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Ecological Health Assessment with the Combination Weight Method for the River Reach after the Retirement and Renovation of Small Hydropower Stations

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Abstract: This study aimed to effectively evaluate the ecological restoration of the river reach where a small hydropower station was retired or renovated. An ecological health index system was constructed based on the environmental characteristics of the upstream and downstream of the small hydropower station after its retirement and renovation. Based on the combination weighting concept of game theory, the combination weights were obtained by the comprehensive analytic hierarchy process (subjective weight) and entropy method (objective weight). This ecological health assessment with fuzzy comprehensive evaluation was applied to assess the health status of Shimen (dam removal) and Changqiao (renovation in ecological flow) reaches of the Tufang River in Changting County, China. The results showed that the ecological health assessment index system proposed in this study was comprehensive and reasonable, and the revision degree of the hydropower station obviously influenced the process of ecological river restoration. The findings from this study would benefit for the rational utilization of water resources and the river ecological health maintenance in mountainous areas.

Keywords: river health; small hydropower stations; retirement and renovation; combined weight; game theory; fuzzy evaluation; entropy method

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1. Introduction

Small hydropower is distributed in small- and medium-sized mountainous rivers [1], and it is recognized as clean energy by the international community. There is no international consensus regarding the definition of “small hydropower”. In China, it can refer to an installed capacity of no more than 25 MW, while the maximum capacity is 15 MW in India. However, it is generally believed that the installed capacity of small hydropower stations is less than 10 MW in Europe [2]. According to the National Bureau of Statistics of China, the number of small hydropower stations was 43,957 by the end of 2020 with a total installed capacity of 81.338 million kW and a total annual generation of 242.37 billion kW·h. Small hydropower stations play a crucial role in rural electrification, economic development, and environmental sustainability in China. However, some rivers have been developed for electricity in a high-intensity and disorderly manner, and the diversion of hydropower stations [3] has especially caused a series of serious ecological problems such as river water reduction and drying up, fish degradation, water quality deterioration, and so forth. In 2021, the Chinese Government issued opinions on further improving small hydropower stations by scientific and comprehensive evaluations as well as dismantling hydropower stations located in the core areas or buffer zones of nature reserves. The government has also required the retirement of illegally built, ecologically dangerous, and oversized structures as well as those failing to meet the requirements for the protection of aquatic organisms. Hydropower stations, whose dams have serious potential safety hazards, needed to be rectified. Currently, the methods most commonly used to improve small hydropower stations are as follows [4]: (1) The dam is removed, and the water is basically restored to the natural river. (2) The dam is not removed, and the bottom hole discharge is carried out to restore the water to the river channel. (3) The water-retaining gate is opened, and the water flow is discharged from the gate during the dry period. (4) The drainage channels are added through reconstruction. (5) Through the transformation of ecological units, the ecological flow is maintained. In spite of the sharp increase in dam demolition projects, the research on the biophysical response of dam demolition is limited [5]. There is not a suitable system for evaluating the ecological health of rivers after the retirement and renovation of hydropower stations to demonstrate and evaluate the restoration of river ecosystems.

The retirement and renovation of small hydropower stations is a workable opportunity for restoring the natural functions of rivers and reconstructing river ecosystems [6]. Climate change leads to more water scarcity and extreme weather events [7–10], and it is necessary to properly evaluate the ecological health of rivers after the retirement and renovation of small hydropower stations. The evaluation indicators must fully reflect the relevant ecological and environmental effects. The river ecological health assessment under the influence of existing small hydropower stations usually involves selecting indicators such as hydrological and water resources, water quality, water temperature, biodiversity, zooplankton community richness, macroinvertebrate community richness, physical habitat quality, and so forth [11–20]. However, small hydropower stations are mostly located in the areas lacking data on small- and medium-sized rivers. The aforementioned indicators have the following shortcomings when used in the postretirement assessment of small hydropower stations: The different characteristics of the reservoir section and the dehydration reduction section are not considered due to the lack of adaptability of the postrenovation assessment of small hydropower stations, which affects the accuracy of the final evaluation results. It is necessary to construct an evaluation index system with reasonable structural levels and standards according to the dynamic changes in the ecological environment, as well as the full impact of the retirement and renovation of small hydropower stations on the river reach. Changes in the natural ecology of the reservoir section and the dehydration reduction section also must be taken into account. An effective evaluation system could be used for the qualitative and quantitative assessment of areas upstream and downstream of the dam, which would reveal the ecological health status of the river section after the retirement and renovation of small hydropower stations.

Many methods are available for river ecological health assessments, mainly including gray clustering [21], principal component analysis (PCA) [22], fuzzy comprehensive evaluation [23], and set pair analysis [24]. River ecological health assessment involves numerous, complex phenomena and interactions among various factors, which include many fuzzy phenomena and fuzzy concepts [25]. It is necessary to incorporate the fuzziness of river ecological health when evaluating the effects of the retirement and renovation of small hydropower stations. In this study, a fuzzy comprehensive assessment is applied to resolve uncertainty problems in the assessment. However, the weight distribution of this method is subjective [26]. Reasonably determining the corresponding contribution rates of leading factors in complex river environments is a crucial part of the ecological health assessment.

Index weights are mainly determined by subjective or objective weighting methods [27]. Subjective weighting methods directly reflect the preferences of decision makers but ignores the values of the original index data. These include the analytic hierarchy process (AHP) [28], expert surveys (Delphi) [29], and others. Although objective weighting methods better integrate the utility of the index data itself, they do not account for the subjective preferences of decision makers. These include PCA [30], entropy weighing [31], and others. A method with the advantages of subjective and objective weighting should be used to determine index weights. Such a combined weighting method [32–34] can comprehensively consider subjective and objective factors in the river ecological health assessment, take into account the utility value of the original data while considering the preferences of decision makers, and improve the accuracy and efficacy of the weight distribution.

