Ecological hydrograph based on *Schizothorax chongi* habitat conservation in the dewatered river channel between Jinping cascaded dams

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Hydropower development changes the river hydrological regime, thereby altering river ecosystem significantly. One important measure for reducing degradation of ecosystem is to determine ecological flow and implement it by reservoir operation. This paper described a method to calculate river ecological flow based on fish habitat conservation and applied it to Jinping River Bend of Yalong River. *Schizothorax chongi* was selected as target species, and the fish habitat model coupling with water environmental model was developed according to the relationship between fish and water environment factors. Moreover, improved hydraulic habitat suitability index (IHHS) and habitat fragment index (HFI) varying with discharge were discussed in this paper. Habitat area representing average annual flow was taken as a reference, and then ecological hydrographs under different habitat conservation levels were calculated considering season variation and life stages of fish. Compared to the natural condition, the model results indicated that the reservoir operation clearly influenced the habitat of the target fish. It was proposed to ensure flow releases to maintain 70%–90% habitat in section after joint while about 60% before joint.

river habitat, habitat assessment, ecological flow, ecological hydrograph

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1 Introduction

Although hydropower is renewable, hydropower dams inevitably make complex and profound ecosystem-wide changes in downstream rivers [1–3]. The major negative influences from hydropower development are as follows: To alter downstream flow regime [4–6] and physicochemical property [7–10], to destroy ecological structure and function [11, 12], and to change regional climate [13, 14] and river ecosystem [15–17].

Among those negative aspects, the deterioration of river

ecological structure and function by dams are drawing more attentions [4, 6, 7, 18–23]. In 2009, essential tasks for river ecosystem recovery were proposed by Dong [24], including flow and water quality improvement, river morphological features and species restoration. Whereas meeting ecological water requirement of rivers is the basis for river ecosystem recovery [25].

Ecological water requirement of rivers was portrayed first by the United States Fish and Wildlife Service in 1940s to prevent river ecosystem from deterioration. Since then, researchers have carried on a large amount of studies on river ecological flow from different angles and against different types of rivers. General and narrow concepts of eco-

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logical water requirement were proposed [26]. In addition, plenty of papers which have outlined series methods for calculating ecological water requirement were published [27–57].

There are lots of methods for calculating ecological flow, which could be classified as hydrology and hydraulics methods, integrated methods and habitat methods. Hydrology and hydraulics methods [27–34] are easy to use, which emphasize on relationship between river physical characters and discharge, but are lack of consideration on species response to hydrology and hydraulics factors. Integrated methods [36, 37] are based on entire river functions, which are more specific with complicated factors, furthermore, more human impacts are introduced into evaluation through experts experience on flow diversion. Habitat methods [38–48] consider both flow environment and biological process, and define ecological water requirement by aquatic organism reacting to water environmental factors. Although they require more data on monitoring, this would no longer be a problem with the development of advanced survey technology.

Habitat methods for ecological flow calculation, which correlate hydrology, hydrodynamic, physiognomy factors and species preferences, are used to simulate correlations of habitat variation and discharge, and then to determine the proper ecological water requirement. They are not only more meaningful in ecology than hydrology and hydraulics methods, but also easier and more objective than integrated methods, and have already achieved good results in practice [58].

Fish is the climax community in river ecosystem. It could be affected by water environment, and has influence on the structure and function of water ecosystem [59, 60] in return. Therefore, fish habitat study is effectual and objective for evaluating river healthy. Still, there are some shortages in ecological water requirement calculation based on river habitat: First, only the correlation between discharge and habitat area is established, in which habitat quality is ignored. Second, the results of ecological flow are usually single valued and no ecological meaning is reflected. Aiming at problems above, a new habitat method for calculating ecological flow is established in this paper, considering habitat suitability and fragment, seasonal water environment factors and life stages of fish.

2 Model development

This paper proposes a method for calculating ecological flow based on fish habitat conservation, including to set up fish habitat model, to establish relationship between habitat and discharge, to calculate ecological flow considering hydrological seasonal variation and life stage of fish, and finally, to recommend proper ecological flow.

