway Phase II Project has also been projected to increase ideal spawning areas for the FMCCs, thereby facilitating their spawning and reproduction [40]. Based on ecological monitoring data collected from 2011 to 2016, a comprehensive index evaluation was performed to assess the conditions of the waterway in the Jingjiang reach, confirming that conditions improved after the implementation of the waterway project [41,42]. Collectively, the water projects implemented in the middle and lower reaches of the Yangtze River have produced relatively beneficial ecological effects. In terms of the design of waterway projects, however, no systematic investigation has yet been conducted into the relationship between waterway engineering schemes and eco-hydraulic indicators regarding the habitats of FMCCs.

This study addressed the 6.0 m water depth channel project that is currently being implemented in the middle reaches of the Yangtze River. Using spawning habitat hydraulic indices, the suitable water depth, flow velocity, habitat area, and microhabitat area for the spawning of the FMCCs were simulated and calculated under representative flow level conditions. This was achieved by employing a planar, two-dimensional mathematical model to explore and analyze the ecological hydraulic effects of the channel project.

2. Study Area and Site Survey

2.1. Study Section

The Daijiazhou reach lies in the middle reaches of the Yangtze River, located between the 915 and 945 km distance markers. It has a total length of ~30 km (Figure 1a). The protected germplasm resource area for the FMCCs is located downstream in the Huangshi section of the Yangtze River [14]. The studied reach encompasses the Chihugang mid-channel bar, Bahe point bar (which was essentially washed out in 2011), Daijiazhou mid-channel bar (including the low bar), and the Lejiawan point bar. Three phases of waterway projects were implemented in the Daijiazhou reach before 2018 (Figure 1b). The first phase was carried out from 2009 to 2010; it included the construction of one longitudinal dam, three submerged spur dikes, three bar protection strips, and bank protection at the head of the Daijiazhou bar, the latter of which guarded the low bar and shoreline at the head of Daijiazhou. The second phase of the project was implemented from 2010 to 2013, with the aim of protecting the lower section of the bar boundary at the right edge of Daijiazhou. The third phase of the project ran from 2012 to 2014; it constituted the installation of two bar protection strips in the Guafuji area and guarding of the bar boundary in the middle and upper sections of the right edge of Daijiazhou. After the completion of these three phases and following maintenance and adequate dredging measures, the channel reached the target dimensions of 4.5 m × 200 m × 1050 m (water depth × navigation width × bending radius, respectively).

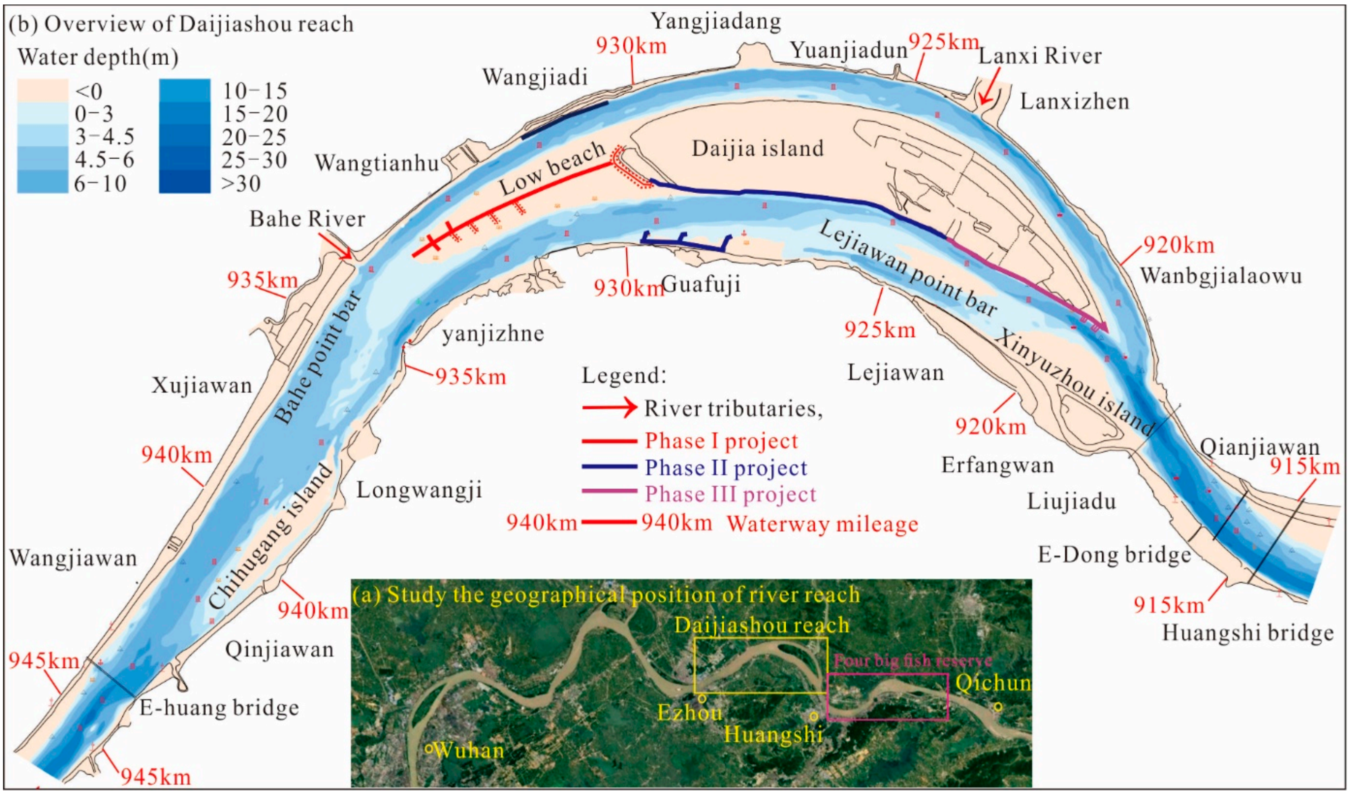

Figure 1. Schematic representation of the studied reach and related project. (**a**) Location of study area; (**b**) Daijiazhou reach.

2.2. Navigation Channel Regulation Project in Daijiazhou Reach

From 2018 onwards, several engineering schemes have been carried out during the Daijiazhou Reach Project with the aim of achieving the target waterway dimensions of 6.0 m × 110 m × 1050 m (Water depth × width × bending radius) from Wuhan to Anqing reach.

(1) Daijiazhou Front Protection Project: The fish-bone type dividing dike at the new front beach was extended by 2736 m. The extension has an elevation of 6.53 m (compared to the Yellow Sea as the base; the same applies below) at the head, which is connected smoothly to the already constructed fish-bone-type dividing dike at the tail. Five tooth-shaped beach protection structures were built in this extension, with a length of 144 m, 139 m, 137 m, 172 m, and 206 m.

(2) Chihugang Beach Protection Project: Two beach protection belts were constructed on the beach of Chihugang, which are 701 m and 708 m in length.

(3) Lejiawan Coastal Control Project: Five beach protection belts (point bars) were constructed in the Lejiawan region, with a length of 474 m (with a 150 m long hook), 680 m (with a 150 m long hook), 569 m, 669 m, and 1063 m (with a 300 m long hook). The beach protection belts #4 and #5 have dams as foundations, which have an elevation of 6.03 m.

