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# EVALUATING FISH PASSAGE EFFICIENCY IN VERTICAL SLOT FISHWAYS USING THE ANALYTIC HIERARCHY PROCESS

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## ABSTRACT

Based on the Analytic Hierarchy Process (AHP), a comprehensive evaluation system has been developed to assess the performance of vertical slot fishways. This system incorporates 30 factors related to fish passing efficiency, thereby facilitating a detailed analysis of hydraulic characteristics, engineering layout, operation management, and monitoring. For its practical application, the vertical slot fishway at the Laolongkou Hydro-junction project's comprehensive evaluation was assessed and consequently rated as "Operating Excellently". This rating accurately reflects the fishway's operational status. The case study demonstrates that the established index system and the model calculation method are capable of thoroughly considering the operational conditions of fishways and the applicability of the model. Moreover, the methodology offers valuable experiences and guidance for creating evaluation systems in various other water conservancy project sectors.

## KEYWORDS

Analytic hierarchy process (AHP), Vertical slot fishway; Fish passing efficiency; Comprehensive evaluation

## INTRODUCTION

The fishway is a project designed to mitigate the damage to the aquatic ecosystem caused by water conservancy projects. It has gained an increasingly important role as advocacy for ecological protection grows.

Researchers have found that different types of fish are attracted to varying flow velocities and patterns. These variations are present at the entrance of the fishway and throughout the fishway chambers [1]. Through experiments, researchers concluded that the main environmental factors affecting fish passage are flow velocity, discharge, upstream water level, and transparency [2]. They proposed: (1) The key points of fishway entrance design include entrance location, entrance flow, flow pattern, entrance structure, the number of entrances, and the entrance working water level; (2) Induction facilities, such as water replenishment facilities and fish barriers, can help improve entrance efficiency; (3) The key points in the design of the main structure are to ensure that the slope, fishway length, flow velocity, turbulent kinetic energy, and other indicators are moderate to prevent fish fatigue; (4) Strengthen the assessment of fish passage facility effectiveness [3]. Researchers have identified that the effectiveness of a fishway is determined by the upstream water level and the fishway's water temperature. Optimal function occurs only when both conditions satisfy the necessary fishway requirements [4]. It has been found that the upward movement of fish is related to season, water temperature, and discharge [5]. In comparing and selecting design plans, factors considered include topography and geology, operation management, and fish migration patterns, which influence the choice of fish passage facility plans [6]. Researchers have found that by conducting hydrodynamic model experiments and implementing measures including the addition of guide vanes, adjusting the width of gaps, and altering the proportions of the fish pass dimensions, the water flow characteristics in the fishway have been significantly enhanced. The direction of flow distribution is more uniform, and the scale of the resulting counter currents and eddy zones is moderate [7]. The researchers, utilizing staggered arrangements of reed modules, have engineered a fish passage that mimics the natural environment; physical model experiments revealed that these vegetation modules efficiently decelerate the water flow, generating a current akin to that of natural watercourses [8]. Researchers have discovered that placing pylons in the center of fish passages can significantly reduce the size of recirculation zones and decrease the energy of turbulence, with a maximum reduction of up to 18% [9]. Researchers have found that the position of vertical slots can adjust the specific location of the main flow zone within the pool chamber, which in turn influences the layout, size of the recirculation zones, and the overall characteristics of the flow field [10]. Researchers, through studies combining model experiments and numerical simulation methods at three different flow rates, have demonstrated that juvenile silver carp tend to avoid areas with turbulence intensities of 8.5 to 9.2 cm/s during their movement, and prefer waters with turbulence intensities ranging from 5.25 to 8.40 cm/s [11]. Researchers found that the number of fish collected at the outlet of the Ice Harbor fishway is positively correlated with the water level at the dam [12]. In a study of a fishway in Australia, it was noted that environmental factors are associated with fish passage efficiency, with salinity accounting for 21%, flow velocity for 38%, and surface water temperature for 11% [13]. In the Alaskan Steep-pass fishway, researchers observed a significant positive correlation between water temperature and the number of fish passing through [14]. A study on lamprey revealed that the rate of fish entering the fishway increases with temperature [15]. Furthermore, researchers found that water flow velocity within the fishway is positively correlated with fish passage efficiency, while the slope and length of the fishway are negatively correlated with passage efficiency [16]. The researchers' model experiments show that by adjusting the width of the pool, the slope of the fishway, and the roughness of the bottom, it can be confirmed that the flow patterns are significantly influenced not only by the slope and the width of the pool but also by the roughness of the bottom. At the same time, the flow coefficient is constrained by the slope and width of the pool chamber and is not significantly related to the magnitude of the flow and the degree of roughness [17]. According to the researchers' observations, the Iberian barbel fish tend to choose areas with lower turbulence energy as their resting zones and then proceed to move through areas with higher velocity and turbulent energy along the main current [18]. Researchers have found that catfish tend to linger longer in regions where the turbulent energy ranges between 0.02 to 0.043 $m^2/s^2$, suggesting that this level of turbulence is preferred by the catfish [19]. Researchers have found that Reynolds shear stress, $\tau_{uv}$, exerts the greatest influence on fish movement, particularly in fish of smaller size with less swimming capability. This observation is notably pronounced [20]. Judging from current research, many experts and scholars have conducted numerous experiments and identified many factors that affect the efficiency of fish passage. However, due to the multitude of influencing factors, there is currently no scientific, effective, and systematic method for combining these factors to comprehensively evaluate fishway efficiency.