2.1 Fish habitat model

The suitability between target fish and water environment is set up in the fish habitat model. The input parameters are physics-chemistry factors of water environment, while the output is habitat suitable index (*HSI*) [61]. The governing equations of water environmental model, whose results are used as the input to the habitat model, are as follows:

$$\frac{\partial H}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = Q_a, \quad (1)$$

$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = & -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + f_v + v \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\ & + \frac{1}{\rho_0 H} \tau_x, \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = & -\frac{1}{\rho_0} \frac{\partial p}{\partial y} - f_u + v \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \\ & + \frac{1}{\rho_0 H} \tau_y, \end{aligned} \quad (3)$$

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + S + f_R(c, t), \quad (4)$$

where Q_a is the discharge or withdrawal, m^3/s ; H is the water level, m ; u and v are the velocities in x and y directions, m/s ; ν is the horizontal eddy viscosity coefficient, m^2/s ; f is the Coriolis parameter; τ_x and τ_y are the bottom shear stresses, N/m ; c is the concentration, kg/m^3 ; D_x and D_y are the disperse coefficients, m^2/s ; S is the source or sink term, and $f_R(c, t)$ is the reaction term.

In this paper, water temperature is taken into account, and is related to solar radiation and the heat exchange between air and water in the channel, and then, $f_R(c, t)$ in eq. (4) is rewritten to dT/dt :

$$\frac{dT}{dt} = \frac{\varphi}{\rho C_p h}, \quad (5)$$

$$\varphi = \varphi_s - \varphi_e - \varphi_c, \quad (6)$$

$$\varphi_s = \varphi_{so} (1 - \gamma) (1 - 0.65C^2), \quad (7)$$

$$\varphi_e = \beta f(W) (T_s - T_d), \quad (8)$$

$$\varphi_c = 0.47 f(W) (T_s - T_a), \quad (9)$$

where φ is the heat flux to stream, W/m^2 ; ρ is the water density, g/m^3 ; C_p is the specific heat of water, J/(kg K) ; h is the water depth, m ; φ_s is the total solar radiation, W/m^2 ; φ_{so} is the clear-sky total solar radiation, W/m^2 ; γ is the reflectivity of water surface, usually is 0.03; C is the clouds cover; $f(W)$ is the function of wind, $f(W) = 9.2 + 0.46W^2$; W is the wind speed above 10 m of water surface, m/s ; T_s is the tem-

perature of water surface, K; T_d is the temperature of dew-point, K; $\beta=0.35-0.015T+0.0012T^2$, $T=(T_s+T_d)/2$; j_c is the flux of heat conduction, W/m²; T_a is the air temperature above 2 m of water surface, K.

The fuzzy logic method is used to develop the fish habitat model, using the same grid with water environment model. The main steps are follows.

① Set up membership degree function. Several means could be used in function set up, and fuzzy statistics based on fish behavior study is used in this paper. Response of fish behavior to water environment factors is studied by flume experiments [62], and then fuzzy grade classification is conducted. Expert knowledge and field data are used to adjust membership degree function in the end. For the sake of calculation, membership degree is represented by the subordinate function as shown in Figure 1.

② Define fuzzy rule set. Fuzzy rules are used to describe the relationship between input and output variables. In this paper, fuzzy rule set is defined by controlled experiments combined with expert knowledge. For example:

If 'Water temperature' is Low, and 'Velocity' is Low and 'Water depth' is High, then 'habitat (spawning) suitability' is Low.

③ Fuzzy inference. The Max-Min inference method is adapted [63], i.e.,

$$MD_o^k = \max[\min[MD_i^k], \quad (10)$$

where MD_o^k is the the output membership degree to rule k ; MD_i^k is the the membership degree of input i to rule k .

④ Defuzzification. Gravity method, which could consider more effective information, is used for defuzzification in this study [63]

$$e^* = \int_e MD(e)ede / \int_e MD(e)de, \quad (11)$$

where e is the value at the centre of mass of membership degree function.

2.2 Relationship between habitat and discharge

In order to evaluate the relationship between habitat and flow scheme, it is necessary to analyze the effectiveness,

Figure 1 Diagram of membership degree function with water temperature (L=Low suitability, M=Medium suitability, H=High suitability; WT=Water temperature, MD=Membership degree).

size, position and other information of habitat. This paper discusses the hydraulic habitat suitability and habitat fragment based on HSI for habitat patch.

① Habitat patch

Normally, life prefers living in the environment with high suitability and enough space. Within a stream, fish habitats with high HSI aggregated as a patch. If one patch could not provide enough living space for group of fish school, or far away from other patches, the area is not effective. Therefore, this paper puts forward the conception as follows.

HSI is the output from the habitat model with the value in each cell. It varies from 0 to 1, with 0 being the lowest suitability while 1 the highest [61].