In this study, an index system suitable for the ecological health assessment of river reaches after the retirement and renovation of small hydropower stations was constructed. The combination weight, based on game theory, determines the index weights, and fuzzy comprehensive evaluation reveals the ecological health status of the river section. This provides an accurate ecological health assessment while comprehensively accounting for both subjective and objective factors. The Shimen (dam removal) and Changqiao (renovation in ecological flow) river sections of the Tufang River were used as the study area to test the proposed method.

2. Methods

2.1. Index System

Compared to lowland rivers, mountainous rivers containing small hydropower stations show more intense hydrologic changes, more variable gradients and morphologies, poorer nutrition, and clearer spatial variations in the ecosystem under external influences [35]. The ecological impacts of dam demolition are short term and long term. Short-term ecological impacts include flow, water temperature structure, sediment transport, and connectivity. Long-term ecological impacts include biodiversity and morphological structure [36]. These impacts may divide into hydrological characteristics, water quality characteristics, biological characteristics, and morphological structure characteristics. In this study, we considered environmental changes in the upstream and downstream reaches of the dam after the retirement and renovation of small hydropower stations and previous research [37–40] to determine the index system. The hydrological characteristics include the flow reduction degree and water area change degree. Water quality characteristics include the stability of water temperature structure upstream and downstream of the dam, DO, TN, and BOD_5. Biological characteristics include the fish diversity index and benthic animal diversity index. Morphological structure characteristics include lateral stability, sediment type, and longitudinal connectivity. The index system is shown in Table 1.

Table 1. Hierarchy of the ecological health assessment system of the river reach after the retirement and renovation of small hydropower stations.

Target Layer	Criterion Layer	Index Layer
Ecological health of river reach A	Hydrological characteristics B_1	Flow reduction degree C_{11} Change degree of water area C_{12}
	Water quality characteristic B_2	Stability of water temperature structure in upstream and downstream of dam C_{21} DO C_{22} Total nitrogen (TN) C_{23} BOD_5 C_{24}
	Biological characteristics B_3 Morphological structure characteristics B_4	Fish diversity index C_{31} Benthic animal diversity index C_{32} Lateral stability C_{41} Sediment type C_{42} Longitudinal connectivity C_{43}

Small hydropower stations are mostly located in small- and medium-sized ungauged rivers in mountainous areas. The removal of dams, bottom hole discharge, ecological flow renovations, and other different small hydropower stations retirement and renovation methods will directly affect the water supply of the downstream river channel of the dam. The traditional Tennant method to calculate the ecological flow is susceptible to seasonal changes and short-term precipitation [41]. According to the retirement and renovation mode of small hydropower stations and the water diversion situation, a qualitative description of the flow supplied downstream of the dam is more accurate. After the retirement and renovation of the small hydropower stations, the flow velocity of water accelerates, water temperature delamination is weakened due to an increase in water flow mixing, and the overall water temperature structure of the river section is more stable.

Further, the riverbed sediment changes due to adjustments to the river channel morphology, sediment scouring, and silting characteristics. The velocity of water in the upstream of the dam thus accelerates, which erodes the fine sediment in the reservoir area, exposes downstream gravel and pebble bases, and improves the aquatic habitat quality [42]. The sediment supply slowly returns to its natural level, increasing the lateral movement of the river channel and the erosion of the floodplain surface. Therefore, a qualitative description of the sediment condition of the river channel is appropriate.

Finally, "connectivity" reflects the integrity of the river. Qualitative evaluation can provide a rational ecological health evaluation of the upstream and downstream reaches of the dam according to the number of buildings or facilities in the river, which affect its connectivity.

To summarize, our model includes qualitative evaluations of the flow reduction degree, water temperature stability in upstream and downstream areas of the dam, sediment type, and longitudinal connectivity as well as quantitative evaluations of the water area change degree, fish diversity index, benthic animal diversity index, and other indicators.

The change degree of water area: After the removal of small hydropower stations, the hydrological process is in an unregulated natural state. The water is restored to the river, which directly changes the regional microecology and microclimate of the water area formed by the original dam [43]. Compared with before and after the retirement and renovation of small hydropower stations, the change in water area directly affects the distribution of organisms in aquatic zones, land and water exchange zones, and terrestrial zones. A smaller change compared with that before the renovation indicates a higher reduction degree:

$$DC = \frac{|AE|}{BE} \times 100\% \tag{1}$$

where DC is the change degree of the water area, %; AE is the changed water area in the upstream and downstream area of the dam after the retirement and renovation of small hydropower stations, m^2; and BE is the water area before the retirement and renovation of small hydropower stations, m^2.

The fish diversity index and benthic animal diversity index: The study of fish and benthic functional communities in rivers contributes to the restoration of ecologically damaged rivers, restoration of fishery resources and biodiversity, and safety of drinking water sources. Assessments of these communities are mainly based on the difference between the current number of species and the number of species at a historical reference point. Similarly, a benthic animal assessment is mainly based on a comparison of the status of benthic animals at a damaged point and reference point. [44] The study area in our case was a small watershed, where no historical fish reference points or monitoring data exist, so we used the Shannon–Wiener index [45] to evaluate the stability of fish and benthic community structures. A higher such index indicates more stable communities and stronger self-healing abilities among them. For rivers without historical reference points, the Shannon–Wiener diversity index has considerable flexibility and subjectivity:

$$H' = -\sum Pi \cdot lnPi \;\; i = 1, 2, \ldots S, \tag{2}$$

where H' is the Shannon–Weiner diversity index and Pi is the proportion of the number of individuals in the total number of individuals.