Therefore, based on the Analytic Hierarchy Process (AHP), this paper establishes a vertical slot fishway operation evaluation system considering 30 factors for the fishway's operation.

## METHODS

In this study, the Analytic Hierarchy Process (AHP) was primarily used to establish a fishery efficiency evaluation system. In the 1970s, Professor T. L. Saaty [21], an American operations researcher, proposed the Analytic Hierarchy Process (AHP), a method that incorporates both qualitative and quantitative assessments for decision-making. It is designed to tackle evaluation issues involving a variety of scenarios, criteria, and objectives, especially suited for systems that are large in scale, complex in structure, diverse in goals, and abundant in qualitative factors.

## ESTABLISHING AN EVALUATION SYSTEM VIA THE ANALYTIC HIERARCHY PROCESS

### *Basic Principles*

The main principle adopted by the Hierarchical Analysis Method is to gradually decompose a complex issue into multiple levels. Starting from the ultimate goal, it identifies and breaks down the various influencing factors that impact the goal, step by step, thereby constructing a hierarchical diagram. Within this diagram, elements at each level correspond to a set of relative importance criteria. These criteria can be assessed through quantitative analysis in order to calculate the relative weight of each criterion, which then guides the selection of the optimal plan or decision-making.

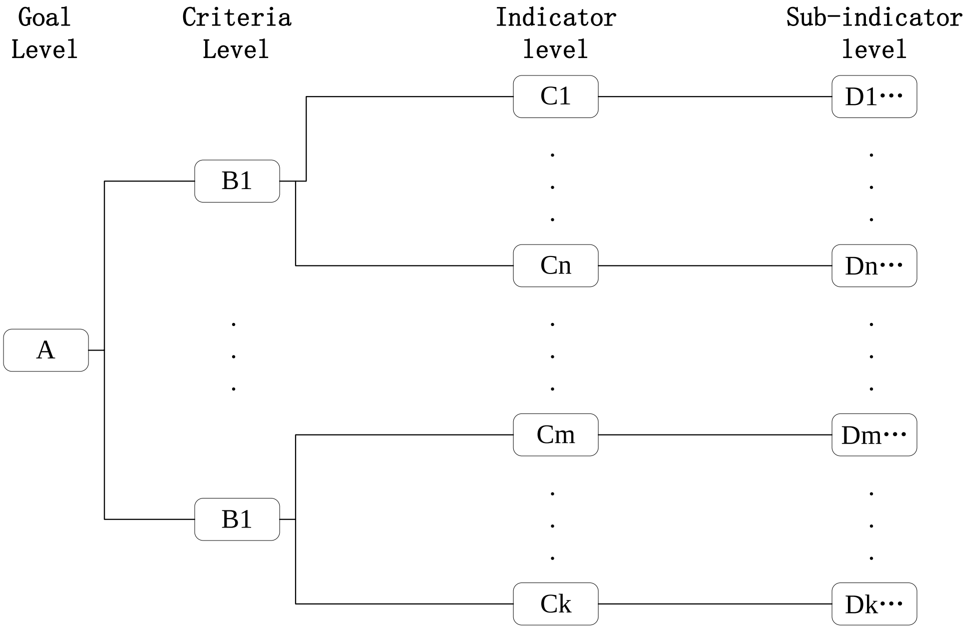


*Fig.1 - Structure concept diagram of AHP*

Implementing the Hierarchical Analysis Method involves the following steps:

1. Creating a hierarchical model: Based on the nature and key characteristics of the problem to be solved, a tiered model structure is formed, which is refined into different levels step by step.
2. Selecting criteria and factors: For each level, determine the relevant evaluation criteria and key factors.
3. Establishing the judgment matrix: Build a judgment matrix based on the relative importance of each criterion and factor. The size of the matrix is determined by the number of relevant factors, and the values in the matrix reflect the relative importance between factors, typically expressed on a scale of 1 to 9.
