Study on the ecological flow process of medium-sized mountainous rivers based on hydraulic habitat protection

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Abstract. The proposal of ecological flow is of great scientific significance to conserve river biodiversity. To date, the parameters given by the Eco-hydraulics method are applicable to large rivers. The reference standard is obtained according to the hydraulic habitat parameter standard for fishes in large river and the characteristics of medium-sized mountainous rivers. It can be applied to medium-sized mountainous river and provide better protection for fish. Taking the Zagunao River as the study background, the prototype observation results prove that the reference standard is reasonable. The modified Eco-hydraulics method and the habitat simulation method were coupled to determine the ecological flow process of the Zagunao River. The ecological base flow of the river channel was 17.43 m^3/s. The proposed peak and valley values of the ecological flow process was 20.9 m^3/s and 17.43 m^3/s during the spawning period, respectively. Given the demand of fish for spawning signals, it is suggested to create 1 or 2 ecological floods before the spawning period. The ecological flow process obtained by the method due to considering the survival requirements of *Schizothorax prenanti* and the hydrological requirements of spawning, can better satisfy the spawning demand of *Schizothorax prenanti*.

1. Introduction

Providing the ecological water requirement (EWR) for fishes is one of the important constraints that need to be followed during the operation of hydropower projects on mountainous rivers. Therefore, determining the EWR process of fishes at different stages becomes an important link in the ecological protection of rivers with the development of hydropower stations [1]. Along with the ever-increasing impact of human activities on the ecological environment of rivers, more and more scholars recognize and start to pay attention to the development of EWR.

The study of river EWR starts late in China, so relatively mature theoretical methods in calculating the EWR are mainly from foreign counties. Currently, the methods widely used to calculate the EWR of river can be divided into three types [2]: 1) the hydrological method, a traditional method to calculate the EWR by using the partial runoff of the hydrological data, such as 7Q10 method [3-5] and Tennant method [6]; 2) the hydraulics method based on hydraulics, such as wetted perimeter method [7,8] and R2-Cross method [9]; 3) the habitat calculation method based on biology, such as IFIM method (Instream Flow Incremental Methodology) [10,11], CASIMIR method (Computer Aided Simulation Model for Instream Flow Requirements in Diverted Stream) [12]. However, both the hydrological method and the hydraulics method cannot clearly connect the physical characteristics and the flow of the river with the habitat selectivity characteristics. The habitat calculation method is favourable to predict the changes of the habitat quality with the flow regime. The key of this method is to combine the hydraulics model with the habitat preference, and to simulate the quantitative relationship between the flow rate and the habitat. Through further studying the IFIM method, a number of related models have emerged, such as PHABSIM model (Physical Habitat Simulation System) [13,14] and River2D model [15,16].

Besides, both the hydrological method and the hydraulic method are restricted to determine the ecological basic flow. For example, the results obtained from the Tennant method can only be used as reference in the early stage, the wetted perimeter method is not suitable for V-shaped mountainous rivers, the R2-Cross method determines relevant parameters of large and medium-sized rivers by only using several cross sections, and its representativeness is poor. In view of the advantages and disadvantages of these methods, the Eco-hydraulics method is proposed to determine the ecological base flow for large and medium-sized rivers [17]. This method takes into account the variation of the hydraulic habitat parameters of the whole river when calculating the EWR, and avoids misjudgement caused by the parameters of a certain section are on the low side, because if the proportion of this section is very small in the entire water reduction reach, the impact on fish survival is relatively small, and the effect of this section can be ignored. The calculation results are more comprehensive.

At present, the main concern and research direction during the exploitation of mountainous rivers in southwest China is maintaining the EWR for the survival of aquatic organisms (especially fishes) in the river. In theory, the Eco-hydraulics method can simulate the variation of hydraulic habitat parameters of fishes with the flow rate. Therefore, it is very suitable to determine the EWR of fishes. However, the standards for hydraulic habitat parameters of fishes are required as the basis when using this method. At present, the standards for hydraulic habitat parameters are only available for fishes in large rivers. These standards fail to take into account the actual habitat needs of every river, especially the small and medium-sized rivers. Therefore, it is necessary to revise these criteria according to the actual situation of each river before using them. In this paper, the prototype observation of the fish habitat was conducted in Zagunao River, the representative medium-sized mountainous river in Sichuan, China, to verify if the new criteria can meet the actual needs of habitat by fishes in Zagunao River.

The modified Eco-hydraulics method was used to calculate the EWR of fishes during the non-spawning at the water reduction reach on the medium-sized mountainous river. Because the Eco-hydraulics method did not fully consider the breeding habits of fish and the hydraulics demand of important habitats during spawning period, the EWR during the spawning period of fish was further determined by using the River2D model of habitat simulation method. The results of the above two methods were coupled to obtain the value of the ecological basic flow of fishes during the non-spawning period and the ecological flow process during the spawning period. By combining the biological data and the river flow, and by considering the changes of the hydraulic habitat parameters, the ecological basic flow obtained from the modified Eco-hydraulics method can better represent the EWR of fish. The habitat simulation method was used to determine the EWR of fishes during the spawning period. The ecological flow process obtained by coupling the results of two methods takes into account the basic requirement of hydrology by fishes in their life cycle, which provides adequate protection of biodiversity in medium-sized mountainous rivers. The principle of determining the EWR for maintaining the stability of aquatic ecosystem can be popularized and applied in the design of water conservancy and hydropower projects at home and abroad.

2. Materials and Methods

2.1. Research area

Located in Sichuan Province, Zagunao River is one of the secondary tributaries of Yangtse River and the second largest tributary of Minjiang River (figure 1). This river has typical mountainous river characteristics, and typical aquatic communities in Sichuan are living in this river (figure 2). The surface width of the original river course is between 24 m and 46 m. It is a medium-sized mountainous river. The Xuecheng Hydropower station (XHS) is a low gate diversion type development on the Zagunao River. The reservoir has daily regulation function.