(4) Daijiazhou Right-edge Revetment Project: The beach protection structure was 8336 m in length.

(5) Straight Channel Dredging Project: Dredging was carried out in the shallow water regions of the straight channels flowing into and out of Daijiazhou, with the dredged surface bottom at an elevation of 0.53 m.

3. Model Establishment, Validation, and Calculation Conditions

3.1. Model Construction

Using Fortran, a two-dimensional water sediment mathematical model was developed and used to simulate changes in water depth, flow velocity, and the hydraulic habitat suitability index (HSI) of FMCCs in the Daijiazhou reach under both the current conditions (March 2018 topography) and the project implementation conditions.

3.1.1. Basic Equations of Flow Movement Used in This Study

Flow continuity was calculated as follows:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial[(h+\zeta)u]}{\partial x} + \frac{\partial[(h+\zeta)v]}{\partial y} = 0 \tag{1}$$

while flow momentum was determined as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\partial}{\partial x}\left(v_e\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(v_e\frac{\partial u}{\partial y}\right) - g\frac{\partial \zeta}{\partial x} + \frac{\tau_{sx}}{\rho H} - \frac{\tau_{bx}}{\rho H} + fv \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{\partial}{\partial y}\left(v_e\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial x}\left(v_e\frac{\partial v}{\partial x}\right) - g\frac{\partial \zeta}{\partial y} + \frac{\tau_{sy}}{\rho H} - \frac{\tau_{by}}{\rho H} - fu \tag{3}$$

$$u = \frac{1}{H}\int_{-h}^{\zeta} u_1 dz \tag{4}$$

$$v = \frac{1}{H}\int_{-h}^{\zeta} u_2 dz \tag{5}$$

where u and v are the components of depth-averaged flow velocity in the x and y directions, respectively; u_1 and u_2 are the flow velocity components in the horizontal plane of the three-dimensional system in the x and y directions, respectively; H is the water level ($H = h + \zeta$), h is the water depth, and ζ is the surplus water depth; f is the Cohen's force coefficient ($f = 2\omega sin\varphi$, where ω is the angular velocity of Earth and φ is the latitude); v_e is the effective viscosity coefficient ($v_e = v_t + v$, where v_t is the turbulent viscosity coefficient); and τ_{bx} and τ_{by} are the bottom shear stress components in the x and y directions, respectively. These latter two components were calculated as follows:

$$\tau_{bx} = \rho c_f u\sqrt{u^2 + v^2} \tag{6}$$

$$\tau_{by} = \rho c_f v\sqrt{u^2 + v^2} \tag{7}$$

where c_f is the bottom friction coefficient ($c_f = n^2 \cdot g/H^{1/3}$, where n is the roughness coefficient of the river bottom), and τ_{sx} and τ_{sy} are the surface wind stress components in the x and y directions, respectively. ρ is the density of water, and the value is 1000 kg·m^{-3}. These wind stress components were calculated as follows:

$$\tau_{sx} = \rho_a k_s w_x |w| \tag{8}$$

$$\tau_{sy} = \rho_a k_s w_y |w| \tag{9}$$

$$|w| = \sqrt{w_x^2 + w_y^2} \tag{10}$$

where k_s is the coefficient. w is the wind speed 10 m above the water surface, w_x and w_y are components along the x and y directions, respectively, and the unit is m·s^{-1}. k_s in the wind stress coefficient, usually 0.0015. ρ_a is the density of air, and the value is 1.2 kg·m^{-3}. The effect of wind stress was not considered in these calculations, so τ_{sx} and τ_{sy} were set to zero.

3.1.2. Unbalanced Transport Equation of Suspended Sediment

Unbalanced transport for suspended sediment was calculated as follows:

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} + v\frac{\partial s}{\partial y} = \frac{\partial}{\partial x}\left(D_x\frac{\partial s}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial s}{\partial y}\right) - \frac{F_s}{h+\zeta} \tag{11}$$

where s is the averaged vertical sediment content, and the unit is kg·m^{-3}. D_x and D_y analysis are the suspended sediment turbulence diffusion coefficients in x and y directions, and the unit is m^2·s^{-1}. F_s is a function of the change of suspended sediment, and the unit is kg·m^{-2}·s^{-1}.

Based on the principle of unbalanced, non-uniform bed load transport, here the unbalanced sediment transport of bottom sediment was deduced according to the depth of the bed load as:

$$\frac{\partial(HN_b)}{\partial t} + \frac{\partial(uHN_b)}{\partial x} + \frac{\partial(vHN_b)}{\partial y} = \beta\omega_s(N_{b^*} - N_b) \tag{12}$$

where N_b and N_b* are the amount of bed load sediment transport and the sediment concentration of the corresponding water depth converted from the bed load transport capacity, respectively, and β is the bed load sediment recovery saturation coefficient. β is related to the dimensionless quantities H, U, ω_S, and L_s; it is expressed as:

$$\beta = \frac{H}{L_s}\frac{U}{\omega_s} \tag{13}$$

where H is the water level, and the unit is m. U is the vertical mean velocity, and the unit is m·s^{-1}; ω_S is the rate of sediment settling, and the unit is m·s^{-1}. L_s is the length, and the unit is m.

For non-uniform sediments, the unbalanced bed load transport was calculated as follows:

$$\frac{\partial HN_i}{\partial t} + \frac{\partial HuN_i}{\partial x} + \frac{\partial HvN_i}{\partial y} = \beta_i\omega_{si}(N_i^* - N_i) \tag{14}$$

where the subscript i denotes the variable corresponding to the ith group of sediments with a specified grain size.

3.1.3. Riverbed Deformation Equation

Riverbed deformation due to the scouring and silting of the suspended load was calculated as follows:

$$\gamma_0\frac{\partial\eta_{si}}{\partial t} = \alpha_i\omega_{si}(s_i - s_i^*) \tag{15}$$

where η_{si} is the thickness of scouring and silting caused by the ith group of suspended sediments of a specified grain size, and γ_0 is the bulk density of sediment on the bed surface.

The riverbed deformation caused by bed load scouring and silting was calculated as follows:

$$\gamma_0 \frac{\partial \eta_{bi}}{\partial t} = \beta_i \omega_{si} (N_i - N_i^*) \quad (16)$$

where η_{bi} is the thickness of scouring and silting caused by the ith group of bed load sediment of a specified grain size.

The scouring and silting thickness of the riverbed was determined as follows:

$$\eta = \sum_{i=1}^{n} \eta_{si} + \sum_{i=1}^{m} \eta_{bi} \quad (17)$$

3.1.4. Model Verification

The model calculation range started from the upstream (945 km) distance marker and ended at the downstream (915 km) distance marker. The model used an orthogonal curvilinear grid containing a total of 109,021 grid nodes (121 × 901 nodes). The roughness coefficient of the riverbed was generally set within the range of 0.015–0.025 for the channel and 0.025–0.035 for the bars. The model was verified using hydrological test data from March 2018, with the model inlet using the daily flow rate at Hankou station and the outlet using the daily water level at Huangshi station. The simulation results showed that the mainstream distribution calculated by the model was essentially consistent with the real data, with the simulated and measured flow velocities being in good agreement, as the coefficient of correlation R^2 = 0.98 and the relative error was less than 0.11 m·s^{-1} (Figure 2). The accuracy of the simulation was in accordance with the Technical Specifications for Sediment Simulation in Inland Waterways and Ports (JTS/T231-4-2018).