Lateral stability: The lateral spatial characteristics of the river are reflected in the interaction between water and land. The lateral morphological structure must remain stable for the river to be stable overall. Small hydropower stations are mostly located in areas without data on small- and medium-sized rivers, as mentioned above, so we calculated the lateral stability using the ratio of river flow to actual river width. The bank is more stable when this ratio is larger [37]:

$$Q_{bi} = \frac{Q^{0.5}}{J^{0.2}B} \tag{3}$$

where Q_{bi} is the lateral stability; Q is the river flow, m^3/s; J is the gradient of the river; and B is the actual river width, m.

2.2. Index Classification Standard

River ecological health is a relatively complex concept. A healthy river ecosystem should have a reasonable organizational structure and good operation function. The material circulation and energy flow within the system should not be damaged, the kinetic energy should remain elastic despite long-term or sudden natural or man-made disturbances, and the system should show diversity, resilience, and complexity. The reasonable overall health status of the river is established according to the evaluation criteria of each evaluation index in this study. According to previous research [37–40] and the environmental quality standards for surface water [46], the health standards of all indexes are divided into five grades: (1) very healthy; (2) healthy; (3) subhealthy; (4) unhealthy; and (5) morbid. The health standards of all indexes are presented in Table 2.

Table 2. Criteria for ecological health assessment index system of small hydropower station.

Index Layer	Very Healthy	Healthy	Subhealthy	Unhealthy	Morbid
Quantitative index score	(80–100)	(60–80)	(40–60)	(20–40)	(0–20)
Qualitative index score *1	100	80	60	40	20
Flow reduction degree $C1_1$	The dam is completely removed, and the water is fully restored to the natural river channel	The dam is not demolished, and the discharge from bottom hole is carried out to restore the water to the river	The dam is not removed, the water-retaining gate is opened, and the water flow is discharged from the gate in the dry season, with diversion in the diversion channel	The ecological renovation is carried out by adding drainage channels and ecological units to maintain the discharge of ecological flow	Diversion power station without ecological flow renovation
Change degree of water area $C1_2$	<15	[15, 30)	[30, 45)	[45, 60)	≥60
Stability of water temperature Structure in upstream and downstream of dam *2 C_{21}	The water temperature structure of upstream and down-stream reaches of dam is the same as that of the natural river, stable and without obvious water temperature stratification	The overall water temperature structure of upstream and downstream of dam is less affected by the dam, close to the natural river state	Reservoir section transports water to downstream of dam through surface overflow, and there is difference in water temperature structure between upstream and downstream of dam	The reservoir section transports the bottom water temperature to the downstream through drainage channels and facilities, and the water temperature structure in upstream and downstream of dam is different and unstable	There is no discharge flow in the reservoir area and no water temperature structure in the downstream of dam
DO [46] C_{22}	≥6	[5, 6)	[3, 5)	[2, 3)	[0, 2)
TN [46] C_{23}	≤0.5	[0.5, 1)	[1, 1.5)	[1.5, 2)	≥2
BOD_5 [46] C_{24}	≤3	[3, 4)	[4, 6)	[6, 10)	≥10
Fish diversity index [38] C_{31}	≥2	[1.5, 2)	[1, 1.5)	[0.5, 1)	<0.5
Benthic animal diversity index [39] C_{32}	≥3	[2, 3)	[1, 2)	[0, 1)	0

Table 2. *Cont.*

Index Layer	Very Healthy	Healthy	Subhealthy	Unhealthy	Morbid
Lateral stability coefficient [37] C_{41}	≥1.5	[1.2, 1.5)	[1, 1.2)	[0.8, 1)	<0.8
Sediment type [40] C_{42}	Bedrock, cobble and gravel, sand, clay of 4 categories appear	Bedrock, cobble and gravel, sand, clay appear in 3 categories	Bedrock, cobble and gravel, sand, clay appear in 2 categories	Bedrock, cobble and gravel, sand, clay appear in 1 categries	Riverbed is hardened without containing any of the above components
Longitudinal connectivity C_{43}	The dam is completely removed without retaining the dam foundation. At the same time, the river channel is cleared, which does not affect the normal migration of fish	The dam is re-moved, the dam foundation is retained, and the water is restored to the natural river channel, which has a small impact on fish migration	The dam is not removed, and the bottom hole discharge is carried out to restore the water to the river, which has a partial impact on fish migration	The water-retaining gate is opened, and the water flows from the gate in the dry season, so the fish cannot migrate correctly	The ecological transformation is carried out by adding drainage channels and ecological units to maintain the discharge of ecological flow, and fish cannot migrate normally

Notes: *[1] If the qualitative index meets the description, the corresponding score will be given. *[2] For the retired hydropower stations, the upstream and downstream of the dam refers to the upstream and downstream of the original dam site.

2.3. Determination of Weight

2.3.1. Analytic Hierarchy Process Determines Subjective Weight

AHP is a sophisticated decision-making method combining qualitative and quantitative analyses. The AHP model is operated by dividing the system into a target layer, criterion layer, and index layer, then constructing the judgment matrix, then calculating the weight of the judgment matrix, and finally checking the consistency of the judgment matrix [47].

(1) Construct judgment matrix
The ecological health assessment of the river section after the retirement and renovation of the small hydropower station is divided into three levels. The target layer is the ecological health of the river reach (A). The criterion layer includes hydrological characteristics (B_1), water quality characteristics B_2, biological characteristics B_3, and morphological structure characteristics B_4, and the index layer includes the flow reduction degree C_{11}, change degree of water area C_{12}, and other indicators as shown in Table 1.