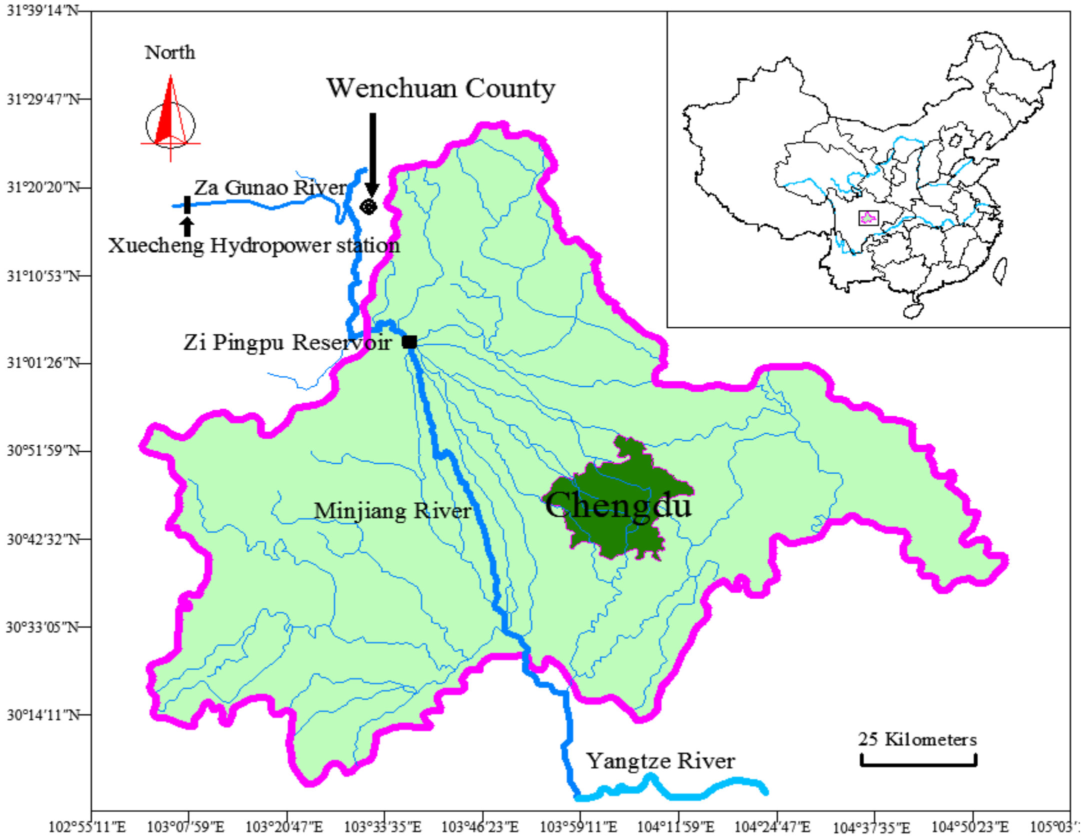


Figure 1. The position of the Zagunao River and the survey region.

(a) A12 [a] (b) A13

Figure 2. The channel conditions of Zagunao River.
[a]A12 and A13 are the two sampling sections in this study, the location of which can be seen in figure 3.

Prenant's Schizothoracin（*Schizothorax prenanti*）is a kind of benthic fish, and mainly distributed at the upstream of Yangtze River, Jinshajiang River, Minjiang River, Daduhe River, Qingyijiang River.

As the endemic species in mountainous rivers at the southwest of China, their breeding season is closely related to their living environment from March to July usually. The current is fast at the upper reach of Minjiang and its tributaries, and the water temperature is low, which is less than 10℃ from March to May,so the breeding period of *Schizothorax prenanti* living in Minjiang and its tributaries is mainly from June to July. The breeding habits of *Schizothorax prenanti* are closely related to the hydrological regime, so they are greatly affected by water reduction. Meanwhile, *Schizothorax prenanti* is the mainly protected fish species in Zagunao River. Therefore, *Schizothorax prenanti* is determined as the indicator species of fish spawning habitat quality in Zagunao River.

2.2. Sampling
The perennial average flow at the dam site of XHS on Zagunao River is provided by the management office of the power station, while the terrain information is measured on the site.