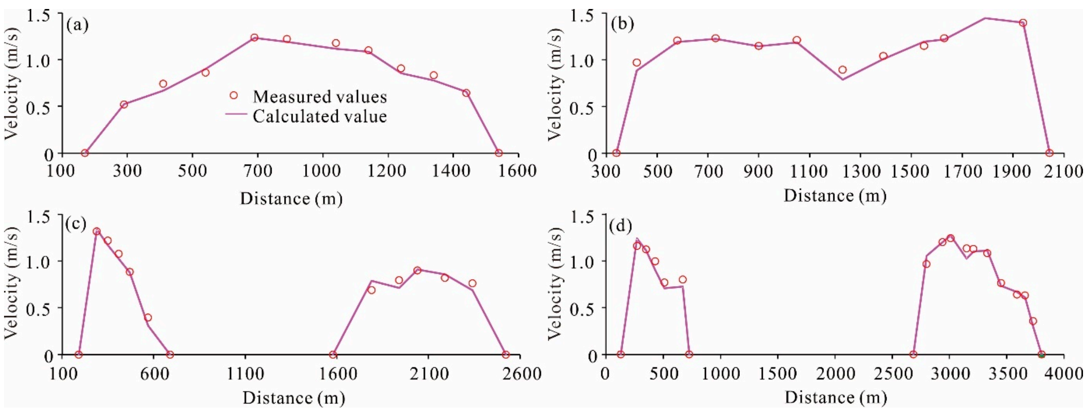

Figure 2. Comparison between modeled and measured velocity with the model inlet using the daily flow rate at Hankou station and the outlet using the daily water level at Huangshi station (March 2018). (**a**) #1 section; (**b**) #3 section; (**c**) #3 section; (**d**) #4 section.

3.2. Hydraulic Indicators and Parameters of Fmcc Habitats

The HSI comprehensively evaluates ecological factors that impose important effects on the species under study; it reflects environmental quality by using an equation containing single or multiple environmental variables. In this way, it quantitatively displays a species' preferences for different habitats [43,44].

The FMCC spawning HSI was calculated as follows:

$$HSI = V_{\mathrm{FMCC}}{}^{\alpha} \times H_{\mathrm{FMCC}}{}^{(1-\alpha)} \quad (18)$$

where α usually takes the value of 0.70.

The *WUA* was obtained using the weighted HSI as shown:

$$WUA = \sum_{i=1}^{i=n} HSI({V_{FMCC}}^{\alpha} \times {H_{FMCC}}^{1-\alpha}) \times A_i \tag{19}$$

where HSI $(V_i \times H_i)$ is the suitability value of the influence factor of each cell i; V_i and H_i denote the suitability values of the flow velocity and the water depth of cell i, respectively; and A_i represents the water body surface area of cell i.

The Daijiazhou reach is located near and upstream of the Huangshi reserve for the FMCCs, serving as an important habitat for the FMCCs to spawn and inhabit. The thresholds for the suitability values are summarized in Table 1 and Figure 3 based on research studies on the habitat indicators of the Huangshi reserve for FMCCs in the Yangtze River [7–9,45,46].

Table 1. Threshold values for suitability of water depth and flow rate.

No.	Water Depth Suitability		Flow Rate Suitability	
	Water Depth (H, m)	Suitability Value (H_{FMCC})	Flow Rate (V, m·s^{-1})	Suitability Value (V_{FMCC})
1	$H < 1.0$	$H_{FMCC} = 0$	$V < 0.25$	$V_{FMCC} = 0$
2	$1.0 \leq H < 5.0$	$H_{FMCC} = 0.25 \times (H - 1)$	$0.25 \leq V < 0.90$	$V_{FMCC} = (V - 0.25)/0.65$
3	$5.0 \leq H < 15.0$	$H_{FMCC} = 1$	$0.90 \leq V < 1.30$	$V_{FMCC} = 1$
4	$15.0 \leq H < 30.0$	$H_{FMCC} = 1 - (H - 15)/15$	$1.30 \leq V < 3.0$	$V_{FMCC} = 1 - (V - 1.30)/1.7$
5	$H \geq 30.0$	$H_{FMCC} = 0$	$V \geq 3.0$	$V_{FMCC} = 0$

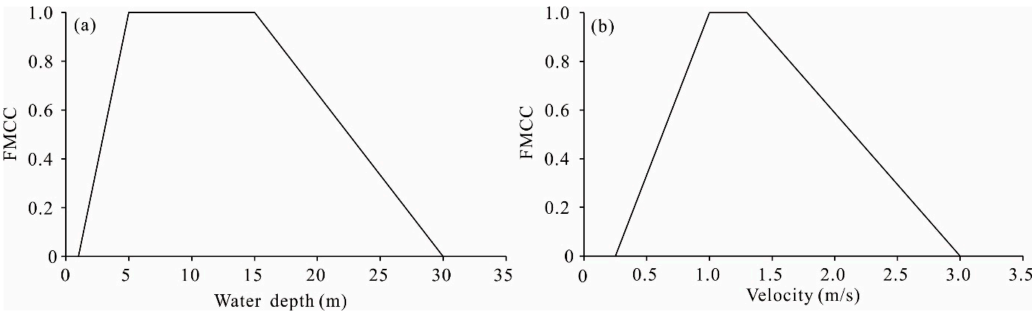

Figure 3. Suitability curves of water depth and flow rate for spawning of four major Chinese carp species (black, grass, silver, and bighead carp) (FMCC). (**a**) Water depth; (**b**) velocity.

3.3. Simulation and Verification of Hydrological and Sediment Conditions

The initial model terrain was taken in March 2018 (at a scale of 1:10,000). The terrain after a complete hydrological year is the post-project terrain. The hydrological year used for calculation was 2016, with a total of 366 days. The year 2016 was a typically wet year for the middle reaches of the Yangtze River (Figure 4). This year was thus selected as a representative hydrological year to test the anticipated effect of the water project. The low water flow in the Daijiazhou reach was 11,900 m^3·s^{-1}, the medium-low water flow was 15,764 m^3·s^{-1}, the average annual flow was 23,300 m^3·s^{-1}, and the flood flow was 50,000 m^3·s^{-1}.

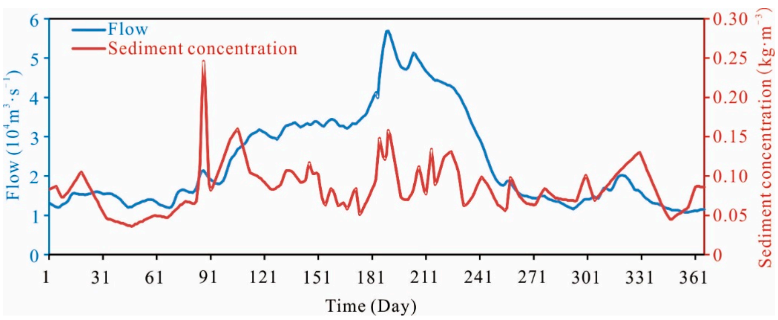

Figure 4. Water and sediment processes measured at Hankou Station in 2016.