4. Calculating weight values: Use mathematical methods to obtain the weight values of each criterion and factor, which are usually presented in the form of a vector.
5. Consistency verification: Conduct a consistency check on the constructed judgment matrix to ensure the reasonableness and accuracy of the obtained weights, thereby increasing the scientific application of the method.
6. Synthesizing weights: By integrating the weights at various levels, we ultimately obtain a weight vector that represents the importance of each factor in the overall structure, which then assists in the assessment of plans or decision-making.

Overall, the Hierarchical Analysis Method is a practical tool for solving complex decision-making problems and is widely applicable to multiple aspects such as investment choices, strategic planning, product development, project management, and risk assessment.

*Tab.1 - Construction form of judgment matrix*

| | C1 | C2 | ··· | Cn |
|---|---|---|---|---|
| C1 | C11 | C12 | ··· | C1n |
| C2 | C21 | C22 | ··· | C2n |
| ⋮ | ⋮ | ⋮ | | ⋮ |
| Cn | Cn1 | Cn2 | ··· | Cnn |

*Tab. 2 - Judgment matrix scale*

| Quantitative scale | Qualitative description |
|---|---|
| 1 | Two factors have equal importance. |
| 3 | One factor is slightly more important than the other. |
| 5 | One factor is moderately more important than the other. |
| 7 | One factor is significantly more important than the other factor. |
| 9 | One factor is extremely important, almost to the sum of all other factors. |
| 2,4,6,8 | Intermediate Judgment Value |

### *System Establishment*

The evaluation of fishway operation needs to include as many factors as possible that can affect the operation from an overall perspective, including the impact of hydraulic characteristics, engineering layout, and operation management and monitoring. Therefore, combined with existing research conclusions, an evaluation system for fishway operation has been established based on the current mainstream evaluation methods. The results are shown in Table 1.