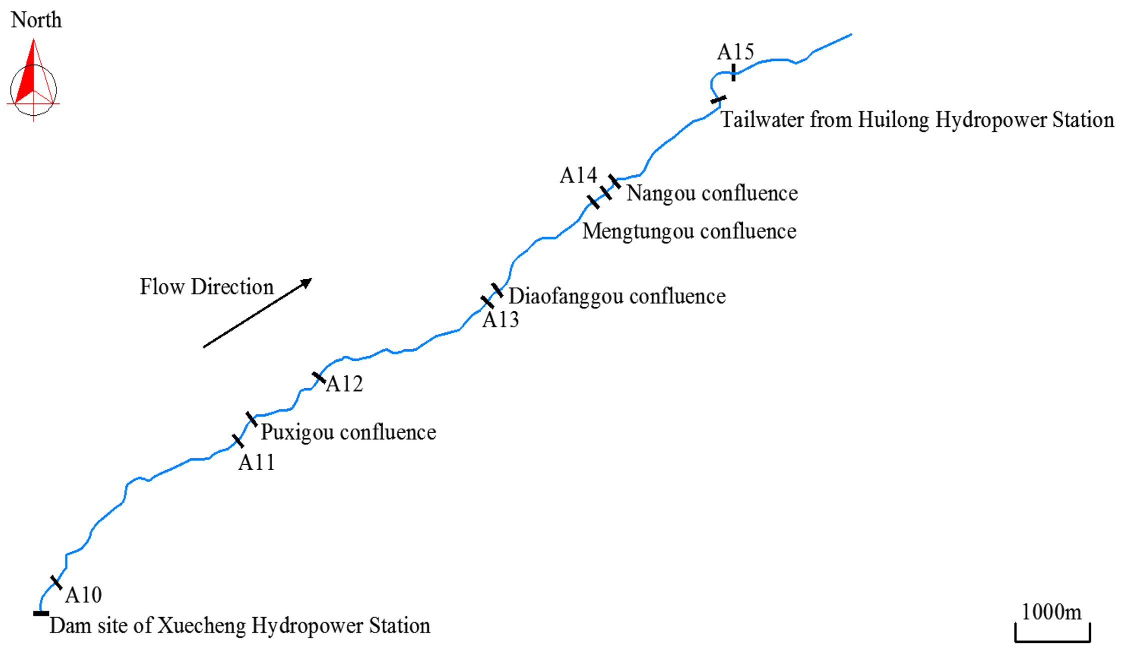


Figure 3. Sampling sections of the Zagunao River.

Table 1. Instruments used during measurement.

No.	Indicators	Instruments
1	Water depth	Depth scale
2	Velocity	Propeller speedometer
3	Section size	Electronic Total Station
4	the body length of the fish	10m round PVC soft tape
5	the body weight of the fish	Precision Electronic Balances

The development of hydropower in mountainous rivers mainly changes the hydrological regimes of the river, so water depth, flow velocity, substrate, water temperature, water surface width, and discharge area are chosen as the hydraulic parameters of the fish habitat. The prototype observation was conducted from April to May. Totally 11 observation sections (shown in figure 3) were arranged on the water reduction reach of XHS on the mainstream of Zagunao River. During observation, the flow velocity, flow rate, water depth and size of cross section were measured on the upstream and downstream control sections of the sampling reach. And then, fishes were sampled, the flow velocity and water depth at the catch position were measured, and the length and weight of captured fishes were measured on site. The hydraulic parameters were measured as follows: setting up 3 to 4 vertical lines on each section, setting the measuring point at 5 cm to 10 cm below the water line, and then calculating the section average. The measurement instruments are shown in table 1.

2.3. Construction of determination method for the ecological basic flow process based on fish spawning requirement

The Eco-hydraulics method is that the water depth, flow velocity, wetted perimeter, water surface width, discharge area, water area and water temperature are main hydraulic parameters of the habitat affecting the number and distribution of species when the flow rate changes. This method includes three modules: (1) Description of aquatic habitat of the river course, which is used to analyse the basic survival requirement of aquatic organisms for water depth, flow velocity, and other hydraulic parameters of the habitat; (2) Hydraulic simulation of the river course, which uses the hydraulics model to achieve 1D to 3D hydraulic simulation of the studied river reach, and calculates the changes of various hydraulic habitat parameters at different flow rates; (3) Determination of minimum discharge flow, which estimates the minimum discharge flow by comparing the changes of hydraulic habitat parameters with their standards. The standards for hydraulic parameters of fish habitat should be referenced when using the Eco-hydraulics method to determine the ecological basic flow of the river. There are standards for hydraulic parameters of fish habitat in large-sized rivers in the "Technical Guidelines for Environmental Impact Assessment of Ecological Water, Low Temperature Water and Fish Pass Structures in the Development of Hydropower Projects (Tentative)" (Environmental Assessment Letter [2006] No. 4) [18], as listed in table 2. According to the guideline, the standards for medium-sized rivers can be handled flexibly.

Table 2. Standards for hydraulic habitat parameters in the Eco-hydraulics method (large-sized rivers).

Habitat parameter index	Standard	
	Minimum standard	Percentage of long segment in the accumulated river reach
Maximum water depth	2 to 3 times of the body length of the fish	95%
Average water depth	≥0.3 m	95%
Average velocity	≥0.3 m/s	95%
Water surface width	≥30 m	95%
Wetted perimeter rate	≥50%	95%
Area of discharge section	≥30 m^2	95%
Surface area of water body	≥70%	
Water temperature	Suitable for fish survival and reproduction	

The standards for hydraulic habitat parameters of medium-sized mountainous rivers are revised on the basis of field investigation data from Zagunao River and Heshui River in Minjiang riverbasin, Meigu River and Xixi River in Jinsha river basins, Nanya River and Baoxing River in Dadu river basins, and other medium-sized mountainous rivers. The revised standards for hydraulic habitat parameters of medium-sized rivers are listed in table 3. The reasons of revision are as follows:

- The water surface width and the discharge area of medium-sized mountainous rivers in Sichuan are usually ≤ 30 m and ≤30 m^2 separately at natural conditions. Fishes can survive and maintain a certain amount at these conditions. Based on these facts, it is suggested that the requirements of water surface width and area of discharge section should be removed from the standard of hydraulic habitat parameters of middle mountain rivers using Eco-hydraulics method.

- The medium-sized mountainous rivers have both rapid flow and slow flow. The natural flow velocity of some rivers at the dry period cannot meet the requirement of ≥0.3 m/s. Therefore, it is suggested that if the natural flow velocity at the dry period can meet the requirement of ≥0.3 m/s all the time, the requirement of velocity in the standards of large-sized rivers can be used in the medium-sized rivers ; if not, the average velocity will not be used as the evaluation index.

Table 3. Standards for hydraulic habitat parameters in the Eco-hydraulics method (medium-sized rivers).

