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Assessment of suitable minimum ecological flow downstream of a dam in the Upper Yellow River based on native fish conservation

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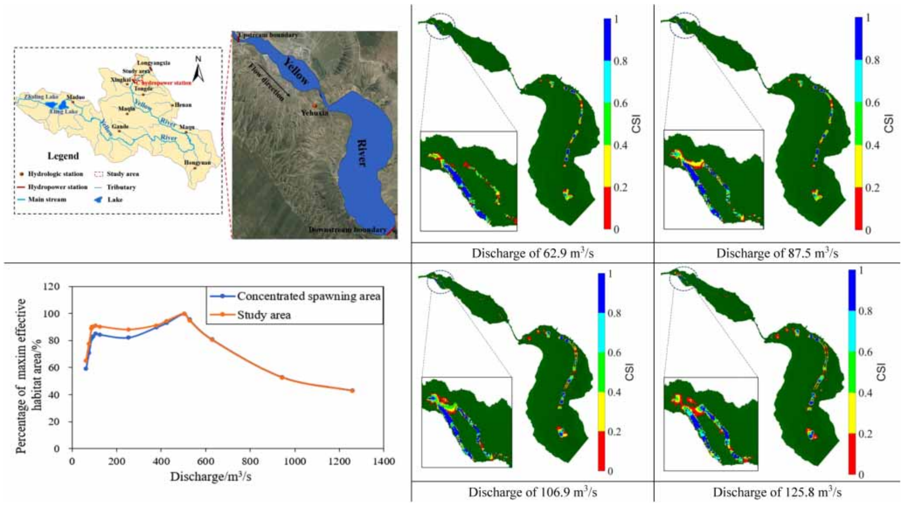
ABSTRACT

To ensure the ecological operation of the proposed C hydropower stations of the Upper Yellow River, the suitable minimum ecological flow of the study reach after the completion of hydropower station is studied. The native plateau fish was considered as an indicator species of the reach downstream of the dam for ecological conservation. The study is based on a 2D shallow water model with high-precision solution methods and GPU-accelerated performance, combined with Tennant, hydraulics method and habitat suitability models to obtain habitat conditions of river for fish survival during non-spawning periods and effective habitat areas during spawning period under different discharges. The results indicated that the suitable minimum ecological flow downstream of the C hydropower station was 87.5 m³/s to protect fish downstream. This achievement not only provides basic data for the optimal operation of C hydropower station based on the ecological response, but also some reference value for the actual operation management of water conservancy projects. Besides, it is of great ecological significance for the protection of native fish habitat in the Yellow River Basin.

Key words: effective habitat area, habitat suitability model, hydraulics method, minimum ecological flow, Tennant

GRAPHICAL ABSTRACT



1. INTRODUCTION

In recent decades, with the continuous development of industrialization and urbanization, the requirements for water resources and energy have increased dramatically (Qiu & Hu 2018; Hough *et al.* 2022). Human beings have built dams, weirs, and different structures in the rivers for water supply and power generation to fully exploit and utilize water resources. However, the presence of these hydraulic projects modified the hydrological regimes of the natural river (Bednarek 2001;

Zhao *et al.* 2018; Homsi *et al.* 2020; Gălie *et al.* 2021; Yan *et al.* 2021), and thus threaten the health and sustainability of the riverine ecosystems (Anderson *et al.* 2017; Ostad-Ali-Askari *et al.* 2019; Shamshirband *et al.* 2019). To balance the contradiction between the economic and social water use and the ecological environment, and further ensure the health of river ecosystem and habitat integrity, ecological flow came into being (Poff & Matthews 2013; Gates *et al.* 2015). The science and practice of the ecological flow as an approach for protecting important ecological services and ensuring the sustainable development of human socioeconomics by managing water flow regimes is of great practical significance (Arthington *et al.* 2018; Wu *et al.* 2022). Especially, for the increasingly constructed hydropower stations, the determination of ecological flow is not only the premise and basis for studying their ecological operation, but also one of the core requirements of sustainable hydropower development (Qiu & Hu 2018; Zhang *et al.* 2019; Yu *et al.* 2021).

It is predicted that, by 2050, the global water demand will increase by 55% (Lucinda *et al.* 2016), the growing large dams and hydropower stations worldwide will be built to meet the demand for water (ICOLD 2020), which further aggravates the contradiction between water use inside and outside the river (Li *et al.* 2013; Salik *et al.* 2016). Thus, ecological flow, which can reflect the flow-ecology relationships within river systems, has become a hot issue in the study of how to better manage water resources and protect riverine ecosystems (Mezger *et al.* 2021). Relevant experts and scholars have performed numerous studies on ecological flow assessment over time, and many methods have emerged, which have mainly been differentiated into hydrological methods, hydraulic methods, habitat simulation methods, etc. (Jowett 1997; Ahmadi-Nedushan *et al.* 2010; Pastor *et al*. 2014; Bussettini & Vezza 2019).