4. Results

4.1. Variation in Spawning Water Depth Suitability Index for Fmccs

The suitability of water depth and spawning area for the FMCCs in the Daijiazhou reach before and after the implementation of the project is shown in Figures 5 and 6, respectively. FMCCs in the inlet section of Daijiazhou increased when the flow was 11,900 $m^3 \cdot s^{-1}$ and 12,764 $m^3 \cdot s^{-1}$ and decreased when the flow was 23,300 $m^3 \cdot s^{-1}$ and 50,000 $m^3 \cdot s^{-1}$. Under medium-low water and flood flow conditions, the area of suitable water depth around the Chihugang mid-channel bar decreased, indicating that the project substantially promoted the silting process; this area increased under average annual flow. At the head of Daijiazhou, the area of suitable water depth decreased under low and medium-low water flows, indicating the clear silting effect of the project; the area expanded under average and flood flows. Under all water flows, the area of suitable water depth universally decreased in Lejiawan.

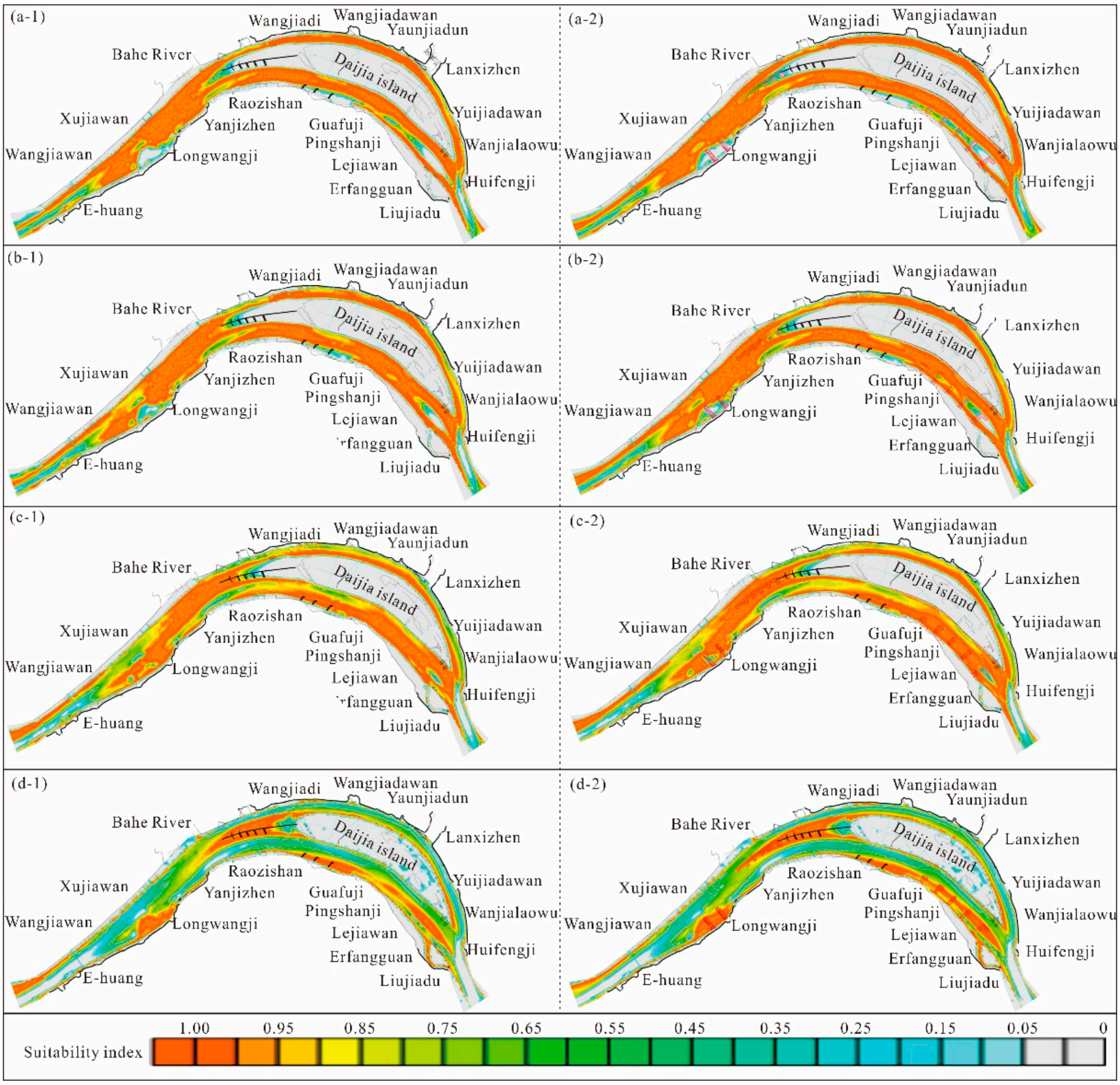

Figure 5. Changes in water depth suitability for spawning of the four major Chinese carp species (black, grass, silver, and bighead carp) in Daijiazhou reach before and after implementation of project. (**a-1**) 11,900 $m^3 \cdot s^{-1}$ before the project, (**a-2**) 11,900 $m^3 \cdot s^{-1}$ after the project; (**b-1**) 12,764 $m^3 \cdot s^{-1}$ before the project, (**b-2**) 12,764 $m^3 \cdot s^{-1}$ after the project; (**c-1**) 23,300 $m^3 \cdot s^{-1}$ before the project, (**c-2**) 23,300 $m^3 \cdot s^{-1}$ after the project; (**d-1**) 50,000 $m^3 \cdot s^{-1}$ before the project, (**d-2**) 50,000 $m^3 \cdot s^{-1}$ after the project.

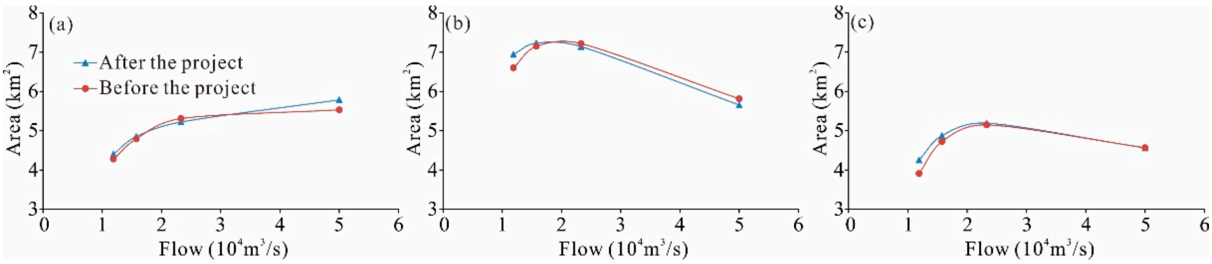

Figure 6. Changes in area of suitable water depth for spawning of four major Chinese carp species (black, grass, silver, and bighead carp) in Daijiazhou reach before and after implementation of project. (**a**) Chihugang; (**b**) Dajiazhou; (**c**) Lejiawan.