Habitat parameter index	Standard	
	Minimum standard	Percentage of long segment in the accumulated river reach
Maximum water depth	2 to 3 times of the body length of the fish	95%
Average water depth	≥0.3 m	95%
Average velocity	≥0.3 m/s	If this can be satisfied 100% at the dry period, it shall meet the requirement for 95% during the water reduction; if not, this item shall be not considered.
Wetted perimeter rate	≥50%	95%
Surface area of water body	≥70%	
Water temperature	Suitable for fish survival and reproduction	

The breeding habits and the important habitats of fishes are not fully considered in the Eco-hydraulics method, so the value calculated by this method can only be used as the recommended value during the non-spawning period. Results from habitat simulation method is recommended during the spawaing period.

The habitat simulation method determines the river flow process according to the simulation of hydraulic conditions of indicator species [19]. This method assumes that water depth, flow velocity, substrate and coverings are main factors affecting the number and distribution of species when the flow rate changes [20]. Through analysing the suitable requirements for water depth, flow velocity and channel index (including substrate and covering conditions) of the indicator species, the suitability curve between the preference (between 0 and 1) of fish and the environmental parameters is plotted. The cross section of the river course is divided into *n* parts with a spacing of w. The environmental preference of each part is determined according to the suitability curve, and then the weight available area（WUA）of each section and each indicator species is calculated. The WUA at different flow rates are calculated and the relationship curve between the flow rate and WUA is plotted. The larger the WUA is, the more suitable of the habitat at this flow rate will be [21,22]. Chen [23] analysed the water depth, flow velocity, and other hydraulic parameters of the natural spawning ground of *Schizothorax prenanti* by using the plane 2D hydrodynamics mathematical model with an average depth. She proposed that the threshold values of water depth and flow velocity are from 0.5 m to 1.5 m and from 0.5 m/s to 2.5 m/s, separately during the spawning period of *Schizothorax prenanti*.

The method of determining the ecological flow process required by fish spawning of medium-sized mountain rivers includes the following steps: (1) Based on the standards for hydraulic parameters of fish habitats, calculate the minimum discharge flow required for the survival of fishes by using the modified Eco-hydraulics method; (2) Using the habitat simulation method to simulate the concentrated spawning grounds of fishes, and obtain the flow rate corresponding to the maximum WUA; (3) Integrating the results of two methods, taking into account the fish spawning requirement for hydrological situations, establish the ecological flow process required by fish spawning.

The research conditions include the field measurement condition and the simulated conditions (table 4). The field measurement condition reflects the field hydrological situation and the habitat characteristics, which can provide comparable basic information for the simulated conditions. The simulated conditions are used to simulate the hydrological situation and the habitat characteristics at different water reduction degrees, which will reveal the variation pattern of habitat hydraulic parameters of the river course at different flow rates.

Table 4. Setting and illustration of research conditions.

Calculated conditions	Condition illustration
Field measurement condition	Measured on the field
Simulated condition 1	5% of Q_d[b]
Simulated condition 2	10% of Q_d[b]
Simulated condition 3	5% of Q[c]
Simulated condition 4	10% of Q[c]
Simulated condition 5	12.5% of Q[c]
Simulated condition 6	15% of Q[c]
Simulated condition 7	20% of Q[c]
Simulated condition 8	25% of Q[c]
Simulated condition 9	30% of Q[c]
Simulated condition 10	Q_d[c]

[b] the perennial average flow discharged from the gate site during the dry period.
[c] the perennial average flow discharged from the gate site.

2.4. Mathematical model and parameterization

HEC-RAS, a one-dimensional model, was employed to carry out hydraulic analysis of steady and unstable flow. Its calculation principle are as follows:

$$Z_{\mathrm{i}} - Z_{i+1} = \frac{Q^2}{2g}\left(\frac{1}{A_{i+1}^{\ 2}} - \frac{1}{A_i^2}\right) + \frac{\Delta s Q^2}{2}\left(\frac{1}{K_i^{\ 2}} - \frac{1}{K_{i+1}^{\ 2}}\right) \tag{1}$$

$$K_i = \frac{1}{n} R_i^{\frac{2}{3}} A_i \tag{2}$$

where, Z_{i}, $Z_{\mathrm{i+1}}$ is the water levels of upstream and downstream, respectively; Q is the flow rate; A_i, A_{i+1} is the flow area of upstream and downstream section, respectively; K is the average flow modulus of cross section; n is Manning roughness coefficient; R isthe hydraulic radius.

Boundary conditions required for HEC-RAS calculation are listed in table 5.

The full name of the River2D model is the two-dimensional mean depth model of river hydrodynamics and fish habitat. This model can facilitate the detailed study of local velocity and depth distributions of the river, and help determine the relationship between the flow rate and the available habitat of fishes. The control equations of this model are as follows:

Table 5. Input boundary conditions for HEC-RAS.

Parameters	Value
Cross-section number	11
Manning roughness coefficient	0.036
Number of profiles	1
Inlet boundary	Flow rate, 0.56 m^3/s
Reach boundary conditions	normal depth, 0.0083[d]

[d] The upstream and downstream normal depth input value is slope.

