Ecological Indicators 154 (2023) 110903

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

A novel index-based method associated with aquatic ecosystem for evaluating river longitudinal connectivity: A case study for cascade dams in the Yalong River, China

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ARTICLE INFO

Keywords:
River longitudinal connectivity
Cascade dams
Flow regime
Fish diversity
The Yalong River

ABSTRACT

Dams as crucial metrics for characterizing aquatic species diversity and river ecosystem have significant effects on river longitudinal connectivity (RLC). Specially, the reduction of RLC can lead to the degradation of suitable habitats and loss of migration opportunities for freshwater fish. However, the assessment of RLC in cascade dams is still limited, particularly in relation to fish species and habitats. Therefore, this paper analyzed the influence mechanism of cascade dams on aquatic ecosystems by simulating the flow field using the Delft3D model. Additionally, a novel index-based method associated with five fish-related indices has been developed to evaluate the RLC. Considering that numerous large dams posed serious threats to the aquatic ecosystem in Southwest China, the Yalong River was chosen as a study case to illustrate the application of this new framework. The results showed that the reservoir area exhibited the most stable flow field, with the lowest values of flow velocity (v), Reynolds number (Re) and Froude number (Fr); and the highest hydrodynamic parameters were observed at the reservoir head. The v from upstream to downstream of the five studied reservoirs (Jinping I, Jinping II, Guandi, Ertan and Tongzilin) showed a decreasing trend, characterized by turbulent flow (Re greater than 500) and sluggish flow (Fr less than 1). These changes in flow regime had a profound impact on fish diversity and habitats due to the construction of cascade dams. Based on the novel index-based method, the RLC was determined to be moderate, with a value of 12.90. Notably, the lowest score occurred in the Tongzilin reservoir, indicating its largest contribution to the reduction of RLC. The different impacts of the five studied dams on RLC were attributed to multiple factors, including their geographical location, distribution, distance, reservoir operations and regulations, as well as the cumulative effects of cascade dams. The results can provide references for decision-making in dam projects and river management, and the framework can be applied to evaluate RLC of other rivers worldwide.

1. Introduction

The concept of river connectivity has been widely used in many fields. It is generally defined as the movement of matter, energy, and organisms within and across water cycles (Chi et al., 2018; Lu et al., 2020). River connectivity can be incorporated into a four-dimensional framework, including longitudinal, lateral, vertical, and temporal dimensions (Lu et al., 2020). Among them, river longitudinal connectivity (RLC) is most directly affected by a large variety of artificial barriers (e.g., dams, sluices, weirs, and fords) from upstream to downstream; and this issue has garnered significant attention in various fields (Best, 2019; Belletti et al., 2020; Rodeles et al., 2020). A complete RLC not only offers essential habitats and living conditions for fish, benthic organisms, and birds, but also promotes the circulation of energy and nutrients, thereby providing important ecosystem services (Shao et al., 2020). However, the first global assessment of river connectivity revealed a discouraging state of the RLC due to the river fragmentation caused by dams and reservoirs (Grill et al., 2019). A recent investigation discovered that more than one million man-made barriers disrupted the RLC in Europe (Belletti et al., 2020). Generally, the loss of RLC induced by artificial

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https://doi.org/10.1016/j.ecolind.2023.110903
Received 14 May 2023; Received in revised form 11 August 2023; Accepted 29 August 2023
Available online 7 September 2023

obstacles can result in significant reductions in the number, length, and watershed area of rivers, as well as the destruction of natural river ecosystems (Milaković et al., 2020; Díaz et al., 2021). Therefore, it is imperative to quantitatively evaluate the RLC, particularly for large rivers with significant human interference.

There exist inconsistent results regarding which degree of RLC can achieve the optimal effect on aquatic ecosystems. Numerous studies have proposed that maintaining the RLC has a positive impact on aquatic organisms and species diversity. A comprehensive review of over 100 previous studies revealed that maintaining RLC improved fish diversity (Shao et al., 2019). Many researchers have found a correlation between increased aquatic biodiversity and improved RLC (Kufel and Lesniczuk, 2014). Nevertheless, a study conducted by Harvey et al. (2019) demonstrated that the optimal nitrogen removal in rivers occurred at a moderate level of river connectivity rather than at the highest or lowest levels, in the northeastern region of the United States. Consequently, understanding the RLC is essential for efficient river ecological protection and management.

The dam serves as a quantitative measure of the impact of human activities on RLC, posing a serious threat to freshwater biodiversity worldwide (Grill et al., 2019; Hu et al., 2021). A total of 58,000 large dams (height greater than 15 m) distributed globally (Mulligan et al., 2020), and over 65% of the 292 large river systems have been affected by these dams (Zarfl et al., 2015). Although dams and reservoirs play important roles in irrigation, energy supply, and flood control, the construction and operation of cascade dams have significant implications for flow regimes. This can result in alterations to the water temperature, sediment distribution, organic matter migration and transformation (Fan et al., 2015; Shen et al., 2022). Moreover, the changes in flow regime caused by man-made barriers have significant influences on the population size, spatial distribution, reproduction, genetic diversity, and community composition of diverse aquatic species (e.g., fish, zooplankton, algae, and benthic animals) (Park et al., 2020; Zhang et al., 2022). However, previous studies have focused more on a single dam for assessing RLC, while the complex cumulative effects of cascade reservoirs have not received sufficient attention in comparison (Deng et al., 2018a; Wang et al., 2019). The concept of cumulative effect was initially introduced by the U.S. Environmental Quality Commission in the environmental assessment method (U.S. EPA, 1999). For cascade reservoirs, the variations in flow regimes (e.g., river discharge, temperature, sediment, and nutrients) can pose a significant cumulative threat to the structure and function of aquatic organisms and ecosystems by altering the physical and chemical properties of the river (Seyedhashemi et al., 2021). Therefore, it is of great practical importance to scientifically evaluate the RLC for cascade dams due to their spatial heterogeneity at a large watershed scale.

Over the past years, various methods have been used for assessing river connectivity, including graph theory, hydrological models, the dendritic connectivity index, the longitudinal functional connectivity index, and others (Deng et al., 2018b). These traditional methods have their own merits and limitations, which vary widely in terms of spatiotemporal scope, specific objectives, required data, and interpretation (Jumani et al., 2020; Rodeles et al., 2020). Therein, graph theory and hydrological models are suitable for assessing the lateral river connectivity. The connectivity functions and indicators are commonly used to evaluate the RLC, which ignore the varying development degrees of individual reservoirs and regard each dam as having an equivalent impact on RLC (Deng et al., 2018b; Lu et al., 2020). In relation to this, many researchers have attempted to improve the methods for evaluating RLC. For example, Deng et al. (2018b) proposed a modified dendritic connectivity index to detect the impact of different degrees of river obstruction on RLC by utilizing the sluice distribution index. An index system encompassing sluice passage efficiency, probability, and cumulative effect of sluices, was developed by Lu et al. (2020) to assess the impacts of urbanization on the RLC. However, few studies have quantitatively established a set of systematic evaluation indices associated with the aquatic ecosystem to assess the impact of cascade dams on the RLC (Hu et al., 2021). The fish species is at the top of the aquatic food chain, making it one of the best indicators to measure the aquatic ecosystem (Shan et al., 2022). Especially, migratory and endemic fish species provide a more comprehensive understanding of the impact of cascade dams on the RLC across a broader spatial and temporal spectrum compared to other aquatic organisms (e.g., phytoplankton, macrophytes, and macroinvertebrates), since their life cycles are deeply influenced by flow regimes and water temperature patterns (Curtis Roegner et al., 2021; Zhang et al., 2022). As a result, the fish species can primarily be regarded as a quantifiable measure for evaluating the RLC of cascade dams (Grill et al., 2019). Therefore, this study developed a novel method to establish a systematic link between fish-related indices and RLC for the high-intensity cascade hydropower development in river basins.