(2) Determine the weight vector and consistency check:

$$A \cdot \omega = \lambda_{\max} \cdot \omega, \tag{4}$$

where A is the judgment matrix, $\lambda_{\max}$ is the largest characteristic root, and ω is a feature vector.

(a) Calculate the numerical product of each row of the judgment matrix A to determine M and calculate the eigenvector W:

$$Wi = \sqrt[n]{M}, \tag{5}$$

(b) Calculate the maximum eigenvalue $\lambda_{\max}$ according to the feature vector W:

$$\lambda \max = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW^T)i}{Wi}, \tag{6}$$

(c) Define the consistency indicators CI:

$$CI = \frac{\lambda\max - n}{n - 1}, \quad (7)$$

(d) Introduce the random consistency index RI:

$$RI = \frac{CI_1 + CI_2 + \ldots + CI_n}{n}, \quad (8)$$

(e) Compare CI with the random consistency index RI to obtain the test coefficient CR. When $CR \leq 0.1$, the consistency is good:

$$CR = \frac{CI}{RI}. \quad (9)$$

2.3.2. Entropy Weight Method Determines Objective Weight

For river sections, the river ecosystem information entropy of evaluation indexes can be calculated as follows [48]:

(1) Form the original data matrix $\text{X} = \left(x_{ij}\right)_{m\times n}$ and normalize x_{ij} to determine P_{ij}:

$$P_{ij} = \frac{x_{ij}}{\sum\limits_{i=1}^{m} x_{ij}} \quad i = 1, 2, \ldots m; j = 1, 2, \ldots n, \quad (10)$$

where Pij represents the proportion of the index j to the sample i and x_{ij} represents the original value of the evaluation indicator j for the sample i.

(2) Calculate the entropy of index j:

$$e_j = -\sum_{i=1}^{m} p_{ij} \cdot \ln p_{ij} \quad i = 1, 2, \ldots m; j = 1, 2, \ldots n, \quad (11)$$

where e_j represents the entropy value and Pij represents the proportion of the index j to the sample i.

(3) The weight of j indicators is calculated:

$$u_j = \frac{1}{e_j} \quad j = 1, 2, \ldots n, \quad (12)$$

$$\beta_j = \frac{u_j}{\sum\limits_{j=1}^{n} u_j}, \quad (13)$$

where β_j represents the weight of the index j.

2.4. Combination Weighting Method

Based on the combination weighting concept under game theory, the subjective and objective weights calculated by AHP and entropy weight methods, respectively, are combined, which would compensate the drawbacks from subjective errors and deviations in data acquisition and processing. The consistency of subjective and objective weighting is determined using the following distance function:

$$d(W^{(1)}W^{(2)}) = \left[\frac{1}{2}\sum_{j=1}^{n} (W_j^{(1)} - W_j^{(2)})^2\right]^{\frac{1}{2}}, \quad (14)$$

When $0 \leq d(W^{(1)}W^{(2)}) \leq 1$, the smaller the $d(W^{(1)}W^{(2)})$, the closer the two weighting results.

The calculation steps of combination weighting based on game theory are as follows [49]:

(1) $U| = \{u_1, u_2, \ldots u_n\}$ is used to represent a basic set of weight vectors, and linearly combine these n vectors into a possible set of weights:

$$U = \sum_{k=1}^{n} \alpha_k u_k^T (\alpha_k > 0), \tag{15}$$

where $U|$ is a basic weight vector set, U represents a possible weight vector of the possible weight vector set, α_k represents the weight coefficient, and u_k represents the weight vector.

(2) The most satisfactory weight vector was found to optimize α_k to minimize the deviation between U and each U_k:

$$\min \parallel \sum_{j=1}^{n} \alpha_j \times u_j^T - u_i^T \parallel_2 \ i = 1, 2, \ldots n. \tag{16}$$

(3) According to the differential property of the matrix, the first derivative condition of Equation (16) optimization is:

$$\sum_{j=1}^{n} \alpha_j \times u_i \times u_i^T = u_i \times u_i^T \ i = 1, 2, \ldots n. \tag{17}$$

(4) Equation (17) was converted into the following set of linear equations:

$$\begin{pmatrix} u_1 \cdot u_1^T & u_1 \cdot u_2^T & \ldots & u_1 \cdot u_n^T \\ u_2 \cdot u_1^T & u_2 \cdot u_2^T & \ldots & u_2 \cdot u_n^T \\ \vdots & \vdots & \vdots & \vdots \\ u_n \cdot u_1^T & u_n \cdot u_2^T & \ldots & u_n \cdot u_n^T \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{pmatrix} = \begin{pmatrix} u_1 \cdot u_1^T \\ u_2 \cdot u_2^T \\ \vdots \\ u_n \cdot u_n^T \end{pmatrix}. \tag{18}$$

(5) The set $(\alpha_1, \alpha_2 \ldots \alpha_n)$ is obtained and normalized as:

$$\alpha_k^* = \frac{\alpha_k}{\sum_{k=1}^{n} \alpha_k}. \tag{19}$$

(6) Determine the combined weight:

$$u^* = \sum_{k=1}^{n} \alpha_k u_k^T. \tag{20}$$

2.5. Fuzzy Comprehensive Assessment

Fuzzy comprehensive evaluation is based on fuzzy mathematics. According to the membership degree theory of fuzzy mathematics, the uncertainty problems restricted by various factors can be quantitatively described. The results are clear and systematic. It is better to solve the fuzzy and difficult to quantify problems and is suitable for solving various uncertain problems [50].