Continuity equation:

$$\frac{\partial H}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0 \tag{3}$$

Momentum equation in direction *X*:

$$\frac{\partial q_x}{\partial t}+\frac{\partial}{\partial x}(Uq_x)+\frac{\partial}{\partial y}(Vq_x)+\frac{g}{2}\frac{\partial}{\partial x}H^2=gH\left(S_{0x}-S_{fx}\right)+\frac{1}{\rho}\left[\frac{\partial}{\partial x}(H\tau_{xx})\right]+\frac{1}{\rho}\left[\frac{\partial}{\partial y}(H\tau_{xy})\right] \tag{4}$$

Momentum equation in direction *Y*:

$$\frac{\partial q_y}{\partial t}+\frac{\partial}{\partial x}(Uq_y)+\frac{\partial}{\partial y}(Vq_y)+\frac{g}{2}\frac{\partial}{\partial y}H^2=gH\left(S_{0y}-S_{fy}\right)+\frac{1}{\rho}\left[\frac{\partial}{\partial x}(H\tau_{yx})\right]+\frac{1}{\rho}\left[\frac{\partial}{\partial y}(H\tau_{yy})\right] \tag{5}$$

where, H represents the water depth, U and V represent the average velocities in x and y directions,respectively; q_x and q_y are flow intensities related with the flow velocity in x and y directions, respectively, q_x=HU and q_y=HV; g represents the acceleration of gravity; ρ represents the water density; S_{ox} and S_{oy} are river bed slopes in x and y directions, respectively; S_{fx} and S_{fy} are resistance slopes in x and y directions, respectively; τ_{xx}, τ_{xy}, τ_{yx} and τ_{yy} are turbulent stress tensors in the horizontal direction.

Historical investigation data indicate that there was a fish spawning ground at the downstream of Puxigou confluence, and the spawning ground is located between section A11 and section A12. The complex terrain of Puxigou region, including river bend, deep pool and shallow pool, was interpolated on the basis of the measured large section according to previous topographic data and water edge information. It can clearly reflect the hydraulic characteristics related to the survival of fishes and spawning grounds in the water reduction reach of XHS. There is no tributary from the power station to section A11.

The input boundary conditions for River2D are shown in table 6.

Table 6. Input boundary conditions for River2D.

Parameters	Value
Generate boundary	1000
Uniformly distributed nodes	19
Q_i	0.35
Inlet boundary [e]	Flow rate, 0.56 m^3/s
Outlet boundary [e]	Fixed elevation, 1624.29 m

Present time	0
Final time	100000s
Time (Δt)	100s

[e] The inlet boundary and outlet boundary are measured values.

2.5. Model validation

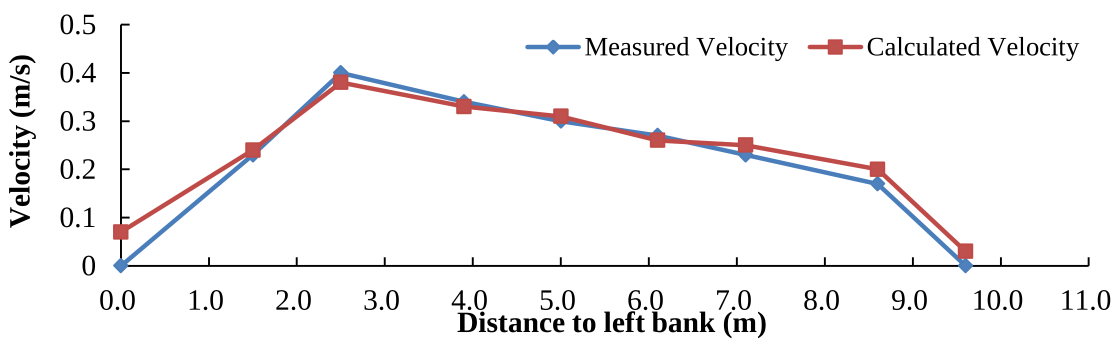
To verify the model used in this study, the water level, flow velocity and water depth was measured in the same research area from April to May. And then, we compared the calculated values and the measured values. The model was calibrated through adjusting the meshes and the input boundary conditions to make the simulated results more close to the measured value. For HEC-RAS, we measured the water levels at 11 cross sections, and then compared the calculated results and the measured values (table 7). For River2D, we measured the flow velocities and water depths at 9 points along a cross section, and then compared the calculated results and the measured values (figure 4).

The comparison between the calculated water level of HEC-RAS and the measured results shows that the error range is 0.01-0.09 m, which is in an acceptable range. Comparing the velocity and depth calculation results of River 2D with the measured results, the accuracy rates were 82.4%-97.1% and 88%-97.6%, respectively.

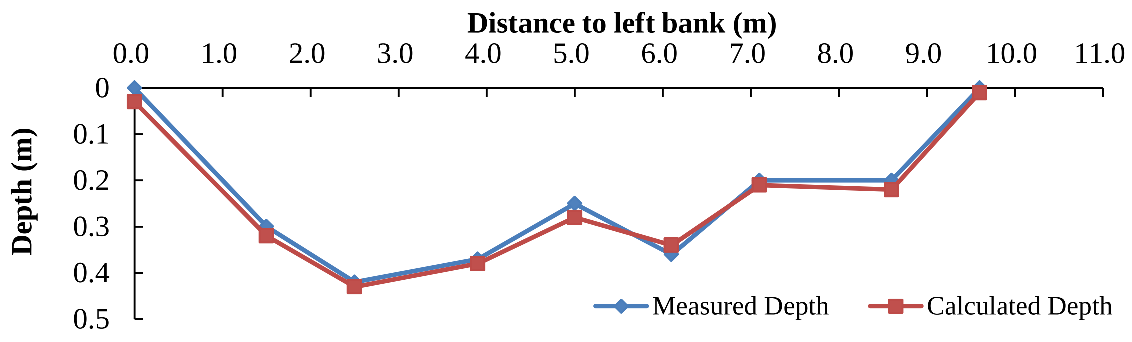
Table 7. Comparison of HEC-RAS calculated and measured water levels at different sections[f].