HSI_{cut} : The threshold of HSI .

Habitat patch: The area where $HSI \geq HSI_{cut}$ with each adjacent cell.

Habitat patch number, n : The number of habitat patch where $HSI \geq HSI_{cut}$.

Habitat patch area, p , m²: Area of habitat patch.

② Improved Hydraulic Habitat Suitability Index, $IHHS$

Hydraulic Habitat Suitability Index (HHS) was first proposed by the US Fish and Wildlife Service [61]. However, it could cause two different HSI distribution patterns for the same HHS value: one is that all of habitat cells are with media value; another is that parts of cells are high and others are low. Actually, fish habitat aggregate in rivers, and HHS could not represent suitability effectively for habitat assessment. Therefore, $IHHS$, aiming at habitat patch, is proposed as follows:

$$IHHS = \frac{1}{A} \sum_{i=1}^n p_i HSI_i, \quad (12)$$

where, p_i is the area of habitat patch i , and A is the calculation area in habitat model, m².

③ Habitat fragment index, HFI

Habitat area per patch is one of the simple and effective indexes for habitat fragment evaluation. The smaller HFI , the more fragmented the habitat.

$$HFI_p = \frac{\sum_{i=1}^n p_i}{n}, \quad (13)$$

where HFI_p is the habitat area fragment index, and p_i is the patch area of cell i , m².

2.3 Ecological flow calculation

The results form the habitat model and the relationship between habitat and flow scheme could be used to calculate the ecological flow. In this paper, seasonal water environment factors and life stages of fish are included particularly.

① Effected by seasonal variation

The earlier study of ecological flow calculation did not

consider seasonal variation impact. As for fish in a certain stream, the influences of water environment variation caused by season have great impact on fish habitat, especially for daily activity area – feeding ground.

Hydraulic parameters and water temperature are all simulated in the habitat model, and *HSI* can be different under the same flow regime due to water temperature variation, as can be read from Figure 2. The effect on water temperature variable is the reason for curve cluster existence. It is noticed that the curves group by season. Consequently, corresponding curves should be used to calculate ecological flow requirement in different periods.

② Effected by fish life stage

In addition, the habitat method in earlier study did not consider special flow demand in life stages of fish within a whole year. This paper defines the relationship between life stages of fish and water environment factors for ecological flow calculation. The rules are listed in Table 1.

3 Study area and data collection

The study area in this paper is the channel with water reduction of Yalong River (Jingping River Bend, Figure 3) caused by cascade hydropower development in Sichuan. The length of the river bend is 152 km, while the straight distance is 20 km, the natural water head is 350 m, and the mean annual discharge of Luning hydrometric station is 1370 m³/s. Jingping I power plant is of high dam, and Jingping II is low dam downstream. Hydroelectricity will be generated by water head drop, after headrace tunnel is put into use.

Figure 2 Diagram of *HSI* responding to discharge of feeding ground.

Table 1 Regulation for flow determination

Stage	Rules
Overwintering	Based on wintering habitat, and not less than the intersection point with feeding habitat.
Spawning	Based on spawning habitat, not less than the intersection discharge with feeding habitat; and not less than the discharge of velocity curve larger than x m/s with the same proportion.
Feeding	Based on normal life condition and typical hydraulic elements in this channel.
Overwintering	Based on wintering habitat, and not less than the intersection discharge with feeding habitat.

However, it can cause 110 km channel to have water reduction, where the traditional habitat of *Schizothoracinae* is. In order to reduce the impact on river ecosystem, water requirement process of aquatic organism should be determined as a basis for eco-regulation by Jingping cascade dams.

The hydrological and meteorological data based on typical hydrological years were collected from hydrological and meteorological stations at Maomaotan, Dashuigou and Jiulong River to establish the water environmental model, including cross-section geometry, daily averaged discharge, water level, water quality parameters, wind solar radiation as well as river bend bathymetry.

Schizothorax chongi is selected as the target species after fish resources survey carried out in 2007 and 2008 [64]. It is one of the dominant species and native commercial cold-water fish in the Yalong River, living in rapid river flow and growing slowly. Its spawning season is April to July annually, when water temperature varies from 12°C to 18°C.

The absent hydrodynamic and water quality parameters were measured, and the occurrences frequency of target fish were recorded during fish resources survey. Single-factor controlled experiments under different life stages were carried out in laboratory. Finally, three dominant parameters (water depth, velocity and water temperature) were selected as the inputs of the habitat model [65].