(1) Determine the evaluation set:

$$V = \{V_1, V_2, \ldots V_i\}, \tag{21}$$

where V_j represents the criteria of the level $i(i = 1, 2, 3, \ldots, 5)$ comment set corresponding to the target layer, criterion layer, and index layer, including five states of very healthy, healthy, subhealthy, unhealthy, and morbid. The comment set specifies the scope of the description of the evaluation results.

(2) Determination of membership

When the standard value and weight value of each index are known, the trapezoidal distribution membership function can determine the fuzzy membership of the index layer, criterion layer, and index layer:

The membership function of the smaller and better index is:

$$r(x) = \begin{cases} 1, x < a \\ \frac{b-x}{b-a}, a \le x \le b \\ 0, x > b \end{cases}, \tag{22}$$

The membership function of the larger and better index is:

$$r(x) = \begin{cases} 0, x < a \\ \frac{x-a}{b-a}, a \le x \le b \\ 1, x > b \end{cases}, \tag{23}$$

where x is the critical value of each evaluation factor, a and b are the critical values classification of each evaluation factor, and $r(x)$ is the membership expression corresponding to each level of the evaluation set.

(3) According to the characteristics of each index, the membership function of each index is drawn up, and the membership matrix R_i is established. Then, the comprehensive evaluation model is:

$$R_i = \begin{bmatrix} r_{i11} & r_{i12} & r_{i13} & r_{i14} & r_{i15} \\ r_{i21} & r_{i22} & r_{i23} & r_{i24} & r_{i25} \\ r_{i31} & r_{i32} & r_{i33} & r_{i34} & r_{i35} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{im1} & r_{im2} & r_{im3} & r_{im4} & r_{im5} \end{bmatrix}, \tag{24}$$

where R_i is the membership matrix of the I criterion layer, which represents the number of indicators contained in the I criterion layer.

(4) Multilevel fuzzy comprehensive evaluation

The river health ecological assessment system is composed of three structural levels: the target layer, the index layer, and the criterion layer. It can be divided into an index layer reflecting the criterion layer and criterion layer reflecting the two-level fuzzy comprehensive assessment of the target layer.

(a) The fuzzy evaluation of the indicator layer reflecting the criterion layer is:

$$B = \{B_1, B_2, B_3, B_4\}^T, \tag{25}$$

$$B_i = \omega_c \circ R_i = (\omega_{ci1}, \omega_{ci2}, \ldots, \omega_{cim}) \circ \begin{bmatrix} r_{i11} & r_{i12} & r_{i13} & r_{i14} & r_{i15} \\ r_{i21} & r_{i22} & r_{i23} & r_{i24} & r_{i25} \\ r_{i31} & r_{i32} & r_{i33} & r_{i34} & r_{i35} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{im1} & r_{im2} & r_{im3} & r_{im4} & r_{im5} \end{bmatrix}, \tag{26}$$

where B_i is the fuzzy evaluation result of the criterion layer of level $i (i = 1, 2, \ldots, 4)$.

(b) The recursion to the criterion layer to reflect the fuzzy evaluation of the target layer is:

$$A = \omega_B \circ B = (\omega_{B1}, \omega_{B2}, \ldots, \omega_{Bm}) \circ \begin{bmatrix} \omega_{c1} \circ R_1 \\ \omega_{c2} \circ R_2 \\ \omega_{c3} \circ R_3 \\ \omega_{c4} \circ R_4 \\ \omega_{c5} \circ R_5 \end{bmatrix} = (A_1, A_2, A_3, A_4, A_5), \quad (27)$$

where $A_i (i = 1, 2, 3, \ldots, 5)$ is the membership degree of the grade comment i, ω_B is the combined weight of the criterion layer relative to the target layer, ω_c is the combined weight of the index layer relative to the criterion layer, and "$\circ$" is a fuzzy composition operator.

3. Study Region

The Tufang River is located in Tufang Town, Changting County, Longyan City, China. It has a catchment area of 150 km^2, a river length of 40 km, and a river slope of 8.1‰. It is a typical mountainous river with a steep slope, a rapid natural flow, and many gravels and boulders at the bottom of the riverbed. Xiyuan, Hongfang, Tufang, Laifang, Shimen, Changqiao, and other diversion-type small hydropower stations are successively distributed from upstream to downstream of the Tufang River. This density of hydropower stations has resulted in a long river cutoff length which does not align with the water usage habits of local residents.

In this study, the upstream and downstream reaches near Shimen and Changqiao stations were taken as key research areas to explore the ecological restoration of the river after the retirement and renovation of small hydropower stations. Shimen and Changqiao are diversion hydropower stations located in Jingkou Village and Changqiao Village, Tufang Town, Changting County, China, respectively. In 2015, Shimen was completely retired, the dam was demolished, and the river channel was basically restored to its natural state. The Changqiao dam was not demolished, only ecological flow reconstruction to maintain the ecological flow supply occurred there. Accordingly, the "retirement degree" of Shimen was greater than that of Changqiao. The data we used here were derived from field investigations and the satellite remote sensing of upstream and downstream reaches of Shimen and Changqiao stations in the dry seasons of 2018 and 2019. The river system distribution of Tufang River is shown in Figure 1.

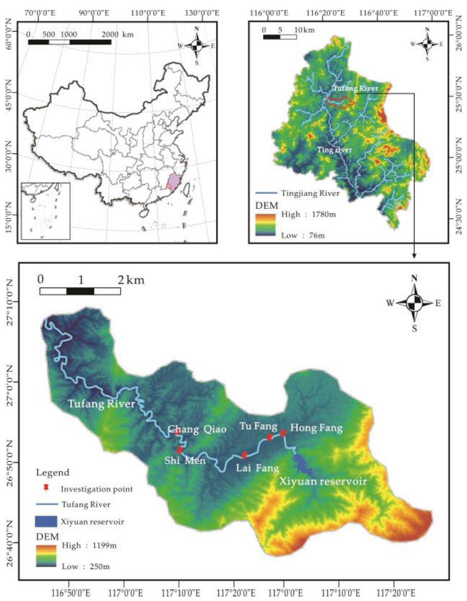

Figure 1. The river system distribution of Tufang River System.