The hydrological method is widely used because of the availability of hydrological data (Hughes & Hannart 2003), included in, Tennant, Texas, etc., and it is considered as the simplest approach (Li & Xu 2012; Bussettini & Vezza 2019). But the obtained ecological flow value is small and can only support the short-term basic survival of fish and other aquatic organisms (Zou & Wang 2007). The hydraulic method measures the changes in simple hydraulic variables of single sections of a particular river, to substitute habitat factors known or assumed to be target biological limiting factors, aimed at determining the minimum or preservation flows required (Caissie & El-Jabi 2003; McDonough *et al.* 2017), the wetted perimeter and R2-Cross method are widely employed. In the case of complete filed data, more detailed hydraulic data can be provided for the habitat simulation method (Dunbar *et al.* 1997). The habitat simulation method, the second most widely adopted method worldwide, determines ecological flow based on the hydraulic conditions required by indicator species, which includes IFIM and CASiMiR (Noack *et al.* 2013; Ma *et al.* 2020). As a natural extension of the hydraulic method, the habitat simulation method is considered a valuable tool for assessing instream flows, but it tends to be applied for targeted species and for specific life stages (Jowett & Davey 2007).

To obtain a more reasonable ecological flow, it is important not to rely on only one method, but rather on the best available knowledge pertaining to all instream flow approaches (Caissie & El-Jabi 2003). Hence, the combined approach is adopted to evaluate ecological flow, such as the combination of two or more methods of hydrological, hydraulic, and habitat simulation (Zhao *et al.* 2020), aimed at providing a more suitable physical habitat for aquatic organisms.

With the increasing awareness of ecological protection, we should not only pursue efficient utilization of water resources and maximization of economic benefits for the numerous water conservancy projects in the Upper Yellow River, but also pay attention to the protection of the health and sustainability of river ecosystems. In the proposed C hydropower stations, native fish were considered as indicator species of the reach downstream of the dam for ecological conservation through field surveys. The 2D shallow water model with high-efficiency and high-resolution, the ecological flow calculation methods combined with Tennant, the hydraulics method, and habitat suitability model were applied. Habitat conditions, such as hydraulics, flow patterns, and river morphology of the reach during non-spawning periods and effective habitat areas of native fish during the spawning period under different discharges were analyzed. Through the detailed analysis, a more reasonable and suitable minimum ecological flow downstream of the dam was obtained to construct and develop eco-friendly hydropower projects.

2. MATERIALS AND METHODS

2.1. Study site

To further develop the rich hydropower resources in the Upper Yellow River, the C hydropower station is proposed to be built at the junction of Xinghai County and Guinan County, Hainan Prefecture, Qinghai Province. This hydropower station is about 75 km away from Banduo hydropower station and is connected to Longyangxia hydropower station about 100 km away downstream, the regulated storage of which is 239 million m^3. The area where the proposed dam site of C Hydropower

Station is located has an average annual temperature of 2.3 °C, an average annual precipitation of 403.8 mm, and an average altitude of 2,625 m. While this area is involved in the Sanjiangyuan National Nature Reserve of China, the development of hydropower resources should be based on ecological environment protection and reasonable development. The reach downstream the dam of C hydropower station is mainly composed of two wide valleys upstream and downstream of Yehuxia Gorge and is the main habitat and breeding area of native fish on the plateau. To protect the habitats of native fish and unique fish on Qinghai plateau, and alleviate the impact of hydropower project on fish resources and the aquatic ecological environment, it is vital to determine the reasonable minimum ecological flow after the completion of the hydropower station. The location of the study area is shown in Figure 1.

2.2. Survey on aquatic ecological environment

The survey results of fish resources in 2017 are shown in Table 1. It is found that most native fish belong to the key protected aquatic wildlife and the economic fish species in Qinghai province, some fish resources are vulnerable or endangered. Meanwhile, it can be seen from Table 1 that the native fish resources captured are large in the study area, among which *Gymnocypris eckloni* and *Triplophysa siluroides* are the dominant species. As a natural fish spawning ground, the typical habitat characteristics of Yehuxia spawning ground are shown in Figure 2. This figure shows that the river bed is wide and shallow, gentle water flows, the substrate is gravel and sand, which indicates habitat conditions of the reach are suitable for native fish spawning. Thus, native fish can be taken as indicator species of ecological conservation.

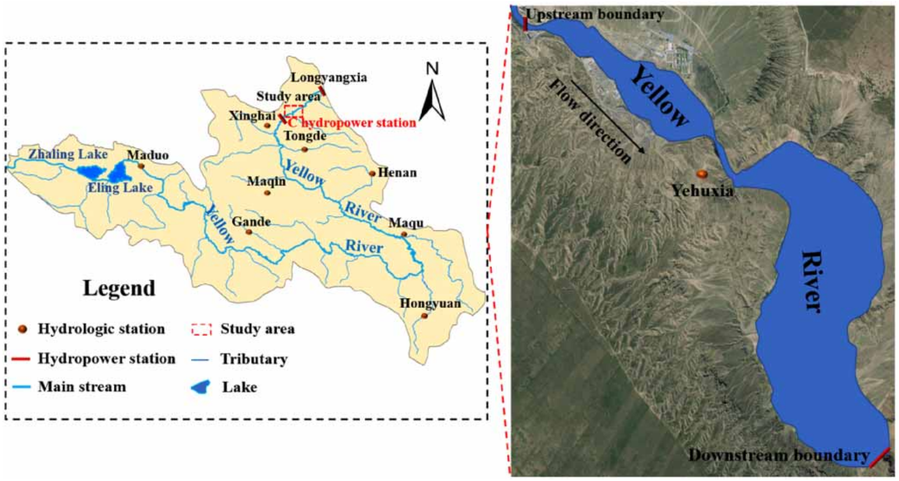


Figure 1 | Location of the study area.