The Yalong River is the largest tributary in the upper reaches of the Yangtze River with multiple cascade dams and abundant fish resources (Zhang et al., 2022). As the third largest hydropower base in China, 22 cascade reservoirs have been approved and constructed in the mainstream of the Yalong River, altering the composition and origin of aquatic organisms (Fang et al., 2022; Zhao et al., 2022). Compared to the rivers in Northern China, the water resources in the Yalong River are abundant with relatively small interannual variation. Thereby, more attention is paid to the effects of RLC on aquatic organisms rather than the physical connectivity, as there is no seasonal disconnection of the river. However, the evaluation results of RLC in the Yalong River have not been reported previously, and there is still a lack of comprehensive understanding regarding the cumulative effects on RLC. Furthermore, the index-based assessment of RLC in aquatic ecosystems, specifically in relation to fish species, has not received sufficient attention. Therefore, a systematic index-based method was established to evaluate the RLC for cascade dams. Additionally, the factors contributing to the variations in RLC among the five studied large dams in the Yalong River were further discussed. The results can provide valuable information for dam prioritization decisions and river management.

2. Materials and methods

2.1. Study area

The Yalong River is the largest tributary in the upper reaches of the Yangtze River in Southwest China (26°32′ N ~ 34°05′ N, 96°52′ E ~ 102°48′ E) (Fig. 1). The river is located in the Qinghai-Tibetan Plateau and originates from the Bayan Har Mountains, with a total length of 1.57×10^3 km, a drainage basin area of approximately 1.36×10^5 km^2, an annual average estuary runoff of 1.86×10^3 m^3/s, and a total natural drop of 3.83×10^3 m (Zhao et al., 2022). The annual average runoff is abundant (1220 m^3/s), primarily replenished by precipitation, groundwater, and melted ice and snow (Liu et al., 2021a). The study area belongs to the subtropical monsoon climate zone, with the temperature and precipitation of − 4.9 ~ 19.7 °C and 500 ~ 2470 mm, respectively. Additionally, more than 70% of the rainfall is concentrated in short periods from June to October.

The fish resources in the mainstream of the Yalong River are abundant. However, the diversity of fish species is comparatively limited, and the fauna composition is relatively simplistic when compared to most rivers within the Yangtze River Basin (Deng et al., 2023). Specifically, the existing migratory fish species mainly include *Lepturichthys fimbriata*, *Jinshaia sinensis*, *Jinshaia abbreviata, Lepturichthys fimbriata* and *Botia superciliaris* in the Yalong River. Among them, *Leptobotia rubrilabris*, *Jinshaia sinensis*, and *Jinshaia abbreviata* are endemic fish. The possible exotic fish species are *Luciobarbus capito* and *Oncorhynchus mykiss*. Notably, the endemic and migratory freshwater fish are most significantly affected by cascade dams (Zhang et al., 2020). The dams upstream were primarily in the planning stage, while the dams downstream were predominantly either under construction or already

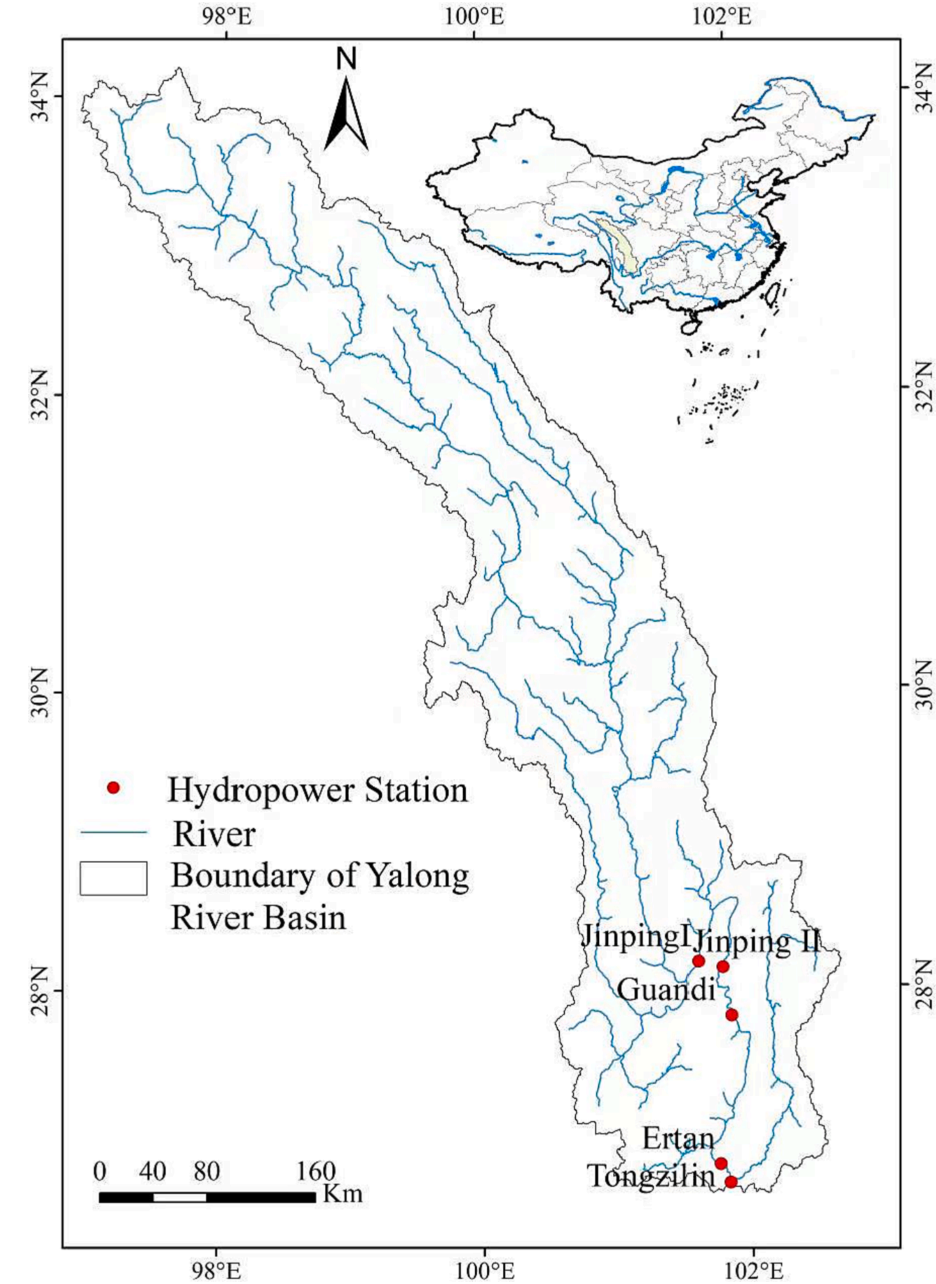

Fig. 1. Locations of the study area.

Table 1
Information on cascade dams in the lower reaches of the Yalong River Basin.

Hydropower station	Commencement date	Operation date	Catchment area ($\times 10^3$ km^2)	Total storage (km^3)	Regulation storage (km^3)	Installed capacity (MW)	Annual generation capacity (10^8 kW·h)	Distance to the river outlet (km)	Regulation performance
Jinping I	November 2005	August 2013	102.6	7.76	4.91	3600	180.90	358.0	Annual
Jinping II	January 2007	December 2012	102.7	0.02	0.01	4800	258.80	350.5	Daily
Guandi	October 2007	March 2013	110.1	0.76	0.03	2400	99.50	178.0	Daily
Ertan	September 1991	1998	116.4	5.80	3.37	3300	176.70	33.0	Seasonal
Tongzilin	October 2010	October 2015	127.6	0.09	0.01	600	30.20	15.0	Daily

completed (Wang et al., 2019). Therefore, this paper mainly focused on five typical hydropower stations (Jinping I, Jinping II, Guandi, Ertan, and Tongzilin) situated in the lower reaches of the Yalong River with high regulation capacity. The basic information on cascade dams is shown in Table 1.