4.2. Variations in Flow Rate Suitability Indices for Fmccs

The flow rate suitability and area for spawning of FMCCs in the Daijiazhou reach before and after the implementation of the project are shown in Figures 7 and 8, respectively. The area of suitable flow rate increased in the deep trough near the inlet of the Daijiazhou reach under all flow levels. This area also increased near the Chihugang mid-channel bar under all representative flow levels. Around the head region of Daijiazhou, the area of suitable flow rate increased under low, medium-low, and multi-year average water flows; it only slightly decreased under flood flow conditions. This area uniformly decreased in Lejiawan under all flow conditions, however; the magnitude of decrease diminished with increasing flow.

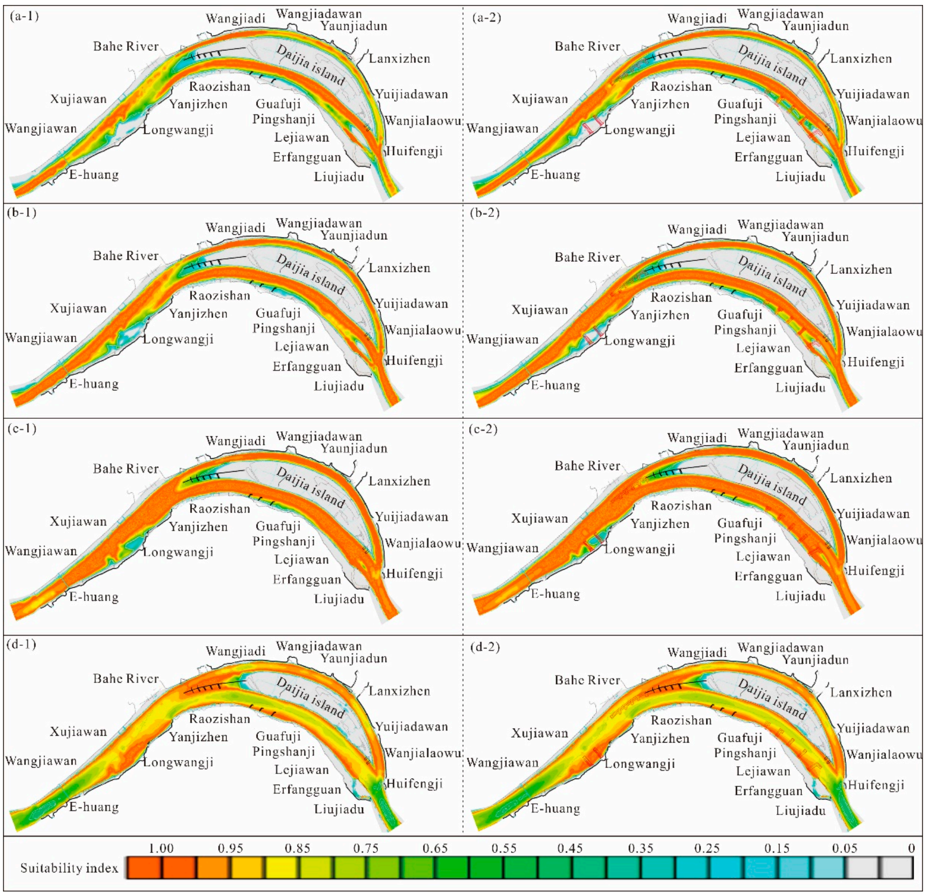

Figure 7. Changes in flow rate suitability for spawning of the four major Chinese carp species (black, grass, silver, and bighead carp) in Daijiazhou reach before and after project implementation. (**a-1**) 11,900 $m^3 \cdot s^{-1}$ before the project, (**a-2**) 11,900 $m^3 \cdot s^{-1}$ after the project; (**b-1**) 12,764 $m^3 \cdot s^{-1}$ before the project, (**b-2**) 12,764 $m^3 \cdot s^{-1}$ after the project; (**c-1**) 23,300 $m^3 \cdot s^{-1}$ before the project, (**c-2**) 23,300 $m^3 \cdot s^{-1}$ after the project; (**d-1**) 50,000 $m^3 \cdot s^{-1}$ before the project, (**d-2**) 50,000 $m^3 \cdot s^{-1}$ after the project.

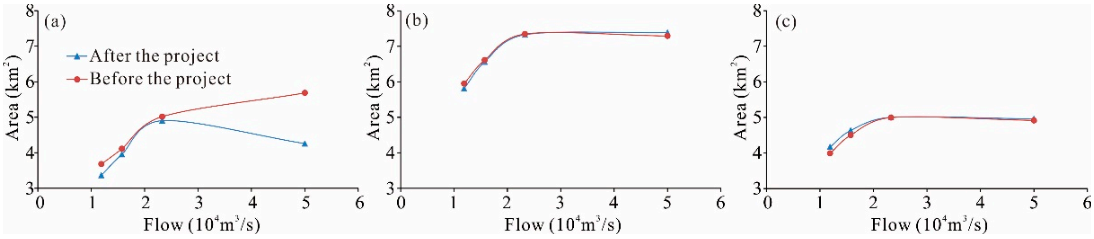

Figure 8. Changes in area of suitable flow rate for spawning of four major Chinese carp species (black, grass, silver, and bighead carp) before and after project implementation. (**a**) Chihugang; (**b**) Dajiazhou; (**c**) Lejiawan.

4.3. Project-Driven Changes in Distribution of Fmcc Habitat Suitability

The suitability index distribution and area of suitable FMCC habitat before and after the implementation of the Daijiazhou Reach Waterway Project are shown in Figures 9 and 10, respectively. The area of suitable habitat in the deep rough near the inlet of the Daijiazhou reach increased under all flow conditions; it also uniformly increased at the Chihugang mid-channel bar and at the head of Daijiazhou under individual representative flow levels. Both the habitat suitability and area of suitable FMCC habitat decreased around Lejiawan under all flow levels; the habitat area decreased at a slower rate with increasing flow rate.