Table 1 | Statistical investigation of native fishery resource in 2017

		Site (tails)	
Family	**Species**	**Downstream of the dam**	**Study area**
Cyprinidae	*Gymnocypris eckloni*	259	137
	Acanthogobioguentheri	54	99
	Platypharodonextremus	6	48
	Gymnodiptychuspachycheilus	1	–
	Schizopygopsispylzovi	29	62
	Chuanchialabiosa	6	33
	Triplophysa siluroides	168	47
Cobitidae	*Triplophysa pseudoscleroptera*	101	68
	Triplophysa pappenhaimi	10	36

Figure 2 | Typical habitat characteristics of Yehuxia spawning ground.

2.3. Numerical models

2.3.1. 2D Shallow water model

The 2D shallow water model, called the GPU-accelerated surface water flow and associated transport model (GAST), is adopted in this paper, in which the kinetic and turbulent viscous terms, wind stresses, and Coriolis effects are neglected (Liang & Borthwick 2009). The cell-centered finite volume (CCFV) method of the Godunov scheme is applied to solve this model (Hou *et al.* 2014). In addition, GPU high-speed parallel computing based on CUDA architecture is introduced into the model to improve the calculation efficiency (Yang *et al.* 2021). The governing equations in a matrix form of the model can be written as,

$$\frac{\partial \boldsymbol{q}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} + \frac{\partial \boldsymbol{G}}{\partial y} = \boldsymbol{S} \tag{1}$$

$$\boldsymbol{q} = \begin{bmatrix} h \\ uh \\ vh \end{bmatrix}, \ \boldsymbol{F} = \begin{bmatrix} uh \\ u^2h + gh^2/2 \\ uvh \end{bmatrix}, \ \boldsymbol{G} = \begin{bmatrix} vh \\ uvh \\ v^2h + gh^2/2 \end{bmatrix}$$

$$\boldsymbol{S} = \boldsymbol{S}_b + \boldsymbol{S}_f = \begin{bmatrix} 0 \\ -gh\partial z_b/\partial x \\ -gh\partial z_b/\partial y \end{bmatrix} + \begin{bmatrix} 0 \\ -C_f u\sqrt{u^2+v^2} \\ -C_f v\sqrt{u^2+v^2} \end{bmatrix} \tag{2}$$

where t is the time, s; x and y are the $x-$ and $y-$direction coordinates, respectively; q is the vectors of flow variables; F is the $x-$direction fluxes; G is the $y-$direction fluxes; S is the source vector, which includes bed slope source S_b and friction source S_f. h is the depth of water, m; u, v are the velocity in the $x-$ and $y-$directions, respectively, m/s; z_b is the bottom elevation of the river bed, m; C_f is the bed roughness coefficient, $C_f = gn^2/h^{1/3}$, in which n is the Manning coefficient, and g is the gravitational acceleration, $\mathrm{m/s^2}$.

2.3.2. Combined approaches

The Tennant method is representative of hydrological methodology often used as preliminary flow targets (Tharme 1997; Dunbar *et al.* 1998). In this paper, the minimum ecological flow 10% the mean annual flow considered to maintain survival habitat for aquatic biota in the Tennant method as a preliminary flow target to provide the basis for other methods. Meanwhile, an assumed direct relation between hydraulic characteristics and fish habitat, wetted perimeter, and R2-Cross method are considered to achieve basic hydraulic parameters, flow pattern, and river morphology of cross-section during non-spawning periods, thus further reflecting habitat availability of target fish throughout the life cycle. Besides, based on IFIM, the habitat suitability method considering the habitat suitability index (HSI) is developed. A composite suitability index (CSI) and a weighted used area (WUA) are obtained (Yi *et al.* 2014; Ma *et al.* 2020). The details are as follows:

$$\mathrm{CSI}(\mathrm{DHSI}_i, \mathrm{VHSI}_i, \mathrm{SHSI}_i) = \min(\mathrm{DHSI}_i, \mathrm{VHSI}_i, \mathrm{SHSI}_i), \tag{3}$$

$$\mathrm{WUA} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{CSI}(\mathrm{DHSI}_i, \mathrm{VHSI}_i, \mathrm{SHSI}_i) \times A_i, \tag{4}$$

where i is the number of control cell; A_i is the area of control cell i, m^2; DHSI$_i$, VHSI$_i$, SHSI$_i$ are the suitability indices of water depth, velocity, the substrate in the control cell i, respectively, which are from 0 to 1; CSI is the comprehensive habitat suitability index, which is a value between 0 and 1.