2.2. New evaluation system for the RLC

The Yalong River with high hydropower development was selected as the study area to illustrate the application of the new evaluation system framework for the RLC, as depicted in Fig. 2. First, the characteristics of fish resources in the Yalong River were analyzed through field investigations and calculations of diversity indices. Then, the flow regime changes in the reservoir area, reservoir head, and reservoir tail were explored using the Delft3D model and hydrodynamic parameters, in order to explore the influence mechanism of cascade dams on aquatic ecosystems.

2.3. Flow regime characteristics

2.3.1. Delft3D model simulation

The Delft3D model was developed by Delft University and was widely used in various fields. This model can simulate the hydrodynamics and sediment transport processes in reservoirs, rivers, lakes, and estuaries in two- or three- dimension. Considering that the hydrodynamic conditions in the Yalong River involve many complex ecological and environmental factors, field investigations alone will be insufficient to effectively and accurately analyze the changes in the flow field of the Yalong River. The well-recognized model can feasibly and realistically simulate the hydrodynamic characteristics based on available data (Wang et al., 2022). As the most basic hydrological elements, the variations in water depth (h) and flow velocity (v) have fundamental and direct influences on fish species and habitats (Shan et al., 2022). Therefore, the Delft3D-Flow module was employed to simulate the h and v in the study, and the Delft3D-GRID module was used to generate the simulation grid. All the required input data was imported into the module. The alternating direction implicit calculation in the finite difference method was used to discretely solve the equations, including continuity equations, momentum equations, and transport equations.

To ensure the availability, integrity, and representativeness of the data, verification and calibration were conducted upstream of the Jinping II station and downstream of the Tongzilin station in the Yalong River. Therein, the dam behind (i.e., reservoir head), dam area (i.e., reservoir area), and dam front (i.e., reservoir tail) were taken into account. As a result, six river sections were simulated in the model. The simulation was conducted on July 15, 2014 in high water period. The simulation time step was 5 min to ensure the model convergence and computational accuracy. The simulated flow field was closest to the actual condition when the Manning roughness coefficient was 0.012 during calibration. The model's performance was evaluated using the relative error rate.

2.3.2. Hydrodynamic parameters

To explore the flow field characteristics under the cascade dams of the Yalong River, v, Reynolds number (Re) and Froude number (Fr) were analyzed in this study. They are calculated as follows (Yang et al., 2023):

$$Re = \frac{Uh}{v} \tag{1}$$

$$Fr = \frac{U}{\sqrt{gh}} \tag{2}$$

where v is the average velocity of the river section (m/s), h is the average water depth (m), U is the water viscosity coefficient (m^2/s), and g refers to the acceleration of gravity (m/s^2). The U-value is 1.14×10^{-4} m^2/s at 15°C by referencing the hydrodynamic viscosity coefficient table.

2.4. Diversity index

Species diversity is a key metric for assessing ecosystem stability and biodiversity. The diversity index is a robust measure of species diversity that primarily encompasses three spatial scales. Specifically, the alpha-diversity (α) index quantifies the number of species within a given habitat, also known as within-habitat diversity (Qiao et al., 2022). The beta-diversity (β) index represents the difference in biological community structure in different habitats, and the gamma diversity (γ) index is the number of species at a regional scale (Chi et al., 2018). This study mainly focused on α diversity to assess the fish diversity in the Yalong River, and the $D_{g\text{-}f}$ index was applied based on information measures. The $D_{g\text{-}f}$ measures the distribution inhomogeneity in the two-level classification of family and genera based on the Shannon-Weiner index. The formulas are as follows:

$$\mathrm{p_i} = \frac{\mathrm{W_{ki}}}{\mathrm{W_k}} \tag{3}$$

$$D_f = \sum_{k=1}^{m} D_{fk} = -\sum_{k=1}^{m}\sum_{i=1}^{n} p_i \ln p_i \tag{4}$$

where D_f refers to the family diversity index, W_{ki} is the number of species in the ith genus of the kth family, W_k is the number of species in the kth family, n is the number of genera in the kth family, and m is the number of family.

$$\mathrm{q_j} = \frac{\mathrm{W_j}}{\mathrm{W}} \tag{5}$$

$$D_g = \sum_{j=1}^{p} D_{gi} = -\sum_{j=1}^{p} q_j \ln q_j \tag{6}$$

$$D_{g-f} = 1 - \frac{D_g}{D_f} \tag{7}$$

where D_g is the genus diversity index, $D_{g\text{-}f}$ is the species diversity index, W_j represents the number of species for the jth genus, W represents the number of species, and p represents the number of genera.

Meanwhile, the Margalef species richness index (D), Shannon-Wiener diversity index (H'), and Pielou evenness index (J') were used to analyze the fish community's diversity in this study. The formulas are as follows (Liu et al., 2022).

$$D = \frac{(S-1)}{\ln N} \tag{8}$$

$$H' = -\sum_{i=1}^{S} P_i \ln P_i \tag{9}$$

$$J' = \frac{H'}{\ln S} \tag{10}$$

where S is the total number of recorded species, N is the recorded number of individuals of all species, and P_i is the proportion of the number of the ith species to the number of all species.

2.5. The proposed evaluation index system

(1) Fish resources status.

The fish resources have been jeopardized by water conservation projects in regulated rivers worldwide. This study primarily assessed the fish resources status using the D_f and D_g. According to the field survey and investigation of fish resources in the Yalong River, the evaluation criteria for the index were classified into 5 levels (Table 2).

(2) Fish pass rate.