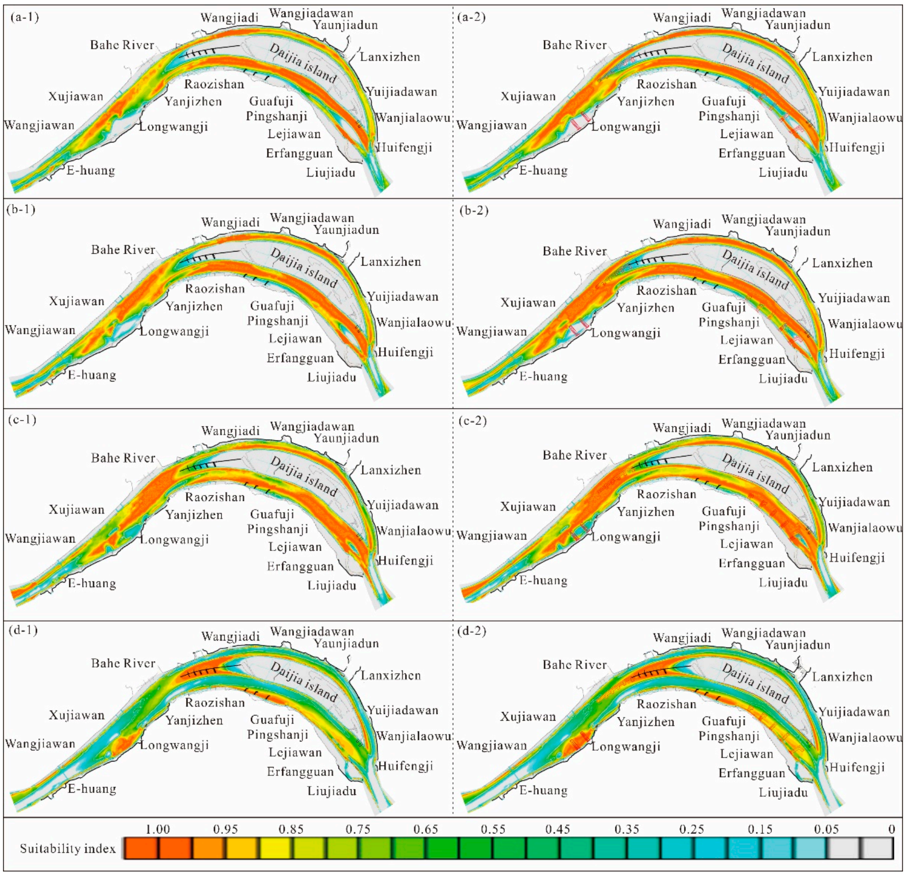

Figure 9. Changes in suitability index distribution of the habitat of the four major Chinese carp species (black, grass, silver, and bighead carp) before and after project implementation. (**a-1**) 11,900 $m^3 \cdot s^{-1}$ before the project, (**a-2**) 11,900 $m^3 \cdot s^{-1}$ after the project; (**b-1**) 12,764 $m^3 \cdot s^{-1}$ before the project, (**b-2**) 12,764 $m^3 \cdot s^{-1}$ after the project; (**c-1**) 23,300 $m^3 \cdot s^{-1}$ before the project, (**c-2**) 23,300 $m^3 \cdot s^{-1}$ after the project; (**d-1**) 50,000 $m^3 \cdot s^{-1}$ before the project, (**d-2**) 50,000 $m^3 \cdot s^{-1}$ after the project.

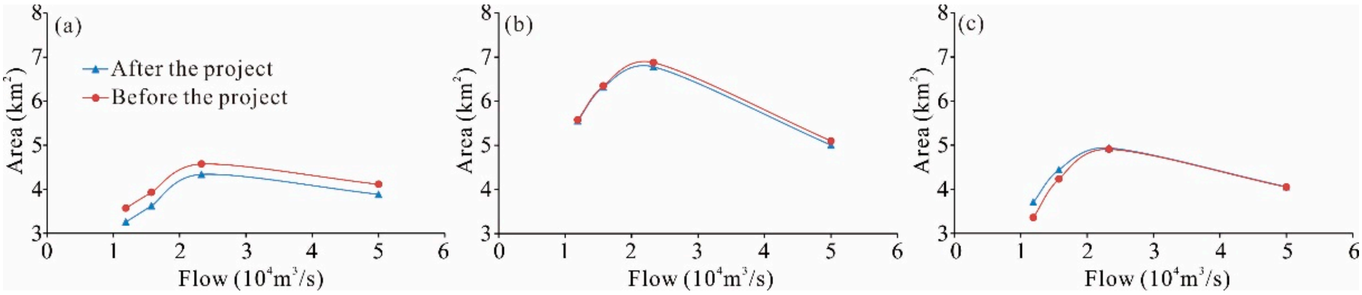

Figure 10. Changes in area of suitable habitat before and after project implementation. (**a**) Chihugang; (**b**) Dajiazhou; (**c**) Lejiawan.

5. Discussion

5.1. Impacts of Project on HSI for Fmccs in Daijiazhou Reach

Figure 11 shows the area of the FMCC HSI under individual flow levels following the implementation of the 6.0 m depth waterway project in the Daijiazhou reach. The major changes observed are summarized here:

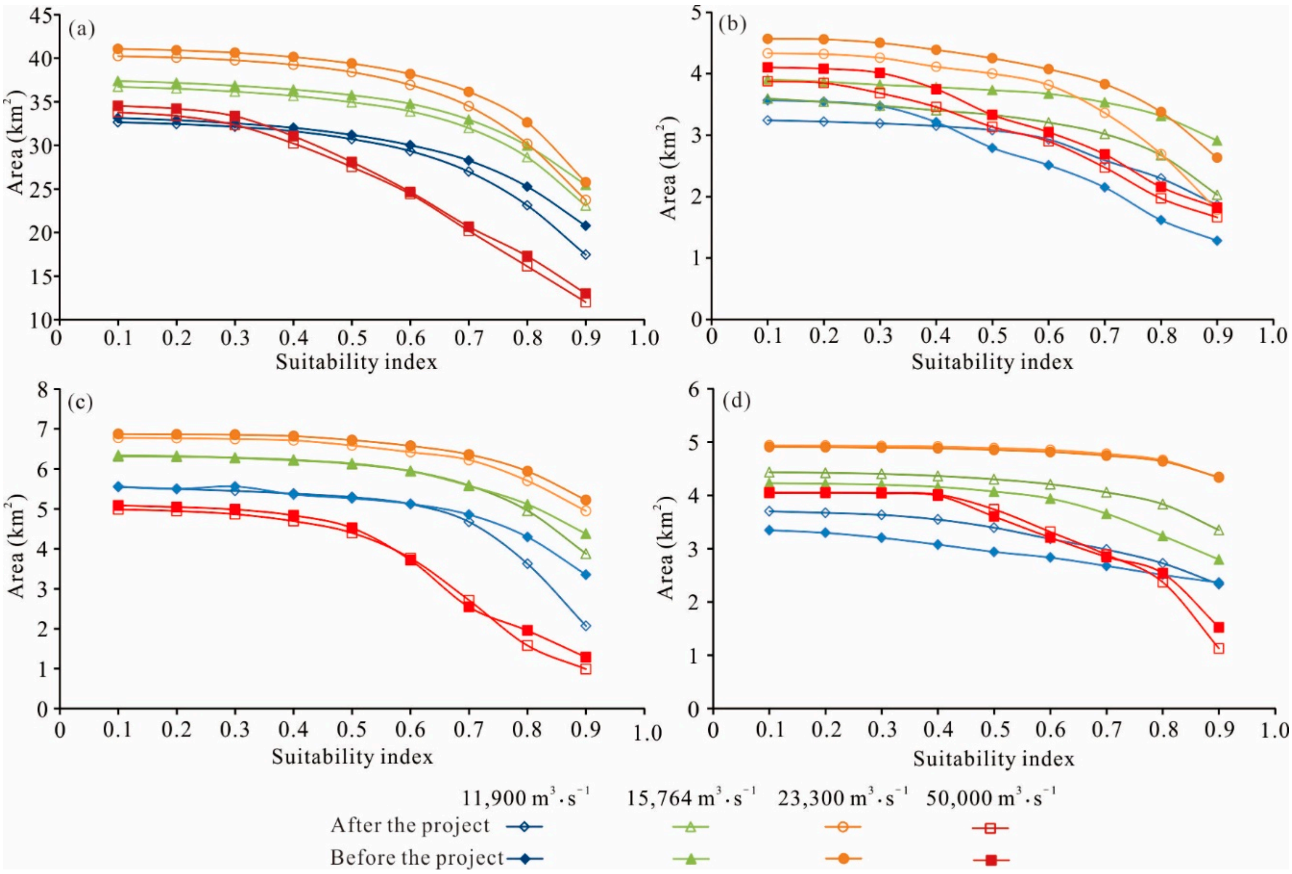

Figure 11. Changes in habitat suitability index area in Daijiazhou reach before and after project implementation. (**a**) Daijiazhou reach; (**b**) Chihugang; (**c**) Daijiahzou; (**d**) Lejiawan.