2.4. Numerical models

2.4.1. Discharges and water levels

According to the statistical analysis of the runoff series from 1919 to 2016, the mean annual runoff at the dam site of C hydropower station is 629 m^3/s and the average annual discharge of the low flow year is 424 m^3/s. The Tennant method is applied to propose the recommended minimum ecological flow with fixed percentages based on the average annual flow of 629 m^3/s. Combined with the measured flood surface line survey, the downstream water levels of the study reach under the corresponding discharges are obtained by interpolation, as shown in Table 2.

In addition, the measured water levels and the simulated water levels under the flow of 636 m^3/s were used to select the comprehensive roughness, as shown in Figure 3. When the roughness is 0.040, the simulated water levels were in good agreement with the measured, so the comprehensive roughness is determined to be 0.040.

2.4.2. Indicator species and their key factors

Under natural conditions, the main breeding period of *Gymnocypris eckloni* and *Acanthogobioguentheri* is from May to June, and that of *Triplophysa* is from late March to early June, April to May for breeding peak. It can be seen that the main spawning periods of native fish are mainly concentrated in May and June. Based on the field investigation, the suitable water depth and velocity for spawning and reproduction of native fish were determined. Meanwhile, the main substrate in this reach is a fine particle, such as medium-sized pebbles and sand gravel, which are suitable for most native fish to spawn. Hence, native fish are taken as the indicator species and May is selected as the spawning period, and water depth, velocity, and substrate as the key influencing factors in this paper. Based on the definition of the HSI (Yi *et al.* 2014), the suitability curves of water depth and velocity for native fish in the spawning period are determined, as shown in Figure 4. The main substrates are suitable for most native fish spawning, and the substrate suitability index is 1.0.

Table 2 | Proposed flows and corresponding downstream water levels

Discharges (m^3/s)	Percentage (%)	Water levels (m)	Discharges (m^3/s)	Percentage	Water levels (m)
62.9	10.0	2,576.349	106.9	17.0	2,576.676
75.5	12.0	2,576.433	125.8	20.0	2,576.678
87.5	14.0	2,576.533	424.0	67.4	2,579.070
94.4	15.0	2,576.581	629.0	100.0	2,580.247

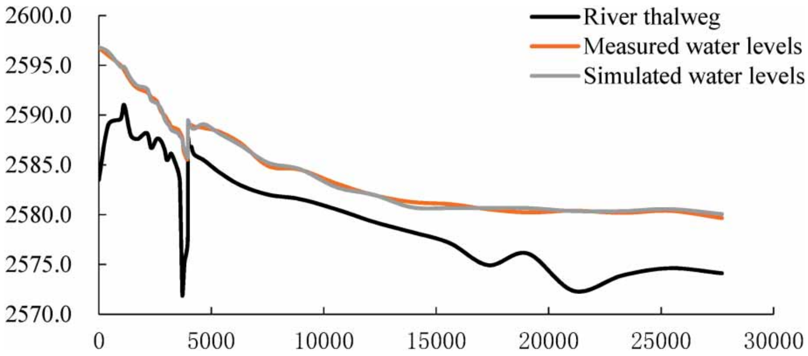


Figure 3 | Comparison between simulated and measured water levels in the study area.

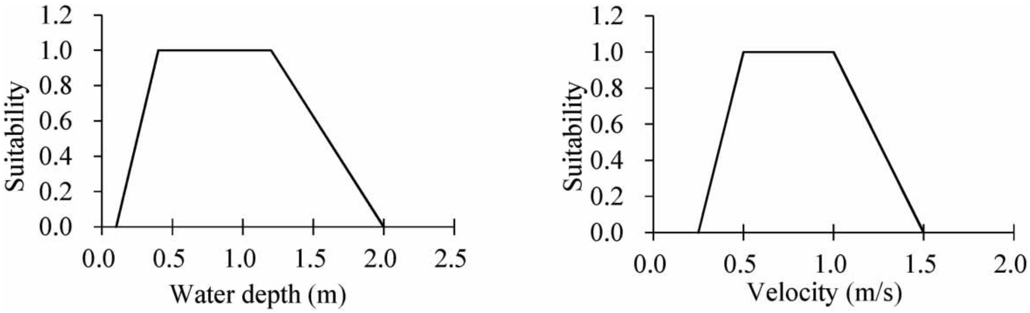


Figure 4 | Suitability curves of major habitat factors.

2.4.3. Criteria for hydraulic parameters suitable habitat for fish based on the surveys

Through the field surveys of the habitat status of native fish under natural conditions, the cross-sectional hydraulic parameters are studied, to pay attention to the non-spawning habitat conditions of native fish. According to the living habits of native fish on the plateau, species, body length, feeding reproductive habits, etc., as well as the preferred flow pattern of fish, it is found that cross-sectional basic hydraulic parameters, such as maximum water depth H_m, average water depth H_a, average velocity V_a, water width B, discharge section area A, and wetted perimeter W, have a certain impact on fish habitats. Meanwhile, the flow pattern can be divided in detail into rapids ($\geq$1 m/s), relatively rapids (0.5–1 m/s), relatively tranquil (0.3–0.5 m/s), and tranquil flow ($<$0.3 m/s) based on the cross-sectional average velocity. Furthermore, on the basis of field observation and judging by the cross-sectional maximum water depth, pool and riffle are identified. When the cross-sectional maximum water depth is greater than 10 m, it is considered as a pool. While the maximum water depth is less than 0.5 m in the range of 5 m, and the bank slope near the river is less than 10°, it is treated as a riffle.