*Tab .3 - Vertical slot fishway operation evaluation system*

| Goal Level | Criteria Level | | Indicator level | | Sub-indicator level | |
|---|---|---|---|---|---|---|
| Vertical slot fishway operation evaluation system | B1 | Hydraulic characteristics | C1 | Water depth | D1 | Water depth at entrance |
| | | | | | D2 | Head difference between the upstream and the downstream |
| | | | | | D3 | Water depth in fishway |
| | | | C2 | Flow rate | D4 | Inlet flow rate |
| | | | | | D5 | Maximum flow rate |
| | | | | | D6 | Flow velocity amplitude |
| | | | | | D7 | Outlet flow rate |
| | | | C3 | Discharge | D8 | Maximum discharge |
| | | | | | D9 | Runoff volume |
| | | | C4 | Other characteri-stics | D10 | Water temperature |
| | | | | | D11 | Transparency |
| | | | | | D12 | Salinity |
| | | | | | D13 | Sand content |
| | | | | | D14 | PH |
| | | | | | D15 | Turbulence kinetic energy |
| | | | | | D16 | Vortex |
| | B2 | Engineering layout | C5 | Fishway import | D17 | Location |
| | | | | | D18 | Import quantity |
| | | | | | D19 | Hydraulic jump |
| | | | C6 | Inside the fishway | D20 | Slope |
| | | | | | D21 | Total length |
| | | | | | D22 | Length of each level |
| | | | | | D23 | Vertical slot width |
| | | | C7 | Fishway exit | D24 | Export quantity |
| | | | | | D25 | Auxiliary facilities |
| | B3 | Operation management and monitoring | C8 | Management | D26 | Management level |
| | | | | | D27 | Operational model |
| | | | C9 | Monitor | D28 | Species of fish |
| | | | | | D29 | Number of fish passed |
| | | | | | D30 | Seasonal differences |

## ESTABLISH EVALUATION INDICATORS AND ASSESSMENT CRITERIA

### *Quantitative Criteria for Determining Hydraulic Characteristics*

*1) The Standardized Criteria for Determining Water Depth Quantitatively*

Establishing standards based on the ratio of the operational water depth determined by design or measurement to the optimum swimming depth for key fish species.

*Tab.4 - Quantitative Evaluation Standards for Water Levels*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D1 | ＞0.80 | 0.80~0.70 | 0.70~0.60 | 0.60~0.50 | ＜0.50 |
| D2 | ＞0.80 | 0.80~0.70 | 0.70~0.60 | 0.60~0.50 | ＜0.50 |
| D3 | ＞0.80 | 0.80~0.70 | 0.70~0.60 | 0.60~0.50 | ＜0.50 |

*2) Quantitative Determination Criteria for Flow Rate*

Developing standards based on the designed or measured operating flow velocity and the optimal swimming flow velocity ratio of the main fish species.

*Tab.5 - Quantitative assessment standards for flow rate*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D4 | 0.9~1.1 | 0.8~0.9, 1.1~1.2 | 0.7~0.8, 1.2~1.3 | 0.6~0.7, 1.3~1.4 | ＜0.6, ＞1.4 |
| D5 | 0.9~1.1 | 0.8~0.9, 1.1~1.2 | 0.7~0.8, 1.2~1.3 | 0.6~0.7, 1.3~1.4 | ＜0.6, ＞1.4 |
| D6 | 0.9~1.1 | 0.8~0.9, 1.1~1.2 | 0.7~0.8, 1.2~1.3 | 0.6~0.7, 1.3~1.4 | ＜0.6, ＞1.4 |
| D7 | 0.9~1.1 | 0.8~0.9, 1.1~1.2 | 0.7~0.8, 1.2~1.3 | 0.6~0.7, 1.3~1.4 | ＜0.6, ＞1.4 |

*3) Quantitative Assessment Standards for Discharge*

Establish standards based on the ratio of the designed or measured operational flow rate to the preferred flow rate for the primary fish species.