(1) Daijiazhou reach: The HSI area of the Daijiazhou reach increased under all flow levels, indicating that the implementation of the project created more living space that was suitable for the FMCCs to spawn.

(2) Chihugang mid-channel bar: under low water flow, the HSI area expanded when HSI < 0.40 and shrank when HSI ≥ 0.40. The HSI area increased under medium-low water, multi-year average, and flood flows; the rate of increase slowed as the flow increased.

(3) Daijiazhou low bar: when HSI < 0.70, the HSI area near the low bar at the head of Daijiazhou did not substantially change under low and medium-low flow conditions; it increased when HSI $\geq$ 0.70. The HSI area expanded under multi-year average and flood flows.

(4) Lejiawan point bar: under low and medium-low water flows, the HSI area decreased in Lejiawan; it did not change considerably under multi-year average flow. Under flood flow, the area showed no significant change when HSI < 0.40; it decreased when 0.50 $\leq$ HSI $\leq$ 0.70 and increased when HSI $\geq$ 0.80.

5.2. Impacts of Project on WUA in Daijiazhou Reach

Figure 12 shows changes in WUA after implementation of the 6.0 m depth waterway project in the Daijiazhou reach, when HSI $\geq$ 0.80 and HSI $\geq$ 0.90, under individual representative flow levels; the characteristic changes are listed below:

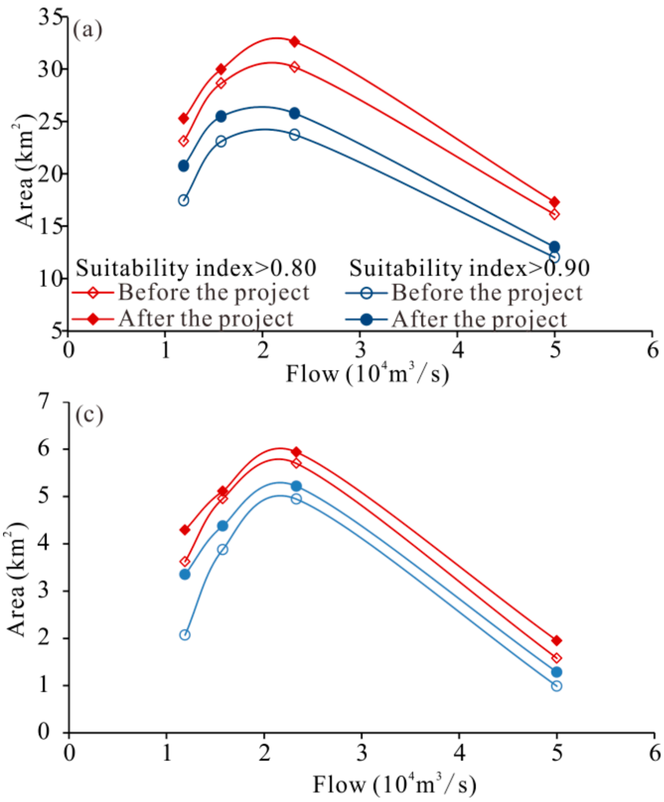

Figure 12. Project-driven changes in weighted useable area in Daijiazhou reach. (**a**) Daijiazhou reach; (**b**) Chihugang; (**c**) Daijiahzou; (**d**) Lejiawan.

(1) Daijiazhou reach: when HSI $\geq$ 0.80 and HSI $\geq$ 0.90 and when the flow increased, WUA initially increased and then decreased. WUA increased after the implementation of the project.

(2) Chihugang point bar: WUA decreased under low water flow when HSI $\geq$ 0.80 and HSI $\geq$ 0.90; it increased under medium-low water, multi-year average, and flood flows.

(3) Daijiazhou head low bar: when HSI $\geq$ 0.80 and HSI $\geq$ 0.90, WUA increased and then decreased with increasing flow. After the implementation of the project, WUA increased under all flow levels, with the largest increase being observed under low water flow.

(4) Lejiawan point bar: when HSI $\geq$ 0.80 and HSI $\geq$ 0.90, WUA increased and then decreased with increasing flow. After the implementation of the project, WUA decreased under all flow levels; the largest decrease was observed under medium-low water flow.

The United States Fish and Wildlife Service (USFWS) proposed the Instream Flow Incremental Methodology (IFIM), which combines suitable habitat conditions of species such as flow, water depth, and riverbed sediment to establish hydrological models. Using IFIM, the WUA for fish was obtained through simulation in the current study. The quantitative relationship between the fish habitat flow rate and WUA was then further established to evaluate the fish habitat suitability. Using the relationship between the WUA and flow rate for the FMCCs in the middle reaches of the Yangtze River, the optimal flow rate for FMCC spawning in the Daijiazhou reach was predicted to be 17,500–22,000 $m^3 \cdot s^{-1}$.

5.3. Measures for Waterway Project Optimization Based on Hydraulic Indicators of FMCC Spawning Habitats

After the implementation of the waterway project, WUA displayed characteristic variations in the Daijiazhou reach and in the specific project areas. Following project completion, the branch channel on the left bank of the Chihugang mid-channel bar did not have running water under low water flow, which reduced WUA to a certain extent. In the low bar near the head of Daijiazhou, the implementation of the bar protection strip and the dredging measures created better conditions in the bar and channel, thereby increasing WUA. The bar protection strip at Lejiawan blocked gullies, thereby decreasing the diversity of the riverbed morphology and thus reducing WUA. To remedy this issue, a stepped bar protection strip could be installed in Lejiawan; i.e., the height of the bar protection structure around the gullies could be lowered to reduce its influence on the HSI and WUA regarding the spawning of the FMCCs.

Based on the relationship between the hydraulic indicators of the spawning habitats of the FMCCs and the project, the point bar and the mid-channel bar protection could be optimized in the following ways:

(1) Point bar with near-bank dry gullies during the dry season (Figure 13(a-1)): the bar protection could be constructed in either a buried or non-buried form; the non-buried form would be more suitable for shallow waterways, and the buried form would be more appropriate for waterways with adequate depth and certain scouring. Under the latter conditions, burying the bar protection would prevent the adverse effects of side bar scouring. Buried projects are implemented by excavating the point bar to a certain depth such that the entire bar does not need to be destroyed. The impact of such a project on the hydraulics of the FMCC habitats would be minor, and the bar protection structure would also provide a benign habitat for benthic organisms. For non-buried projects, the point bar would be in a non-inundated state during the dry season; the impact of such a project on the hydraulic indicators of the FMCC habitats would primarily be reflected under (and above) medium-low water flow conditions. The impact on the hydraulics of the FMCCs habitats in the flow interval suitable for spawning would be minimal; examples of such projects include those on the Shuiluzhou and Guniusha waterway point bars [35].