Generally, the cross-sectional maximum water depth should be considered as 2–3 times the total length of fish (the longest fish is 46.2 cm) to meet the swimming and survival requirements of the longest fish. So the maximum water depth is greater than 1.4 m. Through the field survey and analysis, compared with the average annual discharge of 424 $\mathrm{m^3/s}$ in low flow years, minimum standards for other hydraulic parameters, flow form, and river morphology for the survival of native fish are acquired, as shown in Table 3. Here, the water surface area radio φ is the percentage of the cross-sectional water surface area at a certain discharge to the discharge of 424 $\mathrm{m^3/s}$. Meanwhile the wetted perimeter percentage M_w is the percentage of the cross-sectional wetted perimeter at a certain discharge to the discharge of 629 $\mathrm{m^3/s}$. The number of cross sections M with the rapid and relatively rapid flows and the number of cross sections with riffle M_r are also considered.

Table 3 | Minimum requirements for basic hydraulic parameters, flow form, and river morphology required by native fish of the cross sections in the reach

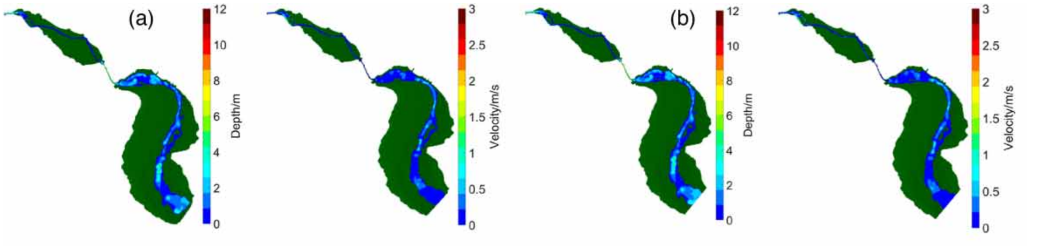
Habitat parameters	Standard	Percentage of minimum river reach
H_m (m)	$\geq$1.4	95%
H_a (m)	$\geq$0.5	95%
V_a (m/s)	$\geq$0.3	95%
B (m)	$\geq$30	95%
M_w (%)	$\geq$50	95%
A ($\mathrm{m^2}$)	$\geq$30	95%
φ (%)	$\geq$70	100%
M	No obvious change	Reduction rates of river lengths with rapids and relative rapids $<$20%
M_r	No obvious change	100%

3. RESULTS AND ANALYSIS

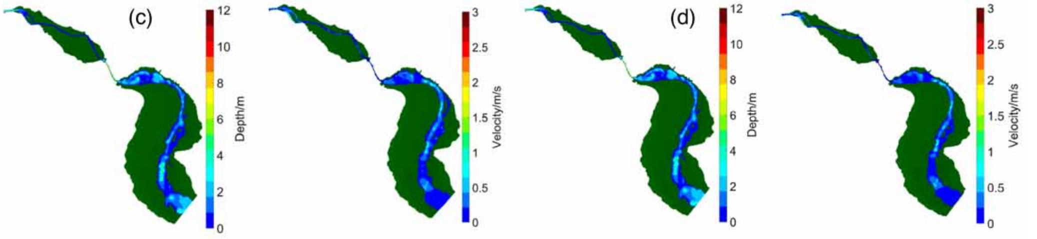
3.1. Ecological flow during the non-fish spawning period

3.1.1. Basic hydraulic parameters

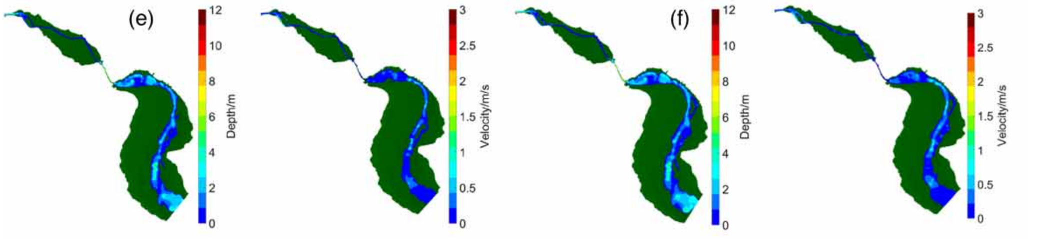
The distribution of water depth and velocity in the study area under different discharges was obtained by the 2D shallow water model, as shown in Figure 5 and Table 4. As can be seen from Figure 5 and Table 4, the average water depth $\bar{h}$ and velocity $\bar{v}$ increased with the discharge increasing. While when the proposed discharges were from 62.9 to 125.8 m^3/s, water flows were mainly distributed in the main channel, and there was little difference in the variation of water depth and velocity.