*Tab.6 - Discharge quantitative assessment standards*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D8 | 0.9~1.1 | 0.8~0.9, 1.1~1.2 | 0.7~0.8, 1.2~1.3 | 0.6~0.7, 1.3~1.4 | ＜0.6, ＞1.4 |
| D9 | 0.9~1.1 | 0.8~0.9, 1.1~1.2 | 0.7~0.8, 1.2~1.3 | 0.6~0.7, 1.3~1.4 | ＜0.6, ＞1.4 |

*4) Quantitative Assessment Standards for Other Characteristics*

*Tab.7 - Quantitative assessment standards for other attributes*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D10 | Best Temperature (±1℃) | Optimal Temperature (±5℃) | Critical Activity Temperature（±10℃) | Unsuitable Temperature（±15℃) | Extreme Temperature（±25℃) |
| D11 | Turbid Water | / | / | / | Clear Water |
| D12 | Specific Fish Species targeted Plan | | | | |
| D13 | Specific Fish Species targeted Plan | | | | |
| D14 | 7.12~7.20 | / | 7.04~7.12, 7.20~7.34 | / | ＜7.04, ＞7.34 |
| D15 | ＜0.15 m²/s² | 0.15~0.2 m²/s² | 0.2~0.3 m²/s² | 0.3~0.5 m²/s² | ＞0.5 m²/s² |
| D16 | without eddy | There are a few small eddies. | Occasional large eddies | Fixed occurrence of whirlpools. | The water flow is particularly turbulent. |

## *Establishing Quantitative Judgment Criteria for Engineering Layout*

*1) Fishway Import Quantitative Assessment Criteria*

The entrance of the fishway is crucial for allowing fish to enter the fishway, and its location, the number of entrances, and the water leap conditions have a significant impact on the efficiency of the fishway operation. Optimizing the placement of the entrance, the number of entrances, and the water leap conditions can greatly improve the operational efficiency of the fishway, facilitating the smooth migration and protection of fish.

*Tab.8 - Fishway Entrance Quantitative Evaluation Criteria*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D17 | The best location is far away from power stations and other hydraulic structures. | The location is suitable, far away from power stations and other hydraulic structures. | The location is average, not far from power stations and other hydraulic structures. | The location is poor, very close to power stations and other hydraulic structures. | The location is very poor, very close to power stations and other hydraulic structures. |
| D18 | more than one | one | / | / | / |
| D19 | no-water jump phenomenon | / | minor water splash effects | | significant water splash effects |

*2) Quantitative Criteria for Inside the Fishway Assessment*

The length of the pool chamber within a fishway, as well as the total length and slope of the fishway, are crucial factors influencing the migration of fish. Additionally, the width of the vertical slots plays a key role in determining the successful passage of migrating fish through the fishway.

*Tab.9 - Quantitative Evaluation Criteria for Inside the Fishway*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D20 | ＜2° | 2°~4° | 4°~6° | 6°~8° | ＞8° |
| D21 | ＜200m | 200~300m | 300~400m | 400~500m | ＞500m |
| D22 | ＜3m | 3~3.5m | 3.5~6m | 6~8m | ＞8m |
| D23 | ＜0.35m | / | 0.35~0.5m | / | ＞0.5m |

*3) Quantitative Criteria for Fishway Exit Assessment*

*Tab.10 - Quantitative Evaluation Standards for Fishway Exit*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D24 | more than one | one | / | / | / |
| D25 | There are floating debris barriers. | / | / | / | No floating debris barriers |

## *Operation, Management, and Monitoring of Quantitative Determination Standards*

*1) Management of Quantitative Determination Standards*

*Tab.11 - Management of Quantitative Assessment Standards*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D26 | Excellent | Good | Average | Below average | Below standard |
| D27 | Beneficial management | / | Partially effective management | / | Ineffective management |

*2) Monitoring Quantitative Determination Standards*

The standards for the types and quantities of migratory fish should be based on the percentage of the fish species and quantities passing through fishways to the total number and species of upstream migrating fish in the basin. Seasonal variations should be considered based on the number of months when major fish migrations occur each year to establish standards.