4 Habitat model set up and validation

The inflow boundaries are at the stations at Maomaotan and Jiulong River, with daily average discharge as boundary condition. The outflow boundary is at the exit of the tunnel (Dashuigou), and the boundary condition is given by daily average water level. The water temperature on each boundary the monthly average value.

Water environmental model was calibrated by data from even year, and then validated by data from wet year (Figure 4).

Figure 3 Study area of Jingping River Bend.

Figure 4 Validation of water environmental model (Luning station wet year, Q : discharge, WT : water temperature).

It could be seen from the results that mean relative errors of discharge and water temperature are 5.4% and 9.1%, respectively. The good results prove that the model could be used to inverse and predict the water environment variation of study area.

Fish habitat model used the same calculate grid with water environment model. The output of daily average values (water depth, velocity and water temperature) form water

environmental model were used as the input of habitat model, for HSI calculation.

Fish habitat usually includes spawning ground, over-wintering ground and feeding ground. Taking the spawning ground as an example, according to the results of single-factor controlled experiment [65], the membership degree function and fuzzy rules were shown in Figure 5 and Table 2.

Taking rear section with more spawning grounds as an example, field investigations showed that there were four spawning sites in this section (Figure 6: A, B, C, D). The results illustrated that HSI in most part of the study section was larger than 0.5. The spawning sites in filed investigation were the first few regions where higher HSI value appeared, and extended during spawning time in simulation. It could be seen that simulated results were in fair agreement with field data.

5 Ecological flow calculation

The river bend was divided into two parts by joint of Jiu-long River, and ecological flows were calculated respectively. The threshold of HSI was set to 0.5 and the section after joint was taken as an example:

5.1 Relationship between habitat patch and discharge

First, the relationship between suitable area proportion to

Figure 5 Membership degree function of spawning ground (WT =Water temperature; WD =Water depth; V =Velocity).

Table 2 Fuzzy rules for the spawning ground (L=Low, M=Medium, H=High, VH=Very high)

WT	V	WD	HSI	WT	V	WD	HSI
L	L	H	L	M	M	M	VH
L	L	M	M	M	M	H	H
L	L	L	L	M	L	H	M
L	M	M	M	M	L	M	H
L	M	H	M	M	L	L	L
L	H	H	L	M	H	H	M

Figure 6 Result of habitat model (A: Qingna; B: Mianshawan; C: Jiangkou; D: Lizhuang).

entire channel and discharge was set up (Figure 7).

Figure 7 shows that the area of suitable feeding ground decreases with discharge, and the maximum proportion is about 40%. The tendency of suitable spawning and overwintering area are the same with the peak values of dis-

Figure 7 Patch area proportion to discharge after joint (top: feeding ground in summer; mid: spawning ground; down: overwintering ground; pcnt.: percentage=(Σ suitable area/total area) $\times$ 100%).

charge around 400 m³/s and 500 m³/s, respectively.

Water depth is one of the most important factors to fish, *Schizothorax chongi* prefers to live in an area deeper than 3 m in winter, and more shallow than 0.5 m when preying. A certain area with depth more than 10 m is necessary to keep flow field. Therefore, the relation between water depth and discharge also focused on those items (Figure 8).

The current is swift in Jingping River Bend, and fish living there is used to the rapid velocity field. After the project finished, the velocity in the bend decreased due to water reduction. In order to meet the velocity require for spawning and living a normal life, the relationship between velocity and discharge was studied, by dividing the velocity into four pieces: very slow, <0.3 m/s; slow, 0.3–1 m/s; fast, 1–3 m/s; fairly fast, >3 m/s. The results are shown in Table 3.

5.2 Relationship between IHHS and discharge

The paper also describes the response of IHHS to discharge for habitat patch (Figure 9). IHHS would increase rapidly at first and then decrease slowly with discharge. The corresponding discharge of the region, where IHHS is higher, is between 360–380 m³/s. Before flow increases to that region, IHHS could be significant improved.

5.3 Relationship between HFI and discharge

Figure 10 illustrates the relationship between HFI and dis-

Figure 8 Depth area proportion to discharge after joint (top: depth>10 m; mid: depth>3 m; down: depth<0.5 m; HSI $\geq$ 0.5).