Section position	Measured water level (m)	Calculated water level (m)	Difference (m)
A10	1681.19	1681.19	0
A11	1638.85	1638.76	-0.09
Puxigou confluence	1635.19	1635.19	0
A12	1624.29	1624.29	0
A13	1599.69	1599.69	0
Diaofanggou confluence	1596.73	1596.74	-0.01
Mengtungou confluence	1580.35	1580.34	0.01
A14	1580.20	1580.19	0.01
Nangou confluence	1577.37	1577.37	0
Tail water from Huilong Hydropower Station	1556.21	1556.21	0
A15	1553.33	1553.33	0

[f] All the sections are on the main stream



(a)



(b)

Figure 4. Comparison of depth and velocity between calculated and measured values as simulated by River 2D.

3. Results and analysis

3.1. Sampling

The annual average flow at the dam site provided by the XHS Management Office is shown in figure 5. Naturally, the average annual flow rate at the dam site of the XHS varies from 20.2 m^3/s~147 m^3/s. The flood season occurs from May to October.

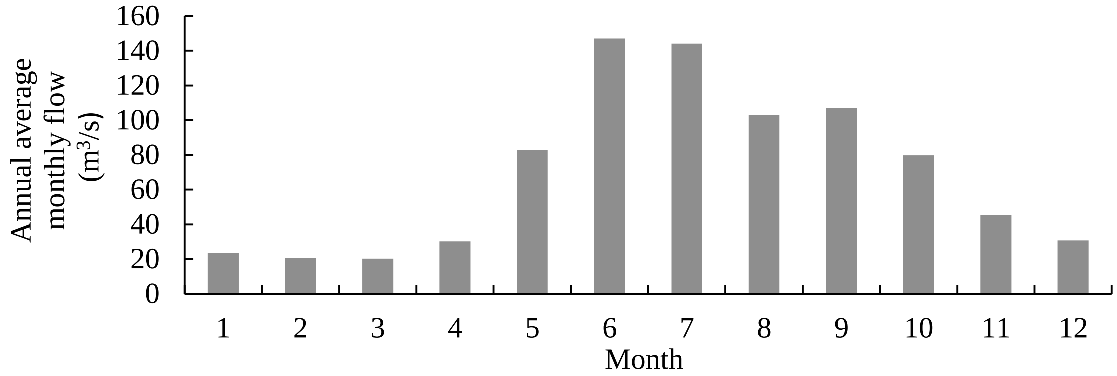


Figure 5. Perennial average monthly flow process at the dam site of XHS.

According to the prototype observation, the measured flow rates at the mainstream and tributaries of Zaguonao River were obtained (table 8), and the hydraulic habitat parameters of fishes at the catch section were obtained (table 9).

According to table 9, the hydraulic habitat parameters for the survival of adult *Schizothorax prenanti* in Zagunao River can be obtained, as listed in table 10.

Table 8. Measured flow rates at the mainstream and tributaries of XHS.

Section name	A10	A11	Puxigou	A12	A13	Diaofanggou	Mengtungou	A14	Nangou	Tail water from Huilong Hydropower Station	A15
Measured flow rate (m^3/s)	0.56	0.56	1.08	1.08	1.08	0.03	1.24	2.35	0.01	12.6	14.95

Table 9. Hydraulic habitat parameters of catch section of *Schizothorax prenanti* in Zagunao River.

Weight (g)	Length (cm)	Section corresponding to the capture site	Flow rate (m^3/s)	Flow velocity (m/s)	Average water depth (m)	Maximum water depth (m)	Discharge area (m^2)	Water surface width (m)
267.0	32.4	A12~A13	1.08	0.18~0.22	0.38~0.39	0.56~0.58	4.94~6.02	13.1~15.6
312.1	36.4	A12~A13	1.08	0.18~0.22	0.38~0.39	0.56~0.58	4.94~6.02	13.1~15.6

Table 10. Hydraulic habitat parameters for the survival of adult *Schizothorax prenanti* in Zagunao River.

Fish name	Minimum value of average depth (m)	Minimum value of maximum water depth (m)	Minimum value of average flow velocity (m/s)	Water surface width (m)	Discharge area (m^2)
Schizothorax prenanti	0.38	0.56	0.18	13.1	4.94

The results in table 10 were compared with the standards for hydraulic parameters of key fish habitats in table 2. The results show that the average water depths are basically the same, but the standard for the average flow velocity in table 2 is higher. Therefore, the recommended standards in table 2 were selected as the habitat standards of fishes in Zagunao River.

3.2. Numerical simulation

At the simulated conditions, the whole river reach was applied with the longitudinal one-dimensional hydraulic calculation. By referencing the standards for hydraulic parameters of fish habitats, the minimum discharge flow of XHS for the survival of fishes was determined. Table 11 reflects the on-way changes of habitat hydraulic parameters at the simulation condition 8.

Table 11. Calculated habitat hydraulic parameters at the simulated condition 8.

Section name	Flow rate (m^3/s)	Flow velocity (m/s)	Discharge area (m^2)	Water surface width (m)	Maximum water depth (m)	Average water depth (m)	Water area (m^2)	Percentage of discharge area to that in the dry period	Percentage of water surface width to that in the dry period
A10	17.99	0.35	51.55	33.18	2.59	1.55	130.26	0.73	0.91
A11	17.99	0.28	64.56	35.94	2.80	1.80	9.22	0.67	0.80
Puxigou confluence	18.51	0.34	54.99	34.14	2.55	1.61	53.24	0.75	0.85
A12	18.51	0.37	50.11	38.20	2.44	1.31	114.75	0.73	0.97
A13	18.51	0.55	33.50	31.94	1.60	1.05	8.94	0.78	0.93
Diaofanggou confluence	18.54	2.25	8.24	16.36	0.69	0.50	53.47	0.71	0.92
Mengtungou confluence	19.78	1.55	12.79	24.44	0.71	0.52	3.53	0.80	0.99
A14	19.78	1.65	11.97	34.96	0.54	0.34	4.50	0.72	0.96
Nangou	19.78	1.19	16.56	35.90	0.69	0.46	96.51	0.76	0.95
Tail water from Huilong Hydropower Station	32.38	1.40	23.19	27.47	1.17	0.84	10.20	0.83	0.99
A15	32.38	1.30	24.85	26.66	1.26	0.93		0.83	0.99