*Tab.12 - Monitoring Quantitative Assessment Standards*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| D28 | 90%~100% | 75%~90% | 60%~75% | 50%~60% | ＜50% |
| D29 | 85%~100% | 75%~85% | 60%~75% | 50%~60% | ＜50% |
| D30 | ＞4 months | 3~4 months | 2~3 months | 1~2 months | ＜1 month |

## INTEGRATED EVALUATION METHOD

### *Construct the Judgment Matrix*

Use the AHP method to determine the weight of each factor, to compare the importance of the various indicators, and to quantify the significance of each factor [22].

Through multi-channel research, 10 expert evaluation forms were collected. These forms underwent screening and analysis, after which the sum-product method was applied to address the problem. The formula for the sum-product method is as follows:

$$\int_{a_1}^{b_1}\int_{a_2}^{b_2}\cdots\int_{a_n}^{b_n} f(x_1,x_2,\cdots,x_n)dx_1dx_2\cdots dx_n=\int_{a_1}^{b_1}\int_{a_2}^{b_2}\cdots\int_{a_{n-1}}^{b_{n-1}}\left[\int_{a_n}^{b_n} f(x_1,x_2,\cdots,x_n)dx_n\right]dx_{n-1}\cdots dx_1 \quad (1)$$

### *Assessment of Consistency in Judgement Matrices*

After constructing the judgment matrix, it is essential to verify that the weights are credible and reasonable by performing a consistency test to determine if the matrix satisfies the required consistency criteria.

To determine whether the matrix satisfies consistency, it should be evaluated based on the Consistency Ratio (CR), which is the ratio of the Consistency Index (CI) to the Random Index (RI). The CI is calculated using the maximum eigenvalue and the order of the matrix, while the RI is derived from a standardized table corresponding to the matrix's order, as shown in Table 11. Generally, if CR is less than 0.1, the judgment matrix is considered consistent; otherwise, if CR is 0.1 or greater, the judgment matrix is not consistent, and adjustments to the matrix are necessary before recalculating and analyzing it again.

*Tab. 13 - Random Index (RI) Values [21]*

| Order n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 | 1.49 |

### *Weight Calculation in Evaluation Systems*

First, we carry out the weight calculation for the criteria layer of the vertical slot fishway operation evaluation system, which includes hydraulic characteristics, engineering layout, operation management, and monitoring. The corresponding judgment matrix is as follows:

$$A=\begin{bmatrix} 1 & 1.33 & 2.5 \\ 0.75 & 1 & 2 \\ 0.4 & 0.5 & 1 \end{bmatrix} \quad (2)$$

After the calculation, the weights for the criteria layer—which comprises hydraulic characteristics, engineering layout, operation management, and monitoring—are as follows:

$$[0.4634 \quad 0.3551 \quad 0.1815] \quad (3)$$

The maximum characteristic root is 3.000, the CI is 0.000, and the RI is 0.520. The calculated CR is 0, which is less than 0.1, indicating that the judgment matrix passes the consistency test.

Similarly, the weights of the indicator layer and the sub-index layer within the vertical slot fishway operation evaluation system have been calculated. The corresponding judgment matrix and the results are presented in Table12 as follows:

*Tab.14 - Computed Weights for the Indicator Layer and Sub-Indicator Layer*

| Criteria Level | The judgment matrix | | Indicator level | Weight | Consistency Test |
|---|---|---|---|---|---|
| B1 | $\begin{bmatrix} 1 & 0.625 & 1.5 & 1.5 \\ 1.6 & 1 & 2.33 & 2 \\ 0.667 & 0.667 & 1 & 0.667 \\ 0.667 & 0.500 & 1.5 & 1 \end{bmatrix}$ | (4) | C1 | 0.2565 | CI=0.005<br>RI=0.89<br>CR=0.006<0.1 |
| | | | C2 | 0.3885 | |
| | | | C3 | 0.1561 | |
| | | | C4 | 0.1989 | |
| B2 | $\begin{bmatrix} 1 & 2 & 2.5 \\ 0.5 & 1 & 2 \\ 0.4 & 0.5 & 1 \end{bmatrix}$ | (5) | C5 | 0.5174 | CI=0.012<br>RI=0.52<br>CR=0.024<0.1 |
| | | | C6 | 0.3042 | |
| | | | C7 | 0.1784 | |
| B3 | $\begin{bmatrix} 1 & 0.652 \\ 1.533 & 1 \end{bmatrix}$ | (6) | C8 | 0.3947 | CI=0<br>RI=0 |
| | | | C9 | 0.6053 | |
| **Indicator level** | **The judgment matrix** | | **sub-indicator level** | **Weight** | **Consistency Test** |
| C1 | $\begin{bmatrix} 1 & 2.143 & 1.5 \\ 0.467 & 1 & 1.154 \\ 0.667 & 0.867 & 1 \end{bmatrix}$ | (7) | D1 | 0.4712 | CI=0.014<br>RI=0.52<br>CR=0.027<0.1 |
| | | | D2 | 0.2613 | |
| | | | D3 | 0.2675 | |
| C2 | $\begin{bmatrix} 1 & 0.8 & 1.4 & 2 \\ 1.250 & 1 & 2.667 & 3 \\ 0.714 & 0.375 & 1 & 1.5 \\ 0.500 & 0.333 & 0.667 & 1 \end{bmatrix}$ | (8) | D4 | 0.2796 | CI=0.006<br>RI=0.89<br>CR=0.007<0.1 |
| | | | D5 | 0.4062 | |
| | | | D6 | 0.1825 | |
| | | | D7 | 0.1317 | |
| C3 | $\begin{bmatrix} 1 & 1.385 \\ 0.772 & 1 \end{bmatrix}$ | (9) | D8 | 0.5807 | CI=0<br>RI=0 |
| | | | D9 | 0.4194 | |
| C4 | $\begin{bmatrix} 1 & 6.5 & 2.091 & 3.6 & 2 & 1.667 & 3.5 \\ 0.154 & 1 & 0.267 & 0.677 & 1.154 & 0.286 & 0.429 \\ 0.478 & 3.750 & 1 & 1.7 & 2.333 & 0.6 & 1.6 \\ 0.278 & 1.5 & 0.588 & 1 & 0.8 & 0.308 & 0.4 \\ 0.5 & 0.867 & 0.429 & 1.25 & 1 & 0.4 & 2.3 \\ 0.6 & 3.5 & 1.667 & 3.25 & 2.5 & 1 & 2.143 \\ 0.286 & 2.333 & 0.625 & 2.5 & 0.435 & 0.467 & 1 \end{bmatrix}$ | (10) | D10 | 0.2950 | CI=0.058<br>RI=1.36<br>CR=0.092<0.1 |
| | | | D11 | 0.0567 | |
| | | | D12 | 0.1579 | |
| | | | D13 | 0.0714 | |
| | | | D14 | 0.1050 | |
| | | | D15 | 0.2128 | |
| | | | D16 | 0.1012 | |