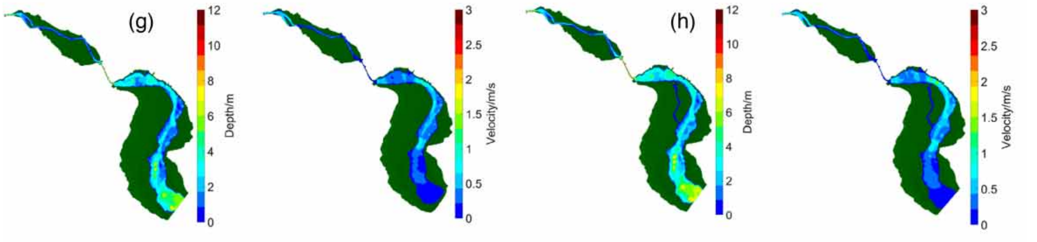
Discharge of 62.9 m^3/s Discharge of 75.5 m^3/s



Discharge of 87.5 m^3/s Discharge of 94.4 m^3/s



Discharge of 106.9 m^3/s Discharge of 125.8 m^3/s



Discharge of 424 m^3/s Discharge of 629 m^3/s

Figure 5 | Distribution of water depth and velocity under different discharges. (a) Discharge of 62.9 m^3/s. (b) Discharge of 75.5 m^3/s. (c) Discharge of 87.5 m^3/s. (d) Discharge of 94.4 m^3/s. (e) Discharge of 106.9 m^3/s. (f) Discharge of 125.8 m^3/s. (g) Discharge of 424 m^3/s. (h) Discharge of 629 m^3/s. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2022.136.

Table 4 | Average water depth and velocity in the study area under different discharges

Discharges (m^3/s)	$\bar{h}$ (m)	$\bar{v}$ (m/s)	Discharges (m^3/s)	$\bar{h}$ (m)	$\bar{v}$ (m/s)
62.9	0.814	0.102	106.9	0.946	0.130
75.5	0.839	0.113	125.8	1.066	0.131
87.5	0.887	0.122	424.0	1.898	0.205
94.4	0.908	0.125	629.0	2.204	0.242

Moreover, basic hydraulic parameters of the selected cross sections of the study reach were calculated through the hydraulic method. According to the calculation results, the percentages of cumulative river length conforming to the standards are analyzed statistically (see Table 5). Combined with Table 3, it can be seen that at the discharge of 62.9 m^3/s, the cumulative river length ratio that meets the minimum standard of cross-sectional maximum water depth, average water depth, average velocity, and wetted perimeter percentage was 92.12, 93.76, 93.83, and 93.43%, respectively. Because these percentages should not be less than 95% as required, it showed that the above cross-sectional hydraulic parameters did not meet the requirements at this discharge. While the discharge is 75.5 m^3/s, all basic hydraulic parameters met the requirements of minimum standard and the proportions of cumulative river length. As the discharge increased, all basic hydraulic parameters were also suitable for native fish.

3.1.2. Flow pattern and river morphology

Based on the cross-sectional average velocity, the number of cross sections, and the cumulative river lengths with different flow patterns, the number of cross sections of riffles under different discharges were counted, as shown in Tables 6 and 7. Compared with the discharge of 424 m^3/s in the low flow year, it could be seen that when the discharge was greater than 62.9 m^3/s, the reduction rates of cumulative river lengths with rapids and relatively rapids flow were less than 20%, and the number of cross sections of riffle did not much vary. Thus, it was concluded that flow pattern and riffle habitat suitable for survival of native fish in the non-spawning periods could be satisfied when the discharge was greater than 62.9 m^3/s.

Table 5 | Statistical results for cross-sectional basic hydraulic parameters in the reach

	Ratio of river reach of habitat parameters (%)						
Discharge (m^3/s)	H_m	H_a	V_a	B	M_w	A	φ (%)
62.9	92.12	93.76	93.83	96	93.43	100	75.1
75.5	96.27	98.24	96.23	97	100	100	78.8
87.5	98.64	99.35	98.63	98.90	100	100	78.8
94.4	100	100	100	100	100	100	78.8
106.9	100	100	100	100	100	100	85.8
125.8	100	100	100	100	100	100	87.2

Table 6 | Flow patterns of the study reach under different discharges

		Discharge (m^3/s)					
Flow pattern		62.9	75.5	87.5	94.4	106.9	125.8
Rapids and relatively rapids flow	M	10	11	11	11	12	12
	River length (km)	7.16	7.91	7.91	7.91	8.55	8.55
	Reduction rates of river lengths	12.86	5.92	5.92	5.92	0	0

Table 7 | River morphology of the study reach under different discharges

River morphology		Discharge (m^3/s) 62.9	75.5	87.5	94.4	106.9	125.8
Riffles	M_r	3	2	2	2	2	1

3.2. Ecological flow during the fish spawning period

3.2.1. Comprehensive habitat index distribution

CSI distributions of the study area under the proposed discharges are shown in Figure 5. The CSI was classified into high (0.6–1.0), medium (0.4–0.6), low (0.2–0.4), poor (0–0.2), and no habitat (0) through blue and cyan, green, yellow, red and no color to display, respectively. As can be seen from Figure 6, under the discharges from 62.9 to 125.8 m^3/s, the effective spawning habitats of native fish were mainly concentrated in the reach close to the dam site and the downstream reach of Yehuxia Gorge. The spawning habitat quality of the lower reaches of Yehuxia was higher in the center of the river, but was worse near a river bank or even no longer existed, while it was higher near the right bank of the river close to the dam site. As the discharges increased, the distribution regions of the spawning habitat reach had been expanded, especially when the discharge was greater than 87.5 m^3/s.