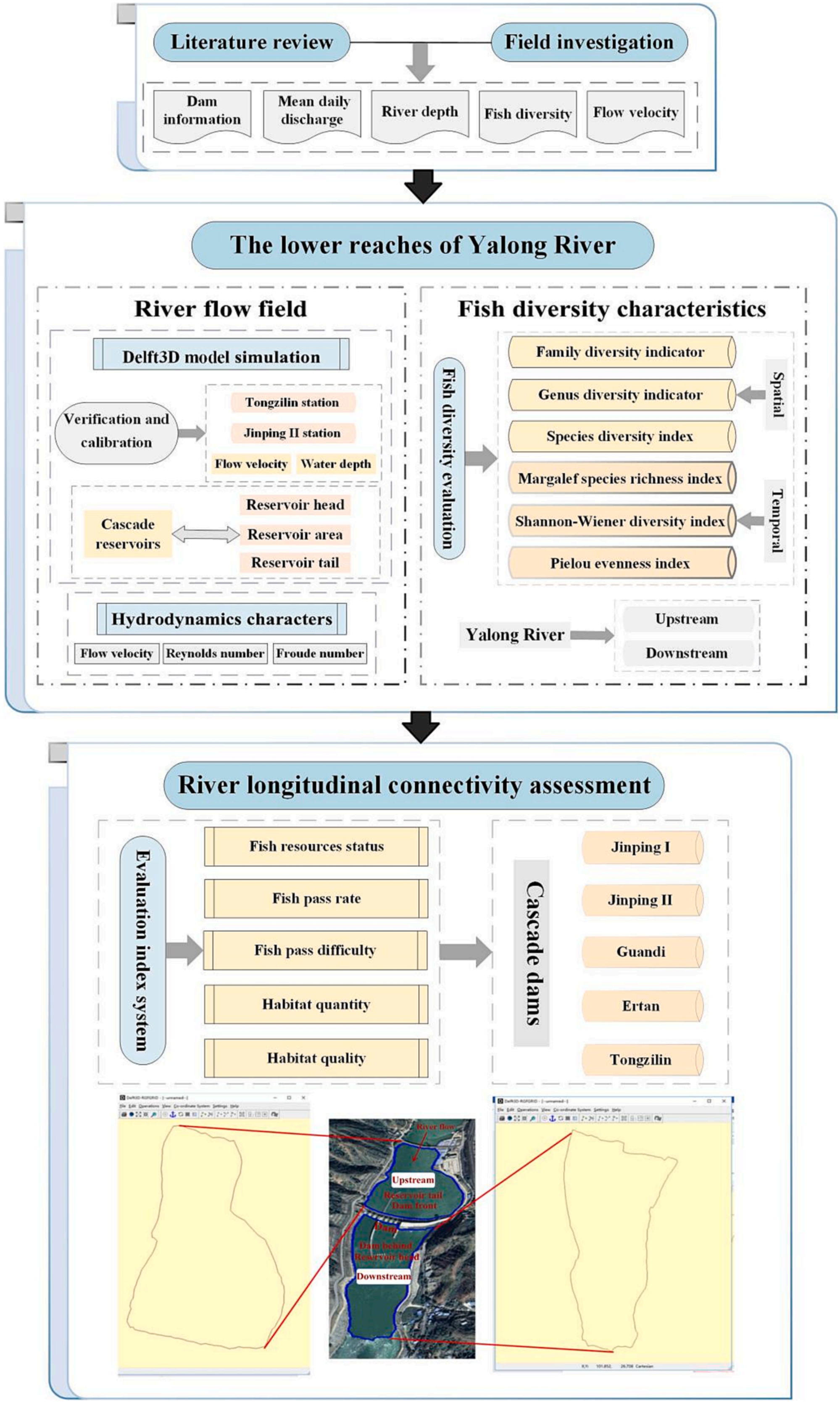

Fig. 2. Schematic diagram of the new evaluation system for the RLC.

Table 2
The criteria of evaluation indices for river longitudinal connectivity (RLC).

Score	Level	Fish resources status Family diversity (D_f)	Genus diversity (D_g)	Fish pass rate	Fish habitat number River connectivity length (km)	Water quality standard	RLC of each dam (C)
5	Excellent	>9	>5	>0.95	>50	Class II	≥20
4	Good	[8,9)	[4,5)	(0.9,0.95]	(40,50]	Class III	[15,20)
3	Moderate	[7,8)	[3,4)	(0.8,0.9]	(35,40]	Class IV	[10,15)
2	Poor	[6,7)	[2,3)	[0.6,0.8]	(30,35]	Class V	[5,10)
1	Very poor	<6	<2	<0.6	≦30	<Class V	<5

Previous studies typically regarded the unidirectional pass rate uniformly as 50% for all dams when assessing the RLC (Deng et al., 2018b; Lu et al., 2020). However, the RLC varied among dams due to environmental heterogeneity, especially concerning fluctuations in flow regimes in cascade reservoirs. The change in water flow velocity significantly influenced fish survival, growth, reproduction, predation, and migration (Xu et al., 2017; Liu et al., 2021b). Therefore, velocity was chosen as a representative parameter to reflect the influence of the change in flow regime on the fish pass both upstream and downstream of the dams. This study developed a new index, referred to as the fish pass rate (P), to quantitatively assess the changes in RLC. The formula is as follows:

$$P = v_u / v_d \tag{11}$$

where v_u is the average flow velocity of the river in the upstream region of the dam head (i.e., reservoir tail), and v_d is the average flow velocity of the river in the downstream region of the dam tail (i.e., reservoir head). The P is classified into 5 levels (Table 2).

(3) Fish pass difficulty.

Given that the evaluation method of RLC in the Technical Outline of National Water Resources Protection Planning in China overlooked the obstructive influence of each dam, this paper introduced the index of fish pass difficulty (D). This index not only considered the distance along the dams but also incorporated the number of dams. The formula can be calculated as follows:

$$D = P_n \times P_{n-1} \tag{12}$$

where P_n and P_{n-1} refer to the fish pass rate of the nth dam and (n-1)th dam upstream, respectively. Meanwhile, the distance between the dams is also considered to comprehensively reflect the score standard of D, as shown in Table 3. For example, if a dam has a P-value of 80% and another dam at its 60 km upstream with a P-value of 70%, the D-value is calculated as 56% with a score of 3.

(4) Fish habitat number.

The river connectivity length was found to have the most direct relevance to the fish habitat number (Nunn and Cowx, 2012; Díaz et al., 2021), thus serving as a measurement in this study. A similar approach was proposed by Liu et al. (2021a) in the Yalong River, who proposed a modified river connectivity length to identify the shortest length for fish to complete their hatching habitats. In this study, the river connectivity length was employed as a representative measure of fish habitat number in the evaluation criteria, in order to establish a universally applicable and easily implementable evaluation index system for other rivers, as shown in Table 2.

(5) Fish habitat quality.

When evaluating the quality of fish habitat, it is imperative to consider the presence of long-standing habitat suitable for fish survival (Quan et al., 2021). In the Yalong River, artificial fish restocking stations were established both upstream and downstream of each dam to improve fish survival and reproduction. Therefore, the water quality standard of each river section was used as an important basis for evaluating the habitat quality, specifically referring to the Environmental Quality Standard of Surface Water (GB 3838–2002) in China (Table 2).

Table 3
The evaluation criterion of comprehensive fish pass difficulty (D).

D	Distance (km) <50	[50,100]	>100
<30%	1	2	3
[30%,70%]	2	3	4
>70%	3	4	5

2.6. The newly developed method for RLC evaluation

In this study, the newly developed method for evaluating RLC was calculated based on the number of river sections fragmented by cascade dams, the length of each river segment divided by each dam, and the total length of the studied river. The novel evaluation method of RLC was performed using a weighted algorithm that incorporated enhanced prioritization of cascade dams. It is calculated as follows:

$$\mathrm{L} = \sum\nolimits_{i=1}^{m} l_i \tag{13}$$

$$C = \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{L - l_i}{(m-1)L}a_{ij} \times Q \tag{14}$$

where C is the RLC of each dam, and l_i is the length between the ith dam and the river outlet (km). The higher the value of l_i, the greater the damage to the RLC is. This principle was further confirmed by Díaz et al. (2021), who demonstrated a negative correlation between fish diversity and the ratio of non-fragmented river sections to the total river length. L refers to the total distance from cascade dams to the river outlet (km), m is the number of cascade dams, n is the number of evaluation indices, a_{ij} is the score of the ith dam on the jth evaluation index, and Q is a comprehensive coefficient that reflects the overall degree of RLC through the number of dams in 100 km (Table 4). The RLC improves as the value of C increases. The C can be classified into 5 levels (Table 2).

2.7. Data source and analysis

Hydrological data were collected from the local reservoir operating agency in the *Hydrological and Water Resources Survey Bureau of Sichuan Province*. Data on average water depth, flow velocity, and discharge were obtained on a daily basis at Jinping II and Tongzi stations from January 2006 to December 2014 to support the Delft3D model simulation. Digital elevation data with a 30 × 30 m resolution was acquired from the Geospatial Data Cloud to demarcate the grid boundary of the model. The climate data from the *National Meteorological Information Center of China Meteorological Administration* were input into the model for calibration (https://data.cma.cn/). All statistical analysis and visualization were performed using SPSS software (v26.0) and Origin 2022.

Table 4
The evaluation criterion of the comprehensive coefficient of RLC (Q).