4. Results

4.1. Weight Consistency Test

The AHP and the entropy method were applied to calculate weights. Therefore, the distance function was used to test the consistency. After testing, the distance function of the weights given by the two methods was within the range of [0, 1], which showed that the weights obtained by the two methods were highly consistent.

4.2. Assessment Index Weight

4.2.1. Weight Calculation by the AHP

Based on expert scoring results, a judgment matrix of the relative importance between the internal indicators of hierarchy was constructed. The weight of a single row of the hierarchy was calculated using the eigenvalue method and its consistency was tested with AHP. The calculated judgment matrix of water quality and biological indicators is shown in Table 3. Other indicators were calculated similarly.

Table 3. Judgment matrix and weight of water quality and biological characteristics of Tufang River (2018) by AHP.

Water Quality	**Stability of Water Temperature Structure in Upstream and Downstream of Dam**	**DO**	**TN**	**BOD_5**	**Weight Value ψ**	**Parameter Value**
Stability of water temperature structure in upstream and downstream of dam	1	1/5	1/3	1/3	0.078	$\lambda_{max} = 4$ $CR = 3.33 \times 10^{-16}$
DO	5	1	3	3	0.522	
TN	3	1/3	1	1	0.2	
BOD_5	3	1/3	1	1	0.2	
Biology	Fish diversity index		Benthic animal diversity index		Weight value ψ	Parameter value
Fish diversity index	1		1		0.5	$\lambda_{max} = 2$ $CR = 0 < 0.1$
Benthic animal diversity index	1		1		0.5	

4.2.2. Weight Calculation using the Entropy Method

The field survey data of the water quality and biological characteristics of the Tufang River in 2018 were substituted into Equations (10)–(13) to calculate the index weight. The results are shown in Table 4. The weights of other indicators were calculated similarly.

4.2.3. Weight Calculation Results

According to game theory, the weights were calculated using Equations (15)–(19). Then, the combined weight was determined via the subjective weight from the AHP and the objective weight from the entropy method in Equation (20). The weighted evaluation index systems of the Tufang River in 2018 and 2019 are shown in Figures 2 and 3, respectively.

Table 4. Weight of water quality and biological characteristics index layer in Tufang River (2018) using the entropy method.

River Reach	Stability of Water Temperature Structure in Upstream and Downstream of Dam		DO		TN		BOD_5	
	Actual Value	−Pi · lnPi	Actual Value	−Pi · lnPi	Actual Value	−Pi · lnPi	Actual Value	−Pi · lnPi
Shimen	100	0.24	8	0.33	1.29	0.35	7.26	0.35
Changqiao	40	0.36	6.9	0.36	1.38	0.34	7.4	0.35
e_j		0.60		0.69		0.69		0.69
u_j		1.67		1.45		1.44		1.44
w_j		0.28		0.24		0.24		0.24

River Reach	Fish Diversity Index		Benthic Animal Diversity Index	
	Actual Value	−Pi · lnPi	Actual Value	−Pi · lnPi
Shimen	1.81	0.20	1.17	0.33
Changqiao	1.15	0.37	1.02	0.36
e_j		0.67		0.69
u_j		1.50		1.45
w_j		0.51		0.49

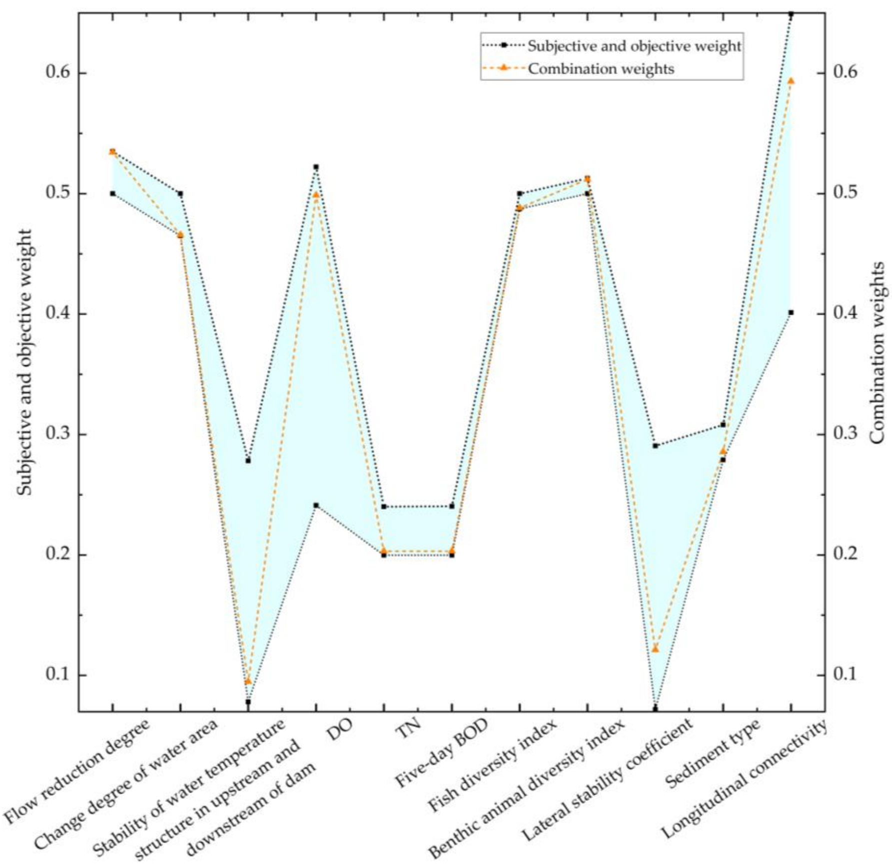

Figure 2. Weight calculation results of Tufang River assessment index (2018).