3.2.2. Effective habitat area

To further obtain the change law of effective spawning habitat area, the weighted used areas being suitable for native fish spawning were calculated under different discharges. The Yehuxia spawning ground is divided into parts: the spawning ground upstream and downstream. The spawning ground of Yehuxia downstream becomes the concentrated spawning ground of native fish due to favorable current conditions. The weighted used areas of the study reach and the concentrated spawning reach were achieved under different discharges, as shown in Table 8. Based on the results, the trends of effective habitat areas of both the entire study reach and the concentrated spawning reach in spawning periods under different discharges are shown in Figure 7.

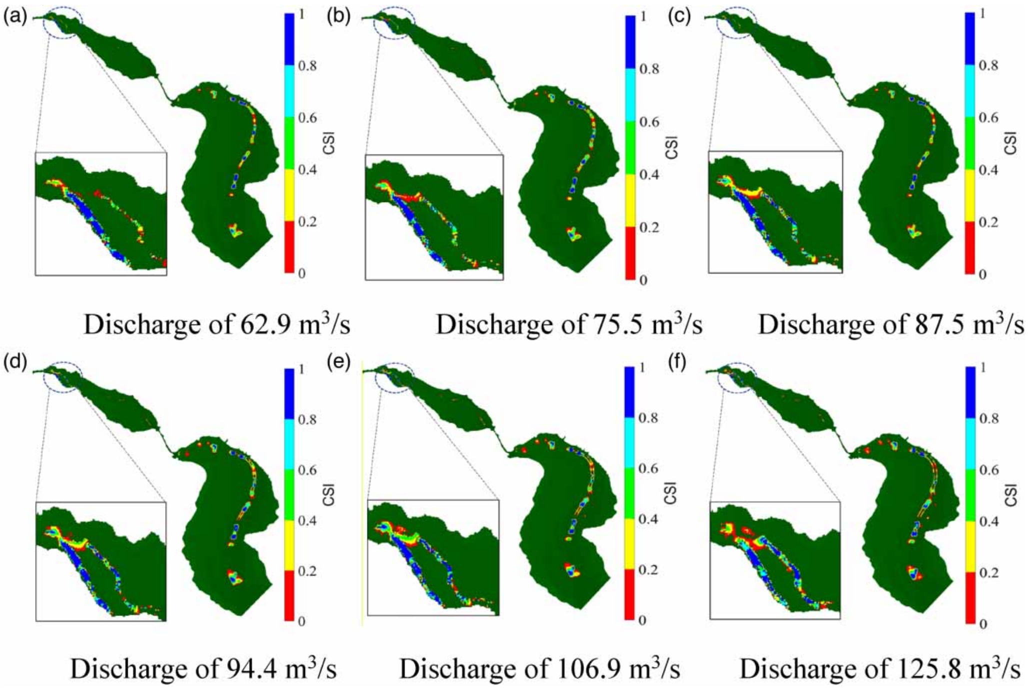


Figure 6 | CSI distribution of the study reach under different discharges. (a) Discharge of 62.9 m^3/s. (b) Discharge of 75.5 m^3/s. (c) Discharge of 87.5 m^3/s. (d) Discharge of 94.4 m^3/s. (e) Discharge of 106.9 m^3/s. (f) Discharge of 125.8 m^3/s.

Table 8 | WUA of native fish in the study area in the spawning periods

	WUA (m^2)			WUA (m^2)	
Discharge (m^3/s)	**Concentrated spawning reach**	**Study reach**	**Discharge (m^3/s)**	**Concentrated spawning reach**	**Study reach**
62.9	172298.524	190778.787	377.4	241436.952	289484.484
75.5	205203.479	228152.155	424.0	250023.551	300262.386
87.5	235618.487	262836.598	503.2	264601.299	322659.074
88.1	238219.931	265645.613	527.0	251392.181	308168.158
94.4	239097.771	268611.979	629.0	212664.332	260676.295
106.9	241010.275	274832.225	943.5	139022.662	170405.064
125.8	239258.200	272251.235	1258	113212.621	138760.886
251.6	233042.334	265170.147	377.4	241436.952	289484.484