Definition standard (pcs/100 km) Q	1	0.75	0.5	0.25	0.1
Number of dams per 100 km	<1	[1,2)	[2,3)	[3,4)	≥4

3. Results

3.1. Flow regime changes in cascade dams using Delft3D simulation

The Jinping II station and Tongzilin station were selected for model calibration and verification in the lower reaches of the Yalong River from upstream to downstream. As shown in Fig. 3a, the simulated average *h*-values were 19.71 m, 19.15 m, and 17.26 m at the reservoir area (section 1), reservoir tail (section 2), and reservoir head (section 3) of Jinping II, respectively. Compared to the measured *h*, the relative error rate of the simulated *h*-value was less than 8%. Additionally, the simulated *v*-values were 1.26 m/s, 1.56 m/s, and 1.38 m/s at section 1, section 2, and section 3 of Jinping II, respectively (Fig. 3b). Compared with the measured *v*, the relative error rate of the simulated *v*-value was less than 2%. The distance from the Jinping II and the Tongzilin station to the Yalong River outlet was 2.69×10^5 m and 12×10^5 m, respectively. The average water depth and velocity from the Jinping II station upstream to the Tongzilin station downstream decreased by 7.10 m and 1.10 m/s, respectively. Similarly, the average relative error rates of water depth and velocity were 10% and 4% in the Tongzilin station, respectively (less than15%). These results showed that the model performed well in simulating hydrodynamic process, making it feasible for the study area.

To investigate the changes in flow regime caused by a dam, a hydrodynamic simulation was conducted at the Ertan station as an example. As shown in Fig. 4a, the hydrodynamic parameters in Ertan exhibited a "high-low–high" trend with significant fluctuations. The highest values of *v*, *Re*, and *Fr* occurred in the dam behind (i.e., reservoir head). Comparatively, the lowest *v*, *Re*, and *Fr* were observed at the reservoir area, with values of 0.29 m/s, 2.88×10^4, and 0.03, respectively. Then, the flow field became relatively unsteady at the dam head (reservoir tail), with the values of *v* and *Fr* increasing by 0.05 m/s and 0.005, respectively. Regarding the cascade dams (Fig. 4b), the *v* showed a significantly decreasing trend from upstream to downstream of the study area, with values ranging from 2.62 m/s to 1.38 m/s. The *v*-value from Jinping II to Guandi station dropped dramatically, accounting for over 50% of the total decrease in *v*. Besides, all *Fr*-values were less than 1 in the five studied reservoirs, indicating that the water belonged to supercritical flow. All *Re*-values were larger than 2300 thus the flow being turbulent.

3.2. Characteristics of fish diversity in the Yalong River

A total of 60 fish species from 4 orders were found in the Yalong River, based on our field investigation and a literature survey conducted by Sichuan Agricultural University (Table 5). The fish species were highly adapted to rapid and lotic water habitats in the study area. Spatially, the D_f decreased by 2.02 and D_g increased by 0.36 from the upstream to downstream (Fig. 5a). Compared with the upstream river reach, the D_g increased in a narrow range, but the D_f and $D_{g\text{-}f}$ decreased significantly. Therefore, the fish species diversity had a significant decrease from the upstream to downstream in the lower reaches of the Yalong River, with the value of $D_{g\text{-}f}$ falling from 8.19 to 6.17. On the temporal aspect, there were 79 fish species in the Yalong River in the 1980 s, and the number has decreased at an average rate of 24.05% over the past 30 years. As seen in Fig. 5b, the *H'* showed an increasing trend from 2004 to 2012, followed by a significant decline from 2013 to 2018. The *J'* and *D* revealed a slight increase from 2004, but subsequently showed a downward trend after 2015.Fig. 6..

3.3. Evaluation results of RLC in the Yalong River

The results of the evaluation indices for each dam are shown in Table 6. The highest and lowest scores occurred at the Guandi and Tongzilin hydropower stations, with total score values of 20 and 14, respectively. According to formulas (10) and (11), the RLC in the lower reaches of the Yalong River was moderate, with a value of 12.90. To provide references for decision-making regarding river ecological protection and management, three scenarios were established based on the actual status and future development plans of cascade reservoirs in the Yalong River. The number and distribution of cascade dams in the lower reaches of the Yalong River remained unchanged after the completion of the project in 2016. Scenario 1 aimed to enhance the hydropower development, resulting in a 10% decrease in the fish passage rate. Based on formula (9), the fish pass difficulty increased accordingly. The fish resources status, fish habitat quantity and quality were not affected by this scenario according to the evaluation criteria mentioned above. In Scenario 2, the objective was to maintain the existing status of cascade hydropower development. Scenario 3 was to improve the fish passage facilities, contributing to a 10% increase in the fish pass rate. Overall, the RLC in scenarios 1, 2, and 3 were 11.22, 12.90, and 14.74, respectively (Fig. 5b).

4. Discussion

4.1. Effects of cascade dams on river flow regime

The flow regime showed significant spatial heterogeneity in the

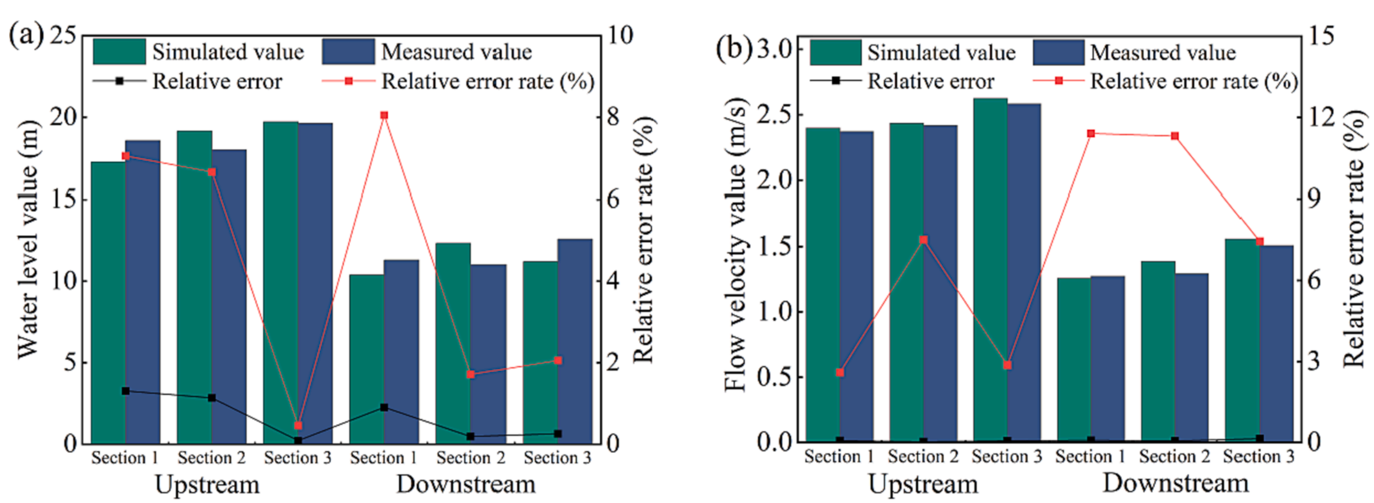

Fig. 3. Comparison of simulated and measured values of water level (a) and flow velocity (b) in the upstream (Jinping II station) and downstream (Tongzilin station) of the study area. Section 1, section 2 and section 3 refer to the reservoir area, reservoir tail and reservoir head, respectively.