(2) Point bar with bank gullies that remain filled with water during the dry season (Figure 13(a-2)): bank gullies that are filled with water provide a suitable habitat for the FMCCs. The trough in such areas should not be filled. Instead, it is recommended that bottom protection projects with a lower height are implemented or that an ecological conservation zone is established. During dam construction, it is recommended that a stepped, permeable structure should be used around the gully. As the bottom protection height in such a case would be relatively low, the impact on the hydraulics of the FMCC habitats would be limited; the Jinchengzhou point bar represents a good example of this [36]. Trough filling is not recommended because it limits the spawning habitat space for the FMCCs and blocks their migration routes.

(3) Low bar at the head of a central bar (Figure 13(b-1)): the elevation of a low bar at the head of a central bar will be relatively low. The bottom elevation of such a bar protection strip or dam would be lower than the minimum designed water level or low water level. Therefore, it would be preferable to maintain the top elevation at a height lower than the targeted waterway water depth of the project. Low bar protection projects can increase the height differences of local bars and troughs and create complex flow patterns; these

conditions are conducive to the spawning and other activities of the FMCCs. The protection project at the head of Laohutan in the east flow channel is an example of this [40].

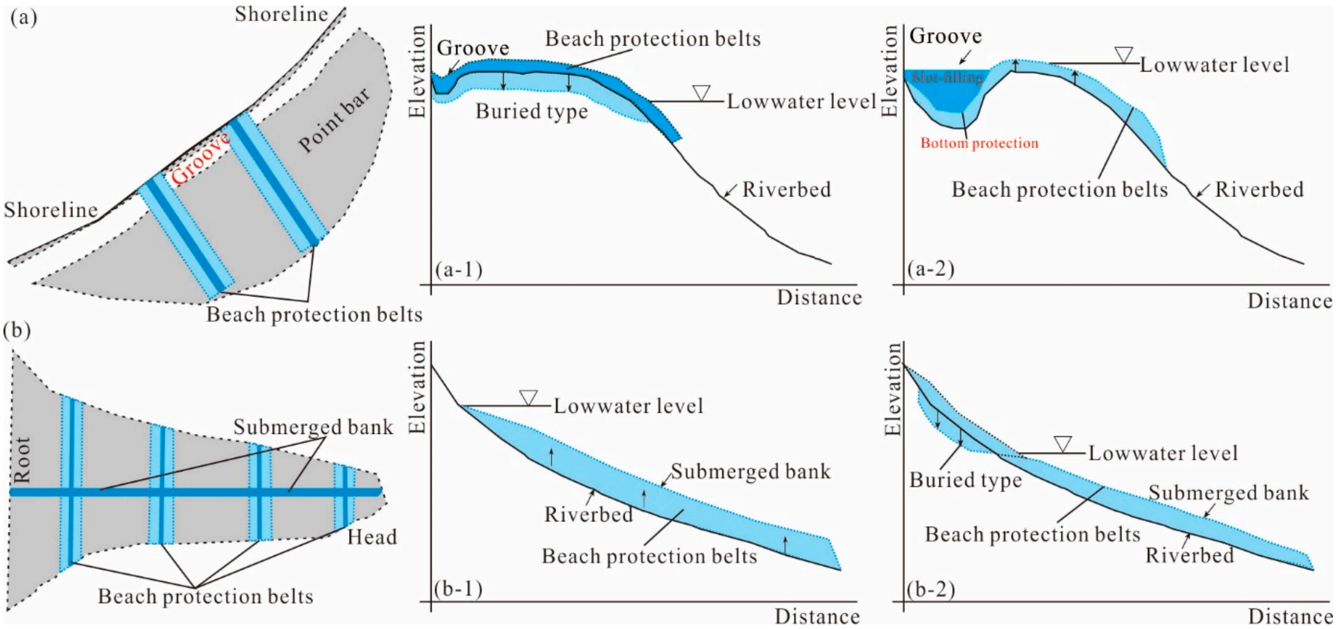

Figure 13. Ideas for navigation channel project layout based on hydraulic indices of spawning habitats of the four major Chinese carp species (black, grass, silver, and bighead carp). (**a**) Point bar; (**a-1**) in dry season, the groove is not filled with water; (**a-2**) in dry season, the groove is filled with water; (**b**) central bar, (**b-1**) low beach, (**b-2**) high beach.

(4) High bar at the head of a central bar (Figure 13(b-2)): permeable bar protection structures are suitable for the part of a low bar that is below the low water level. For the portion above the low water level, scour protection, soil reinforcement, and revetment projects should be considered, as should ecological revetment projects. For instance, the vegetative revetment technique was used in the Daokouyao mid-channel bar of the Ouchikou reach during the Jingjiang Reach Phase I project [47]; this achieved a satisfactory ecological effect.

In this paper, the influence of the navigation channel regulation project on hydrodynamics was studied with respect to the hydraulic indices showing suitability of spawning habitats for FMCCs. The changes in hydrodynamics before and after the project were further studied to show the influence on the habitat environment for FMCCs. With the increasing emphasis on ecological influences due to navigation channel regulation projects, past navigation channel regulation projects have shown positive ecological influences on vegetation [41,42], whereas others have restored or increased aquatic organisms after their completion. Nevertheless, field sample collection is highly random. The importance of this paper is that hydraulic indices were introduced into the conventional mathematical model of river flow and sediment so as to quantitatively study the influence of the implementation of navigation channel projects on the fish habitats. This is of great significance for optimizing the layout and design of the navigation channel project. In the future, it is necessary to pay more attention to the influences of navigation channel projects on biological habitats, accumulate more on-site monitoring data, scientifically evaluate the influence of the project implementation on fish habitats, and support the construction of ecological navigation channels in inland rivers.

6. Conclusions

Here, a mathematical model was established to simulate changes in the hydraulic indicators of spawning habitats of the FMCCs following the implementation of the 6.0 m depth waterway project in the Daijiazhou reach of the middle reaches of the Yangtze River. The main conclusions are listed below:

(1) The multi-phase waterway project being implemented in the Daijiazhou reach achieved the goal of maintaining a transit waterway with dimensions of 4.5 m × 200 m × 1050 m. Since the completion of the early phases of the project, vegetation has flourished on the revetment structure (above the low water level mark on the bank). Moreover, benthic organisms (including fresh mussels) have grown abundantly in the submerged parts of the riprap, thereby providing beneficial ecological effects.

(2) The 6.0 m depth waterway project is ongoing in the Daijiazhou reach. The HSI and WUA of the Daijiazhou reach both increased following the initial implementation of the project, indicating that the project has already created more spawning habitat space for the FMCCs.

(3) The elevation of the Chihugang mid-channel bar is relatively high, and its surface is exposed during the dry season. The HSI and WUA declined under low water flow for this bar, while they increased under medium-low (and above) water flow conditions. The elevation of the low bar at the head of Daijiazhou is relatively low, so it is not exposed during the dry season. The HSI and WUA of the FMCCs increased under all levels of flow following the completion of the project, which provided more habitat space for the FMCCs. The bar protection project at Lejiawan limited the development of bank gullies, which reduced the HSI and WUA for the FMCCs.

(4) According to the relationship between the hydraulic indicators of the spawning habitats of the FMCCs and the waterway project, proper bar protection measures should be implemented in the point bar area without blocking the bank gullies. Either stepped bar (bottom) protection or an ecological conservation zone should be established. In the low-lying area at the head of the mid-channel bar, the elevation of the underwater bar protection project should be lower than the designed water level; ecological revetment could be used for the above-water portion.

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