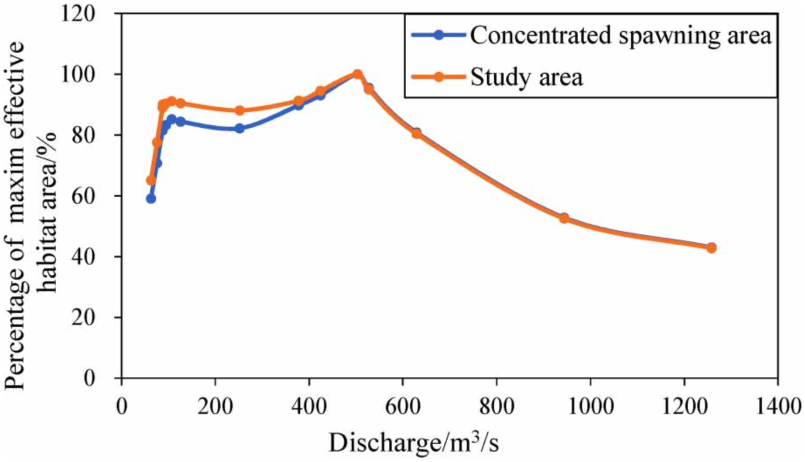


Figure 7 | Trends of effective habitat area under different discharges in the spawning periods.

As can be seen from Table 8 and Figure 7, at low discharge, effective habitat areas both in the concentrated spawning reach and the entire study reach began to increase with the increase of discharge. When the discharge increased to a certain value, effective habitat areas decreased to some extent with the continuous increase of the discharge. Then, it began to increase again and showed a decreasing trend after reaching the maximum values as the discharge further increased. Combined with hydraulic parameters of several sections obtained by the hydraulic method, it was found that the reason for this phenomenon was the existence of some pools and riffles in the study reach, affecting the flow conditions. Thus, it was indicated that pool and riffle had a certain impact on fish habitat. Table 8 shows that when the discharge was 503.2 m^3/s, the effective habitat area (WUA) suitable for spawning and breeding of native fish has reached its maximum, which was 322,659.074 m^2 in the study reach and 264,601.299 m^2 in the concentrated spawning reach, respectively. It showed that the physical habitat of river is very suitable for fish spawning under this discharge.

Meanwhile, according to the results in Table 8, the percentages of effective habitat areas under different discharges were calculated based on the maximum effective habitat area. It can be seen from Figure 7 that when the discharge was 87.5–629 m^3/s, the effective habitat area of the whole study reach accounted for more than 80% of the maximum. In which, the effective habitat area of the concentrated spawning reach also reached more than 90% when the discharge was 87.5–139 and 338–562.5 m^3/s, which put the spawning and breeding habitat of native fish in a better state.

4. CONCLUSION

To realize the sustainable development of river ecosystems, the exploitation of hydropower resources should take into account water ecological protection and include reasonable planning. In this paper, for the proposed C hydropower stations of the Upper Yellow River, the 2D shallow water model and ecological flow calculation methods combined with Tennant, hydraulics method, and habitat suitability model were applied to focus on the impact of hydropower development on the survival and reproduction of native fish in the study reach. The habitat conditions of the reach considering fish survival during non-spawning periods and effective habitat areas of native fish during spawning periods under different discharges were analyzed. Through detailed analysis, the following conclusions can be drawn:

I. Based on the standards of cross-sectional habitat conditions obtained from field surveys that meet the survival requirements for native fish, the ecological flow downstream of C hydropower station should be greater than 75.5 m^3/s to be suitable for native fish survival during non-spawning periods.
II. Under the proposed discharges, the effective spawning habitats of native fish are mainly concentrated in the reach close to the dam site and the downstream reach of Yehuxia Gorge. The trends of the weighted used areas of the study reach and the concentrated spawning reach were consistent and showed double peaks with the increase of the discharge. Combined with the hydraulic parameters of several sections obtained by the hydraulic method, it was found that this was due to the wide and shallow river, and the existence of some pools and riffles, which affect the flow conditions.
III. The effective habitat area of the entire study reach accounting for more than 80% of the maximum at the discharge was 87.5–629 m^3/s, while the effective habitat area of the concentrated spawning reach even exceeded 90% when the discharge was 87.5–139 and 338–562.5 m^3/s, fish habitat can maintain a better state under these conditions.

To sum up, the ecological flow downstream of C hydropower station should be greater than 87.5 m^3/s to be suitable for the breeding and survival of native fish in whole life stages. Thus, it is suggested that the suitable minimum ecological flow was 87.5 m^3/s to construct and develop the eco-friendly hydropower projects, and to take into account the health and sustainable development of water ecology while meeting human needs. This result not only provides basic data for the optimal operation of C hydropower station based on ecological response but also has important ecological significance for the protection of native fish habitat in the Yellow River Basin.

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AUTHORS' CONTRIBUTION

Conceptualization and Methodology: L.Y., J.H., Y.T.; Software: L.Y., J.H.; Validation: L.Y., Y.T., P.W., C.S.; Formal analysis: L.Y., J.H., P.W., L.C.; Investigation: Y.L., J.L., S.X.; Data Curation: P.W., L.C., C.S.; Writing – original draft, Writing – review and editing: L.Y., J.H., Y.T.; Funding acquisition: J.H.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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