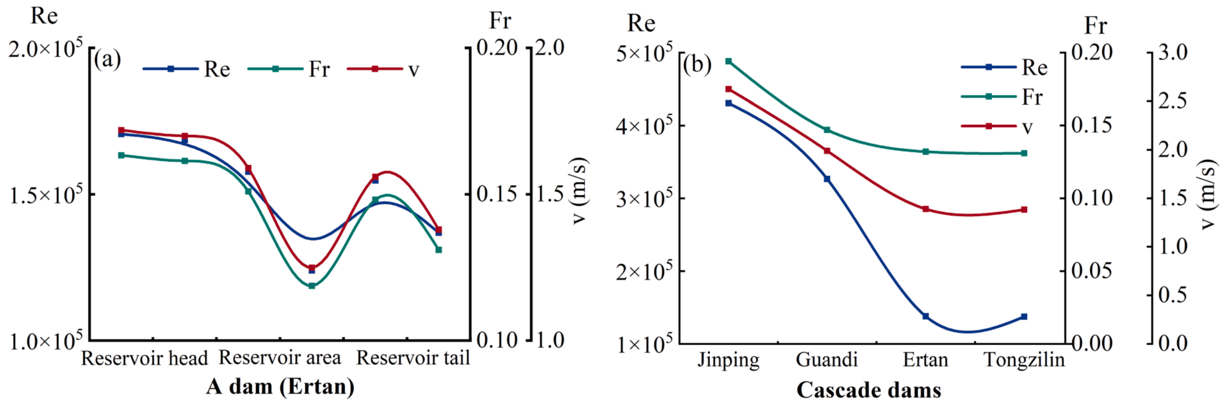

Fig. 4. Hydrodynamic simulation of the flow velocity (*v*), Reynolds number (*Re*) and Froude number (*Fr*) in a dam (a) and cascade dams (b) of the Yalong River.

Table 5
Statistics of fish diversity in the Yalong River.

Diversity	Cobitidae	Cyprinidae	Homalopteridae	Siluridae	Bagridae	Sisoridae	Serranidae	Channidae	Amblycipitidae	Synbranchidae
Genus	5	20	5	1	3	2	1	1	1	1
Percentage (%)	12.5	50.0	12.5	2.5	7.5	5.0	2.5	2.5	2.5	2.5
Family	10	30	6	2	4	4	1	1	1	1
Percentage (%)	16.67	50.00	10.00	3.30	6.67	6.67	1.67	1.67	1.67	1.67

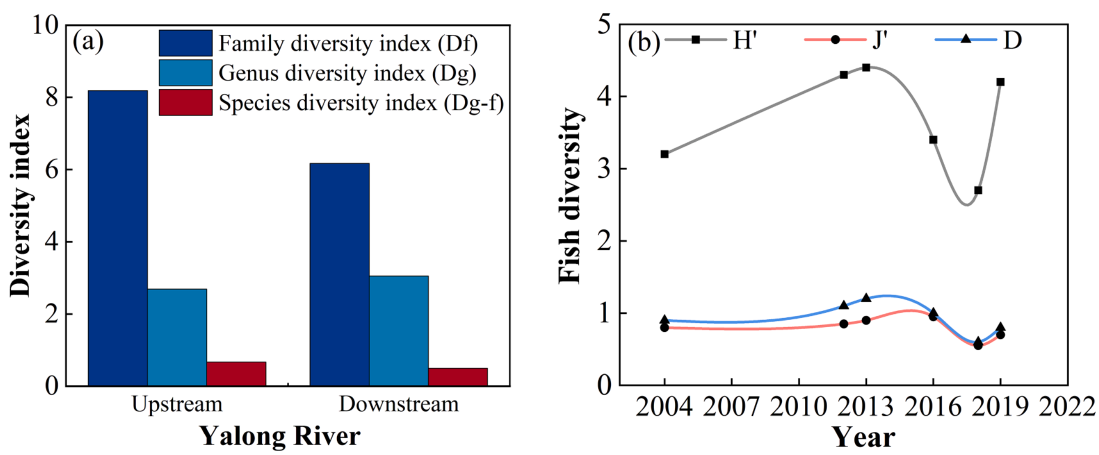

Fig. 5. The fish diversity in spatial (a) and temporal (b) changes in the Yalong River.

lower reaches of the Yalong River. As shown in Fig. 4, the cascade dams had significant implications for *v*, *Re* and *Fr*. Not surprisingly, over 75% of China's hydropower resources was located in Southwest China with the largest runoff variability (0.41%/year), where large numbers of reservoirs and dams have been constructed (Wang et al., 2019). With regard to a dam (Fig. 4a), the most steady flow field occurred in the reservoir area with the slowest velocity, where the vertical stratification pattern (e.g., temperature and sediment) was prone to appear and controlled by the reservoir throughput flow (Kasper et al., 2014; Yang et al., 2020). Then, the flow velocity generally increased in the reservoir head due to the effect of tailwater from cascade reservoirs. The hydrodynamic parameters (*v*, *Re*, and *Fr*) reached their largest values in the reservoir head, where the water and sediment were thoroughly mixed.

The hydrodynamic characteristics of cascade reservoirs were revealed in Fig. 4b. Relatively, the values of *v*, *Re*, and *Fr* showed a decreasing trend from Jinping upstream to Tongzilin downstream in the lower reaches of the Yalong River. Nevertheless, the fluctuation range varied significantly among different dams, which was strongly associated with reservoir operation and regulation (Wang et al., 2019; Shen et al., 2022). Overall, the water depth increased at the reservoir head, the flow velocity decreased in the reservoir area, and the supersaturated discharge varied in different seasons at reservoir tail. The natural river was segmented into a "river-dam-river" pattern by cascade dams, resulting in the destruction of river continuity and variations in flow regime (Best, 2019). The water in the reservoir area belonged to subcritical flow according to the open channel standard (*Fr* less than 1), further increasing sediment deposition due to the decrease in flow velocity and the prolongation of water retention time (Zarfl et al., 2015; Wu et al., 2023).

4.2. Effects of flow regime changes on fish diversity

The changes of flow regime for the cascade dams had a considerable influence on the composition, distribution, and population structure of fish (Barbarossa et al., 2020; Liu et al., 2021a). In the Yalong River, the significant decline from 2.62 m/s in Jinping II to 1.38 m/s in Tongzilin had critical effects on the growth, spawning, and reproduction of freshwater fish, particularly migratory and semi–migratory species (Dibble et al., 2015; Quan et al., 2021). The decline in fish species from upstream to downstream in the Yalong River was mainly due to the

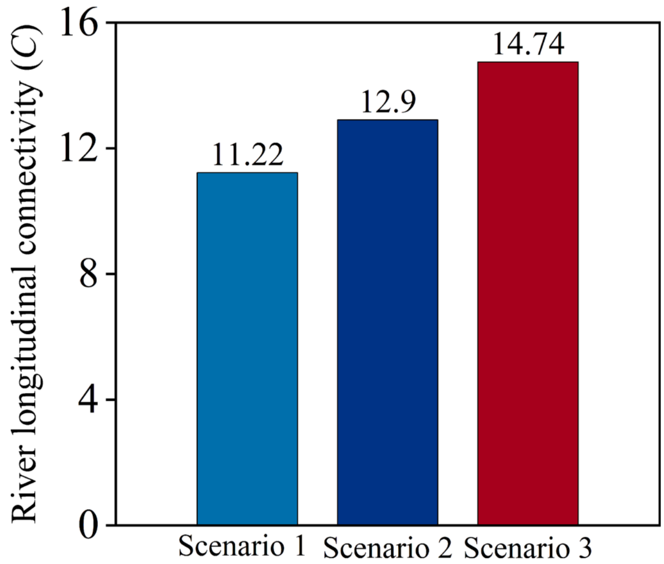

Fig. 6. River longitudinal connectivity in the three scenarios.

Table 6
Results of evaluation indices for RLC in the cascade dams of the Yalong River.