The on-way changes of the habitat hydraulic parameters at various conditions have the following commonness: the gradient of river course from the gate site to the upstream of section A13 is relatively small and the flow velocity is low; while the river course at the downstream has large gradient, and with the increasing of flow rate along the way, the flow velocity is large. The river course at the upstream is narrower than that at the downstream. Meanwhile, the water surface width at the upstream is relatively small and the average water depth is relatively deep. The habitat hydraulic parameters at various conditions were analysed to see if they can meet the standards recommended in table 2, as listed in table 12.

Table 12. Standard-satisfying situations of habitat hydraulic parameters at various conditions.

Habitat hydraulic parameters		Maximum water depth	Average water depth	Average velocity	Water surface width	Wetted perimeter rate	Discharge area	Water surface area
Standard[g]	Minimum standard	2 to 3 times of the body length of the fish	≥0.3m	≥0.3m/s	≥30m	≥50%	≥30m^2	≥70%
	Percentage of long segment in the accumulated river reach	95%	95%	95%	95%	95%	95%	
Measured condition	Measured	77%	63%	43%	0%	43%	0%	51%
Standard meeting situation (simulated conditions)	Simulated condition 1	80%	74%	43%	8%	91%	0%	67%
	Simulated condition 2	88%	76%	61%	10%	100%	0%	72%
	Simulated condition 3	91%	77%	64%	10%	100%	0%	73%
	Simulated condition 4	96%	99%	64%	12%	100%	29%	79%
	Simulated condition 5	100%	99%	72%	40%	100%	35%	82%
	Simulated condition 6	100%	100%	73%	67%	100%	46%	84%
	Simulated condition 7	100%	100%	82%	71%	100%	56%	89%
	Simulated condition 8	100%	100%	95%	72%	100%	57%	92%
	Simulated condition 9	100%	100%	97%	73%	100%	57%	95%
	Simulated condition 10	100%	100%	100%	74%	100%	58%	100%
Recommen-ded condition	Simulated condition 8	100%	100%	95%	72%	100%	57%	92%
Remarks		The fish in this reach is small, and the largest one is only 25 cm.The maximum water depth is set as 0.75 m.			Medium -sized river, no need to be consider ed.		Medium-sized river, no need to be considered .	

[g] This project diverts water with low gate, so the change of water temperature before and after its operation is small. The survival and reproduction of fishes will not be affected .

It can be seen from table 12 that the river reach with the average speed of ≥0.3 m/s accounts for 95% of the accumulated river reach, and the water body area accounts for 92% of that in the dry period, while other parameters can meet the requirements when the perennial average discharge flow is 25% (17.43 m^3/s). Therefore, 17.43 m^3/s is the minimum flow rate satisfying the standards for hydraulic parameters of fish habitat in the Eco-hydraulics method. This flow rate can be used as the recommended minimum discharge flow of XHS.

By using the habitat simulation method, the WUA of concentrated spawning grounds for *Schizothorax prenanti* in the water reduction reach of XHS was simulated:

June and July are the concentrated spawning periods of *Schizothorax prenanti*. The variation of WUA with the flow rate is shown in figure 6. It can be seen that there are WUA at various flow conditions. The value of WUA is increasing linearly when the flow rate increases from 0 to 30% of the perennial average flow; the value of WUA reaches to the maximum when the flow rate in the water course reaches to 30% of the perennial average flow; after that, the value of WUA decreases with the increasing of the flow rate.

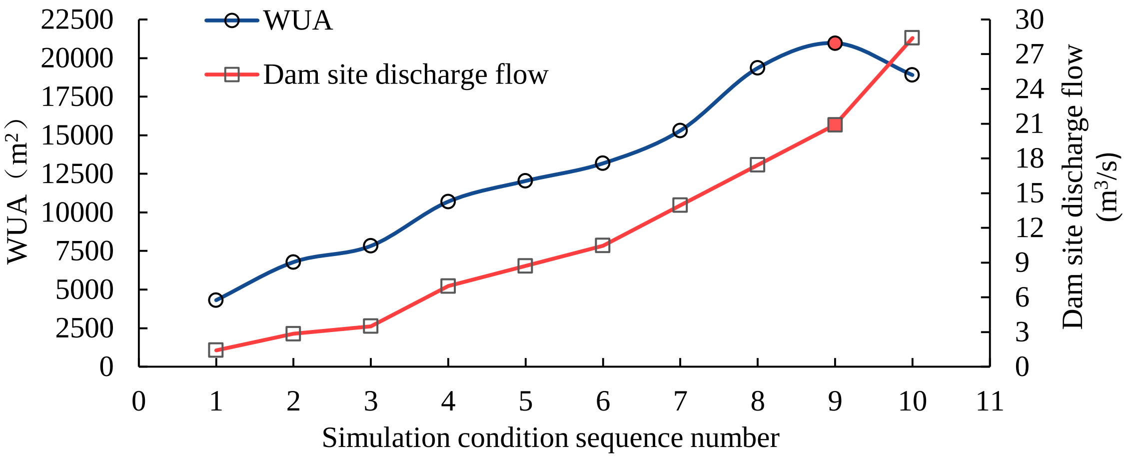


Figure 6. Variation of WUA of *Schizothorax prenanti* with the flow rate at the concentrated spawning period.