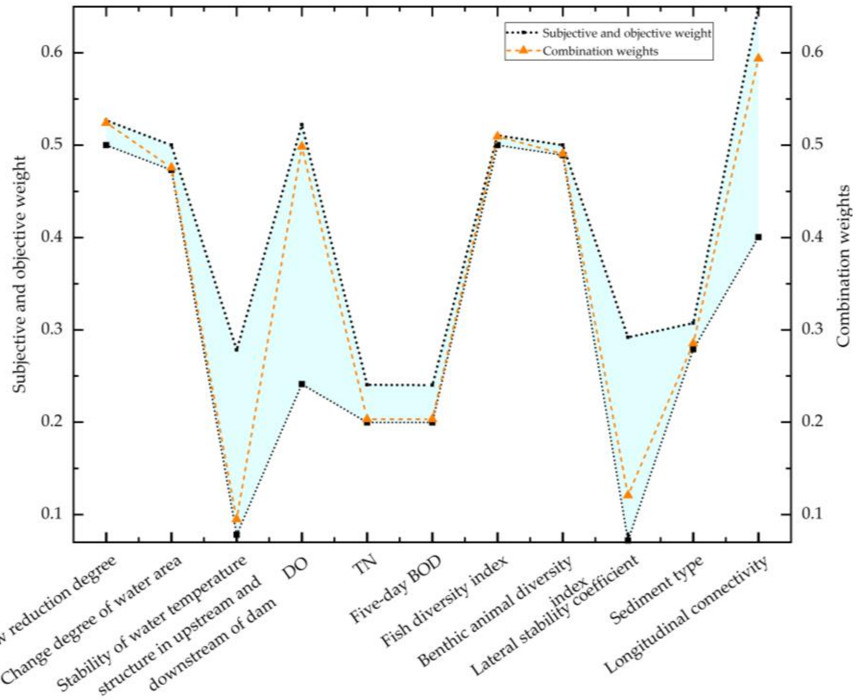

Figure 3. Weight calculation results of Tufang River assessment index (2019).

4.3. Calculation Results of Fuzzy Evaluation

The membership degree of each index layer was calculated according to the trapezoidal distribution membership function of Equations (22)–(23). Taking the river reach of the Shimen hydropower station in 2018 as an example, the calculation results were directly applied to other areas:

$$R_{B1} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0.37 & 0.63 & 0 & 0 \end{bmatrix}, R_{B2} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.42 & 0.58 & 0 \\ 0 & 0 & 0 & 0.68 & 0.32 \end{bmatrix},$$
$$R_{B3} = \begin{bmatrix} 0.62 & 0.38 & 0 & 0 & 0 \\ 0 & 0.17 & 0.83 & 0 & 0 \end{bmatrix}, R_{B4} = \begin{bmatrix} 0 & 0 & 0 & 0.39 & 0.61 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}.$$

The combined weight vector and each fuzzy matrix were combined according to Equation (26), and the fuzzy evaluation results of the criterion layer were obtained:

$$E_{B1} = W_{B1} \circ R_{B1} = \begin{bmatrix} 0.52 & 0.18 & 0.30 & 0 & 0 \end{bmatrix}, E_{B2} = W_{B2} \circ R_{B2} = \begin{bmatrix} 0.60 & 0 & 0.08 & 0.26 & 0.06 \end{bmatrix},$$
$$E_{B2} = W_{B2} \circ R_{B2} = \begin{bmatrix} 0.31 & 0.28 & 0.41 & 0 & 0 \end{bmatrix}, E_{B4} = W_{B4} \circ R_{B4} = \begin{bmatrix} 0 & 0.88 & 0 & 0.05 & 0.07 \end{bmatrix}.$$

The fuzzy evaluation of this level took the fuzzy evaluation result of the criterion level as the evaluation vector to form a fuzzy relation matrix of the upper level. The fuzzy relation matrix of the target level was:

$$B_1 = \begin{bmatrix} 0.52 & 0.18 & 0.30 & 0 & 0 \\ 0.60 & 0 & 0.08 & 0.26 & 0.06 \\ 0.31 & 0.28 & 0.41 & 0 & 0 \\ 0 & 0.88 & 0 & 0.05 & 0.07 \end{bmatrix},$$

The fuzzy evaluation results of the target layer A was obtained by fuzzy operation of the combined weights ω_{B1} and B_1 of the criterion layer:

$$A = \omega_{B1} \circ B_1 = \begin{bmatrix} 0.36 & 0.34 & 0.16 & 0.10 & 0.04 \end{bmatrix},$$

After the retirement of the small hydropower stations in the river section of Shimen, the river health assessment result was 36% in a very healthy state, 34% in a healthy state, 16% in a subhealthy state, 10% in an unhealthy state, and 4% in a morbid state. Thus, the ecological restoration of the river section near Shimen was in good condition after its retirement in 2015.

5. Discussion

Based on the field survey results, the health status of the Tufang River small hydropower station in 2018 and 2019 is shown in Figure 4.