Table 3 Velocity area proportion to discharge (%)

V (m/s)	20	50	100	200	500	660	1000	2000	5000
Very slow	65.5	53.3	45.1	34.8	16.6	13.1	9.8	3.6	0.6
Slow	30.3	30.9	27.5	23.6	13.6	8.9	5.6	3.0	1.6
Fast	4.2	15.8	27.1	41.0	64.5	68.5	66.3	50.5	14.6
Fairly fast	0.0	0.0	0.3	0.6	5.3	9.5	18.3	42.9	83.2

Figure 9 Relationship between *IHHS* and discharge.

charge. The variation trend is the same as *IHHS*, but would decrease rapidly after *HFI* reaches the peak value. It is indicated that *HFI* is more sensitive than *IHHS* to discharge variation within certain limits.

5.4 Recommended ecological hydrograph

Habitat area corresponding to the mean annual discharge was chosen as reference to determine ecological hydrograph (discharge of control section before and after conjunction shown in Table 4). Discharges were calculated inversely, when habitat recovery levels were 30%, 50%, 70% and 90%, respectively, following the rules in Table 1 (overwintering period is from November to December and January to February; spawning period is from April to July). The results of ecological hydrograph by habitat method are shown in Figure 11.

Comparing hydrographs of the two sections indicates that discharge requirement after conjunction for each restoration level was higher than that before. This paper met the flow demand of the section after joint as a priority because 60% habitats of *Schizothorax chongi* were there.

Figure 12 described the *IHHS* and *HFI* with different habitat conservation levels. It shows that *IHHS* increases with habitat conservation in general, but *HFI* peaks at pattern of 70%.

According to the results above, this study recommends the ecological flow patterns in Table 5. Although pattern B could preserve 90% habitat area, but the fragmentation increases obviously compared to pattern A. *IHHS* difference

Figure 10 Relationship between *HFI* and discharge.

Figure 11 Ecological flow requirement under different habitat restoration levels (top: before joint; down: after joint).

of the two patterns is slight, but *HFI* in pattern A is much better than pattern B. If pattern A is selected, according to the history data(mean annual discharge of Jiulong River is 45 m³/s in dry season), only 50 m³/s discharge from the Jin-ping II power station is required, with fairly ideal habitat reservation level (70% of the rear and about 60% of the

Table 4 Mean annual discharge by month (m³/s)

Time (mon)	1	2	3	4	5	6	7	8	9	10	11	12	
Q	Before	358	321	328	435	695	1590	2810	2590	2500	1620	809	488
	After	377	335	341	449	724	1687	2919	2743	2614	1702	849	514

Figure 12 IHHS and HFI under different habitat restoration levels.

front). It could both satisfy habitat conservation and power generation. To sum up, this study recommends pattern A as the proper ecological hydrograph.

6 Conclusions and discussion

Aiming at the influence of water reduction caused by power station regulation on water environment and fish habitat, the purpose of this study was to determine proper hydrograph based on *Schizothorax chongi* habitat conservation. The recommended discharge could meet the demands of 70%–90% habitat area afterward conjunction, and 60%–70% before that. According to this condition, 50–180 m³/s discharge was required from JinpingII power station in dry

season.

For comparison, Tennant method was used to validate the results by habitat method. It could be seen that in Figure 13, discharge of patterns A and B were both within medium and best grades of Tennant method in general, and above the very good grade in dry season. Because the water resource of Yalong River is so abundant in wet season, that recommended ecological hydrograph was lower than Tennant method in July and August. In summary, the method developed in this paper for ecological flow calculation was comparable to the traditional method, especially in dry season. However, compared to hydrology and hydraulics methods, this habitat method, considering life stages of fish and seasonal effect of water environment, is more meaningful in ecology and much more objective.

Habitat area, corresponding to monthly mean annual discharge, was chosen as reference in this study. If data are available, daily ecological hydrograph can be calculated by this method. Mean daily ecological hydrograph is without operability as constraints and objective of regulations, so that only specific life periods need to be ensured, such as high-density pulse in spawning periods in the future work.

Ecological flow is closely related to hydrologic frequency [34]. Seasonal effect of water environment was taken into account in this paper, but the variation of hydrologic frequency not yet considered. The future work will study the relationship between flow pulse within important life stage of fish (spawning period) and hydrologic frequency. It would make it more close to natural condition.

Table 5 Recommended hydrograph (m³/s)

Time (mon)		1	2	3	4	5	6	7	8	9	10	11	12
Q	A	93	87	90	238	320	440	445	448	440	410	102	101
	B	230	205	208	360	550	810	1072	1068	1068	885	254	251

Figure 13 Comparison of ecological flow between habitat method and Tennant method.

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