Hydropower station	Fish resources status	Fish pass rate	Fish pass difficulty	Fish habitat number	Fish habitat quality	Total score
Jinping I	2	2	3	4	5	16
Jinping II	2	3	2	5	5	17
Guandi	2	3	5	5	5	20
Ertan	2	3	4	5	5	19
Tongzilin	2	3	3	1	5	14

original flow regime variations attributed to the cascade dams. These findings were further confirmed by Wang et al. (2019) and Liu et al. (2021a), who highlighted that the dam was considered a key factor impacting runoff and subsequently affecting the fish habitat suitability in the Yalong River Basin. An early study by Yi et al. (2010) also proposed that the fluctuation of h and v in Gezhouba and Three Gorges Dams mostly determined the habitat suitability for fish spawning. Similar findings were also reported in the Mekong River (Grill et al., 2014), Wei River (Wu et al., 2023), Yangtze River (Deng et al., 2023), and other rivers.

Numerous studies have documented that the damming effect, which is associated with alterations in river flow regimes, may pose significant risks to fish species by affecting their habitats, spawning activities, foraging behaviors, migratory patterns, growth rates, reproduction capabilities, and even the overall life and health of fish (Zeng et al., 2019; Liu et al., 2021b). Specifically, the reservoir impoundment can increase the water depth upstream of the dam, thus altering fluvial geomorphology, such as the inundation of river banks and shoal areas. Consequently, the habitat and spawning grounds of shallow water fish (e.g., schistura and plateau loach fish) may encounter the risk of disappearance in the area (Wang et al., 2019). The reservoir discharge can enhance the scouring and erosion downstream of the dam, and the reservoir regulation can periodically inundate and expose fish habitats and spawning grounds during different seasons (Grill et al., 2017; Rodeles et al., 2020). In addition, the flow velocity significantly decreased in the reservoir area, thereby transforming the natural lotic river habitat into a lentic environment (Zarfl et al., 2015). This transformation posed a severe threat to rheophilic fish species, such as Cyprinidae (i.e., Coreius guichenoti), Loaches, Trichopteridae and Sinidae in the Yalong River (Liu et al., 2021a). These endemic fish species accounted for more than 80% of the study area (Table 5). They were more susceptible to the cumulative effects of cascade dams in their life cycles compared to other aquatic organisms in the longitudinal direction of the Yalong River (Zhang et al., 2022). On the other hand, the endemic fish species displayed varying responses to changes in flow regime during spawning. Many studies have proposed that the flow velocity requires to reach a certain threshold (greater than 0.25 m/s) for fish eggs to drift (Yi et al., 2010; Zhang et al., 2022). The formation of drift corridors in response to specific water flow provides a conducive environment for fish eggs to float and hatch. Moreover, the newborn fish have limited propulsive capacity to pass through large cascade dams without sufficient external forces owing to the slow-moving flow. In contrast, fish species that prefer lentic habitats may increase in reservoir areas, such as some bearded catfish, siberian catfish and loaches. However, their proportion was relatively small in the Yalong River, accounting for less than 20% of the total fish population. The spawning grounds for adhesive and demersal eggs can form when the water temperature requirements are met and the necessary substrates are available (Zhang et al., 2021).

Furthermore, variations in other hydrological elements of the river caused by flow regime changes also exerted a profound influence on fish species. In reservoir areas, the rise of h and decline of v prolonged water retention time and enhanced sedimentation, consequently altering the size and composition of natural river substrates (Jung et al., 2022). The composition of river sediments exhibited a gradual transition from coarse stones and gravel to fine sand and silt, which posed a challenge for fish species adapted to habitats with gravel and cobble substrates (Nogueira et al., 2021). On the contrary, in the downstream area of the dam, the sediment had a higher proportion of rocky particles than silty particles. This was mainly due to the scouring of reservoir discharge, which was unfavorable for fish that lived in caves and preferred muddy environments. Further, the stratification of water temperature could result in temperature hysteresis, probably leading to a delay in fish reproduction (Wang et al., 2020). Moreover, the changes in flow regime caused by large cascade dams could also result in fluctuations in the composition and distribution of fish food, posing a threat to a large proportion of demersal fish that fed on algae and benthic aquatic animals in the Yalong River (Nogueira et al., 2021). Obviously, there were many other factors affecting fish species in the cascade dams that needed further exploration, such as water dissolved oxygen, transparency, nutrients, composition, and transport of organic matter (Yang et al., 2020). Aside from these, the reduction in fish diversity was also attributed to multiple other factors, including environmental stressors and the characteristics of fish passes. Specifically, fish species may be injured or even killed by environmental stressors with high-speed and high-pressure water flow when passing through some dam structures, such as spillways and turbines (Alves et al., 2019). The migratory and endemic fish faced challenges in migrating to the upper river reaches to spawn because of the obstacle of dams (Hu et al., 2021). Besides, fish eggs and juveniles may have difficulty being carried downstream to habitats by water flow due to the lentic environment of reservoirs. The channels for material circulation and energy flow necessary for completing their life cycles probably be blocked (Zhang et al., 2022). Moreover, fisheries activities and the presence of pollution sources also contributed to the decline in fish populations in the Yalong River. A similar phenomenon was also found on the Gezhouba dam in the Yangtze River, where overfishing and habitat fragmentation posed a threat to fish diversity (Hoover et al., 2016).

4.3. Analysis of the RLC for cascade dams

An analysis conducted by Hu et al. (2021) revealed that the RLC reduced from 93% in 1960 to 25% in 2018 in China; and over 125 species of freshwater fish were threatened by the degradation and loss of habitats due to dam construction. More than 75% of the endemic fish preferred continuous flowing water environments, and most of them decreased and shrunk to the reservoir tails. For instance, the weight percentage of *schizothoracids* declined from 71.9% to 16.0% after the construction of the Ertan reservoir in the Yalong River (Jiang et al., 2007). Furthermore, the reduction of these endemic fish species and the shrinkage of their habitats would create opportunities for the invasion and colonization of exotic fish species. According to field investigation and literature analysis, 13 exotic fish species were found in the Ertan reservoir, which were well adapted to the lentic environment and sluggish flow (Zhang and Zheng, 2019). Some exotic fish even became common and dominant species in the cascade reservoirs of the Yalong River Basin, including *Neosalanx taihuensis*, *Pseudorasbora parva*, and *Rhinogobius giurinus*. These results were further confirmed by the Institute of Zoology, Chinese Academy of Sciences, which found that the exotic fish *Hemisalanx prognathus* became the primary catch in many reservoirs of the Jinshajiang River Basin in 2014, accounting for 80% to 90% of the total catch in the area. Notably, the Yalong River in Southwest China was identified as one of the most severely damaged hotspots of RLC due to the cascade dams. The RLC was significantly different for the cascade dams of the Yalong River. The Guandi station had excellent RLC (Table 2), with the highest scores for fish pass rate, fish pass difficulty, and fish habitat number among the studied cascade reservoirs. This was mainly because Guandi was the furthest from the upstream adjacent station (Jinping II), with a distance of 173 km. Therefore, the self-resilience and self-regulation of river ecosystems could be exerted over relatively long distances and periods of time. In contrast, the Tongzilin station displayed the lowest score for fish habitat number and a higher score for fish passage difficulty, with values of 1 and 3, respectively. This was mainly attributed to the nearest distance between Tongzilin station and its upstream adjacent station (Ertan). This close proximity resulted in a significant division of the river reach over a relatively short distance, leading to the lowest RLC (12.9). Moreover, the Tongzilin station was constructed in 2015 and put into operation in 2018 with the youngest reservoir age (Fang et al., 2022). Thus, the available time for the aquatic ecosystem to recover was comparatively shorter after the construction of the dam project. Specifically, earth-rock excavation, underwater drilling, and concreting exerted a significant influence on river sediment and topography, resulting in the depletion of crucial habitats, feeding grounds, and spawning areas for fish species (Alves et al., 2019). Notably, the effects of river fragmentation were persistent during the operation period of reservoirs after the project construction (Grill et al., 2019). The *H'* experienced a significant decline after the operations of the Jinping I, Jinping II, and Guandi reservoirs. Likewise, *J'* and *D* showed a downward trend after the operation of Tongzilin (Fig. 5b & Table 1). These findings indicated that the operation and regulation of reservoirs exerted a substantial influence on RLC by reducing fish diversity.