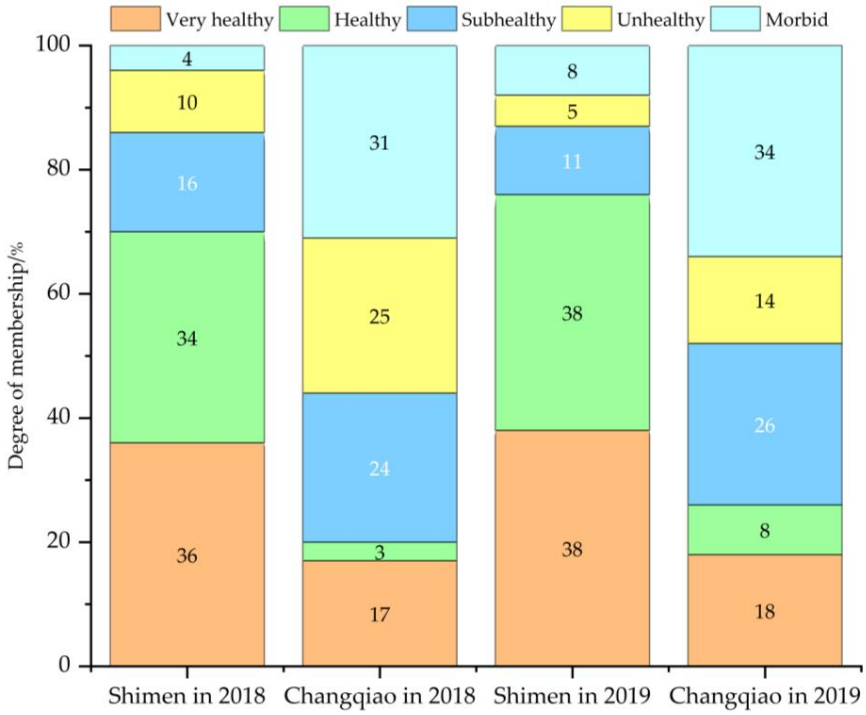

Figure 4. Health assessment results of the small hydropower station in Tufang River.

Taking the Shimen hydropower station as an example, the calculated membership degree of the very healthy state was 36% in 2018 and increased to 38% in 2019, which was consistent with the actual situation. The proposed model appeared to accurately reflect changes in the river ecological restoration status after the retirement of Shimen. It unambiguously and accurately revealed the restoration process of the river's ecological health after the small hydropower station was retired. The index weights calculated with the proposed combination method fell between the subjective weight and objective weight, indicating that the model fully incorporated both subjective and objective information.

Though the assessed river reaches of the Shimen hydropower station and the Changqiao hydropower station were similar, the health status of the Shimen river reach in 2018 and 2019 was significantly better than that of the Changqiao river reach. This was because Shimen completely removed the dam and restored the natural river channel. Additionally, the runoff allocation was directly affected by natural changes. During the dry season, the ecological flow supply was fully guaranteed; the hydrological conditions, such as water depth and flow velocity, were greatly improved; and the richness of the river microhabitat increased. The transportation of nutrients in the upstream and downstream increased, and the lake habitat was gradually transformed into shallow and deep pools, which enriched the habitat of aquatic organisms and provided them with excellent habitat conditions. The river connectivity was enhanced, and the vegetation coverage of the riparian zone increased, which maintained the stability of the river morphological structure.

The health condition of the Changqiao river section in 2019 was slightly better than that in 2018, mainly because the hydropower station was in the maintenance period during the field investigation in 2019. The sluice was opened to discharge water and the river liquidity was significantly enhanced, which significantly improved the hydrology and water quality of the Changqiao river section. The health status of the Shimen river section in 2019 was slightly higher than that in 2018. After the removal of the dam, the integrity of the river was enhanced and the physical habitat improved due to a reduction in flow in the dry season, providing a favorable habitat for fish, benthic, and other aquatic organisms. The evident restoration of the overall ecosystem suggests that the retirement and renovation of small hydropower stations had a significant impact on aquatic ecology in the dry season.

6. Conclusions

In this study, an ecological health assessment index system was established based on changes in river sections after the retirement and renovation of small hydropower stations. Index weights were determined using a combined weighting method based on game theory, combined with a fuzzy comprehensive evaluation method to evaluate the health status in Shimen and Changqiao sections of the Tufang River in Changting County, China. The conclusions are as follows:

According to the mechanism of the impact of the reconstruction of small hydro-power stations on the ecological environment restoration of river reaches, an assessment index system was built with covering hydrology, water quality, biology, morphological structure, and other aspects relevant to these changes. The proposed system includes 1 target layer, 4 criterion layers, and 11 index layers. Changes to the upstream and downstream reaches of the small hydropower station dam site were accurately reflected in the model, allowing for the comprehensive assessment of the ecological health status of the river reaches after the reconstruction and retirement of hydropower stations.

The fuzzy comprehensive evaluation method is used to resolve ambiguity problems in the assessment of ecological health. We weighted indexes in the model by the combination weighting concept of game theory, which produced values falling between subjective and objective weights. This allowed us to not only incorporate the subjective information in each assessment index but also the objective reality reflected by the index data. Therefore, the weight determination was more subjective when using fuzzy comprehensive evaluation; the evaluations were reasonable and scientific. Further, the model was easily operated and readily interpretable.

The health assessment of the river reach in Shimen hydropower station was estimated to be in a "very healthy" state in 2018 and 2019 and that of the Changqiao hydropower station was in a "morbid" state. Generally speaking, the Shimen reach was in a state of gradual restoration after retirement, and it was not completely restored. However, the ecological restoration of Changqiao reach was slow and characterized only by flow renovation. It indicated that the river section was restored to its natural ecology more quickly when the revision degree of the small hydropower station was higher.

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Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author, [initials], upon reasonable request.

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