The corresponding simulation condition when the flow rate reaches to 30% of the perennial average flow is condition 9. The WUA of concentrated spawning grounds in the water reduction reach of XHS is shown in figure 7. It can be known that the flow rate corresponding to the maximum WUA of the concentrated spawning grounds in the water reduction reach of XHS is 20.9 m^3/s.

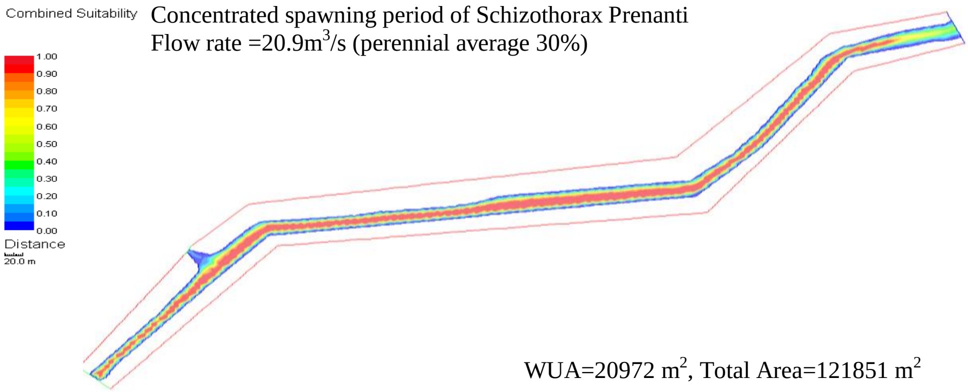


Figure 7. Calculated results of WUA at the simulated condition 9.

4. Discussion

We modified the Eco-hydraulics method through prototype observation, made it more suitable in calculating the ecological basic flow of medium-sized mountainous rivers, and then used it in calculating the ecological basic flow of Zagunao River. The minimum flow for the survival of fishes is 17.43 m^3/s. Therefore, this flow rate is the minimum value of the flow process when determining the recommended ecological basic flow with the consideration of fish spawning requirements.

The ecological flow process after integrating the minimum discharge flow with the flow rate corresponding to the maximum WUA, and after taking into account the fish spawning requirement for hydrological regimes and the standards for hydraulic habitat parameters in the Eco-hydraulics method is: providing 7 days flow fluctuation processes during the spawning period with the maximum flow of 20.91 m^3/s, the minimum flow of 17.43 m^3/s and the frequency of 1 time every ten days; the minimum discharge flow during the non-spawning period is recommended to be not less than 17.43 m^3/s.

In the research of ecological scheduling of reservoirs, the influence of ecological pulse to fish spawning and reproduction is often mentioned [24]. The researches suggest that each river carries its own biological rhythm information, and each river itself is a stream of information [25]. During floods, the information transmitted by flood pulse is more abundant and intense [26]. The observation data show that fishes and other aquatic organisms complete the spawning, incubation, growth, shelter, migration and other activities based on the changes of the hydrological situation. In Pantanal River in Brazil, many kinds of fishes are adapted to lay eggs during the flood pulse season [27]. In the Murray River, Australia, it was observed that the spawning activity of golden perch and silver perch in flood season was significantly higher than that in other periods. Moreover, studies have shown that Murray cod and trout cod's recruitment may be increased when floodplain inundation occurs [28].

There are a considerable number of aquatic organisms showing obvious dependence on flood pulse at different stages of their life. According to the analysis of the natural flow process at the dam site of XHS, the flow rate is large in June and July, which is also the concentrated spawning period of *Schizothorax prenanti*. Therefore, we conclude that the propagation of *Schizothorax prenanti* is closely related to the increasing of the flow rate, which is consistent with the research result of Huang [29]. He believed that the flow keeps rising or falling not only reflects the change of hydrological regime, but also has certain ecological significance. He also gave an example to show that the continuous rising of flow rate at the spawning time is the essential condition for four major Chinese carps to lay eggs. So we suggest the provision of 1 to 2 ecological flood processes that peak flow to 125 m^3/s-200 m^3/s by referring to the natural flood process before the concentrated spawning period (June to July) of *Schizothorax prenanti*. This will satisfy the hydrological signal stimulation of the fish spawning activity by the fluctuation of water level and the flow pulse process, which helps to restore the diversity of the river ecosystems.

5. Conclusions

According to the characteristics of medium-sized mountainous rivers, the standards for hydraulic habitat parameters of fishes in large-sized rivers are revised on the basis of prototype observation, and the reference standards for hydraulic habitat parameters of fishes in medium-sized rivers are obtained. The prototype observation results verify the suitability of applying these reference standards to the mountainous rivers. Based on the verified standards, the fish habitat in Zagunao River is numerically simulated by using the Eco-hydraulics method, and the recommended value of ecological basic flow of fishes in this mountainous river is determined. The habitat simulation method is used to determine the most suitable flow rate during the spawning period of *Schizothorax prenanti*, and 1 to 2 ecological flood processes shall be provided before the concentrated spawning period after taking into account the requirement of *Schizothorax prenanti* for the spawning flow signal. Finally, the variation range of flow rate during the spawning period is determined as 17.43 m^3/s to 20.9 m^3/s, and the flow rate during the non-spawning period shall not be less than 17.43 m^3/s. The obtaining method of the recommended values of ecological water requirement for fishes in specific mountainous rivers can be used as the evaluation method of aquatic ecological environmental impact. In future studies, systematic prototype observation and numerical simulation of fish habitats shall be conducted in different characteristic reaches of medium-sized mountainous rivers, such as torrential reach, deep pool and shallow pool. The standards for hydraulic habitat parameters more suitable to the actual fish habitats in medium-sized mountainous rivers shall be established to obtain more reasonable ecological water requirement.

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