Compared to a single dam, the impact of cascade dams on RLC was mainly manifested in the cumulative effects. The cascade dams probably impeded the fish migration passage, leading to a significant decline in anadromous fish (Zeng et al., 2019) and a shrinkage of fish habitat (Grill et al., 2019; Jumani et al., 2020). Besides, the cascade dams hindered the material circulation and energy flow necessary for fish to complete their life cycles, resulting in a decrease in the fish species diversity and the potential extinction of fish populations (Barbarossa et al., 2020; Rodeles et al., 2020). Meanwhile, cascade dams also isolated fish species distributed in each reservoir with similar environmental conditions. This isolation impeded the genetic information exchange among these species, consequently reducing the diversity of fish species and subsequently impacting the aquatic food chain (Morita et al., 2009). Additionally, the flow discharge with low temperature and gas supersaturation had insufficient time to dilute or recover due to the dense adjacent cascade dams, may causing gas bubble disease in some fish species (Ma et al., 2018). A typical example of an endemic species in the Yalong River was *C. guichenoti.* This migratory fish had drifting eggs and experienced a significant decline due to the cumulative effects of cascade dams (Liu et al., 2021a). Notably, the *C. guichenoti* was listed as one of the priority protected species of the National Nature Reserve for rare fish in the Yalong River. Meanwhile, the reduction of fish diversity caused by fisheries along the Yalong River should also be considered (Zhang et al., 2020). Since the construction and operation of cascade reservoirs have significantly promoted economic development and human activities, the price of fish products has likely risen, thereby exacerbating the problem of excessive fishing driven by financial interests (Faucheux et al., 2022). Furthermore, the noise pollution caused by dam operations may result in the loss of fish orientation, thus increasing the probability of fish being captured.

As shown in Table 6, the RLC did not regularly decrease from upstream to downstream of the Yalong River. This suggested that the cumulative effect of cascade dams on RLC could not be simply described as a regular spatial increase. The distribution and distance of different dams were the most important factors for RLC. Not strangely, the intensive distribution of cascade dams contributed to river fragmentation with strong cumulative effects, thus affecting fish growth, reproduction, spawning, migration, and species diversity (Grill et al., 2017; Ma et al., 2018). The findings were consistent with Miranda and Dembkowski. (2016) who demonstrated that there were significant differences in the diversity of rush-flowing fish from the upstream to downstream areas, which were attributed to the cumulative effects of cascade reservoirs in the Tennessee River. In addition, the regulation and operation of reservoirs, as well as the degree of hydropower development, also had significant impacts on RLC. These factors may compromise the natural conditions of dual stimulation for river temperature and flow, which were essential for most fish species in the study area. Specifically, the scheduling of cascade reservoirs would change the river discharge downstream of each dam. Moreover, the five studied hydropower dams had large reservoir capacities and high regulation performance, making rivers more susceptible to water temperature stratification. Furthermore, the construction of fish passage facilities was an effective measure to increase the RLC, which had implications for improving fish pass efficiency and reducing the negative impacts of changes in natural hydrodynamic conditions (Noonan et al., 2012; Mao et al., 2019). In this study, the improvement of fish migration passage in scenario 3 could significantly recover the RLC, with the value of *C* increasing by 1.84. This finding was further confirmed by Zhang et al. (2020), who found that the fish passage facilities had the optimal effect when the v-value was 500–1500 m^3/s in the Yalong River. Not strangely, the passage facilities could connect fragmented habitats, regulate flow regimes, and restore fish migration, thus realizing the increase of fish diversity by improving RLC (Food and Agriculture Organisation, 2002). In the early 21st century, the Water Law and Fisheries Law of the People's Republic of China established standards for the construction and maintenance of fish passes by assessing the impact of dams on aquatic organisms. As of 2018, China has constructed over 100 large-scale fish passes. The fish passage facilities with a U-shaped structure were constructed in the Yalong River Basin. These facilities were installed with vertical slot fish passes at certain intervals to simulate the natural flow of a river.

Since the requirements of different fish species in fish passages were difficult to simultaneously meet, many fish passage facilities failed to produce the expected effects in the Yalong River. Therefore, fish behaviors (e.g., migration patterns, swimming capacity) and historical traits should be taken into consideration when designing fish passage facilities to achieve the desired practical effects (Zhang et al., 2020). Many studies also reported that selecting the type and position of entrance structures, and the primary operation time, were conducive to achieving the expected effectiveness of fish passage (Mao et al., 2019; Zhang et al., 2022). Many measures were implemented to improve the efficiency of fish passes and promote the RLC, such as the construction of a fish collection gallery, the installation of a fish hoist, and the facilitation of fish migration over a dam through the automated guided vehicles and fish ships. As a result, the number of fish species passing through the cascade dams significantly increased, especially the *Schizothorax prenanti*, *Schizothorax dolichonema*, *Schizothorax kozlovi*

Nikolsky, and *Schizothorax wangchiachii*. Given the inadequate consideration of fish pass design and construction, high maintenance costs, and unclear authority and responsibility for fish pass management, it is necessary to simultaneously complement other compensatory measures such as artificial spawning, proliferation, and fish release. Up to now, four fish restocking stations have been built in the Yalong River Basin covering all the cascade dams, including the Jinping-Guandi, the Ertan-Tongzilin, the Yalong River middle reach, and the Lianghekou fish restocking stations. Overall, it should be noted that the new evaluation index system is a reasonable and easy method for assessing RLC. However, its application is mainly focused on the river upstream with a dense distribution of cascade reservoirs. Further research is needed to improve this index-based method, making it applicable to a wider range of rivers with fewer constraints in future studies.

5. Conclusions

Cascade dams have a profound impact on natural flow regimes, thus affecting the aquatic ecosystem, particularly for endemic and migratory freshwater fish. This study proposed a new index-based method for evaluating RLC, and applied it in the lower reaches of the Yalong River in China. In this study, the Delft3D model was used to compare the flow fields in the reservoir area, reservoir head, and reservoir tail. The results showed that the flow field in the reservoir area was the most stable. Besides, the water belonged to turbulent (*Re* greater than 500) and sluggish flow (*Fr* less than 1) in the reservoir area. These changes in flow regimes had a significant influenced on fish species and their habitats, resulting in a noticeable decline in fish diversity from upstream to downstream of the Yalong River, with a value of $D_{g\text{-}f}$ decreasing from 8.19 to 6.17. Based on the proposed evaluation method associated with five fish-related indices, the study area exhibited a moderate RLC with a value of 12.90. The RLC among the five studied reservoirs was significantly different, probably due to their locations, distributions, distance, reservoir operations and regulations, and the cumulative effects of cascade dams. The lowest and highest scores of RLC occurred in the Tongzilin and Guandi hydropower stations, respectively. By comparing three scenarios, RLC could significantly increase by improving fish passage facilities. Overall, this study conducted exploratory work on the selection and quantification of indices for evaluating RLC, which still needed to be validated in practice. Regardless, this framework provides a novel perspective on the RLC assessment, which can guide cascade reservoir prioritization decisions, such as dam removals and new location selection.

CRediT authorship contribution statement

Zhimin Yang: Conceptualization, Methodology, Formal analysis, Data curation, Writing–original draft. **Jiuhe Bu:** Investigation, Validation. **Zhi Li:** Methodology, Data curation. **Chunhui Li:** Resources, Methodology, Writing–review & editing. **Yunjun Yi:** Validation, Writing–review & editing. **Xuan Wang:** Writing–review & editing. **Qiang Liu:** Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2022YFC3202001), the Joint Funds of the National Natural Science Foundation of China (U2243236)

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