| | | | | | |
|---|---|---|---|---|---|
| C5 | $\begin{bmatrix} 1 & 7.5 & 3.125 \\ 0.133 & 1 & 0.588 \\ 0.320 & 1.7 & 1 \end{bmatrix}$ | (11) | D17 | 0.6954 | CI=0.007 RI=0.52 CR=0.013<0.1 |
| | | | D18 | 0.1049 | |
| | | | D19 | 0.1997 | |
| C6 | $\begin{bmatrix} 1 & 1.067 & 1.154 & 0.364 \\ 0.938 & 1 & 1.250 & 0.692 \\ 0.867 & 0.8 & 1 & 0.588 \\ 2.75 & 1.444 & 1.7 & 1 \end{bmatrix}$ | (12) | D20 | 0.1978 | CI=0.019 RI=0.89 CR=0.022<0.1 |
| | | | D21 | 0.2269 | |
| | | | D22 | 0.1900 | |
| | | | D23 | 0.3853 | |
| C7 | $\begin{bmatrix} 1 & 0.88 \\ 1.136 & 1 \end{bmatrix}$ | (13) | D24 | 0.4681 | CI=0 RI=0 |
| | | | D25 | 0.5319 | |
| C8 | $\begin{bmatrix} 1 & 1.6 \\ 0.625 & 1 \end{bmatrix}$ | (14) | D26 | 0.6154 | CI=0 RI=0 |
| | | | D27 | 0.3846 | |
| C9 | $\begin{bmatrix} 1 & 1.143 & 0.364 \\ 0.875 & 1 & 0.455 \\ 2.750 & 2.2 & 1 \end{bmatrix}$ | (15) | D28 | 0.2265 | CI=0.007 RI=0.52 CR=0.014<0.1 |
| | | | D29 | 0.2231 | |
| | | | D30 | 0.5504 | |

The assessment model built on this premise is complex, with numerous factors impacting the operational efficiency of fishways. However, due to variations in the construction location, environment, and design management of fishways, not all factors are considered in the assessment model. Additionally, certain functionalities are challenging to monitor and indicators are difficult to determine, which hinders the formation of quantifiable results. In such scenarios, it is necessary to eliminate unconsidered or non-quantifiable indicators from the model and recalculate the weights accordingly.

### *Quantitative Grading and Composite Scoring*

The article quantifies sub-indicator levels by referencing various engineering evaluation systems, with scores presented in Table13.

*Tab.15 - Sub-indicator Level Quantification Chart*

| Level | Non-quantifiable Metrics | E | D | C | B | A |
|---|---|---|---|---|---|---|
| score | 0 | 1 | 2 | 3 | 4 | 5 |

After obtaining the quantitative data for various indicators, one can calculate the comprehensive score $S_{sum}$ of the fishway operation level using the following formula.

$$S_{sum}=\sum_{i=1}^{n}\sum_{j=1}^{m_i} W_i \times W_{ij} \times S_{ij} \tag{16}$$

In the formula,'$S_{sum}$' is the comprehensive score of the operational level, 'n' is the number of indicators; '$m_i$' is the number of sub-indicators under each indicator; '$W_i$' is the weight of the indicator; '$W_{ij}$' is the weight of the sub-indicator; '$S_{ij}$' is the score of the sub-indicator.

After calculating the comprehensive score of the fishway operation assessment using the formula, the grade of the evaluated project can be determined according to Table14.

*Tab.16 - Comprehensive Scoring Table for Fishway Operational Efficiency*

| Comprehensive score | Level | Judgment Conclusion |
|---|---|---|
| 0~1.0 | Totally Srapped | The fishway project is in a completely scrapped state, with all indicators failing to meet the requirements. It needs to be redesigned, demolished, and rebuilt. |
| 1.0~2.0 | Operating Marginally | The actual operation condition is poor, and most indicators do not meet the design requirements, which seriously affects the normal operation of the fishway. It needs to be decommissioned and overhauled, and the entire fishway needs to be monitored for a long time after reuse. |
| 2.0~3.0 | Operating Normally | More than half of the actual operating conditions meet the design requirements. The indicators that do not meet the requirements have only a slight impact on the operation of the fishway. It is necessary to improve certain aspects, optimize the operating status, and conduct long-term monitoring of the overall fishway. |
| 3.0~4.0 | Operating Well | Most of the actual operations align with the design specifications, but a small number of indicators do not meet the requirements, which have a minimal impact on the overall operation of the fishway. Regular monitoring of individual components is sufficient. |
| 4.0~5.0 | Operating Excellently | The actual operation conditions meet the design requirements, and all data monitoring is normal. |

### *Computational Procedure for Evaluating the Efficiency of Fishway Operations*

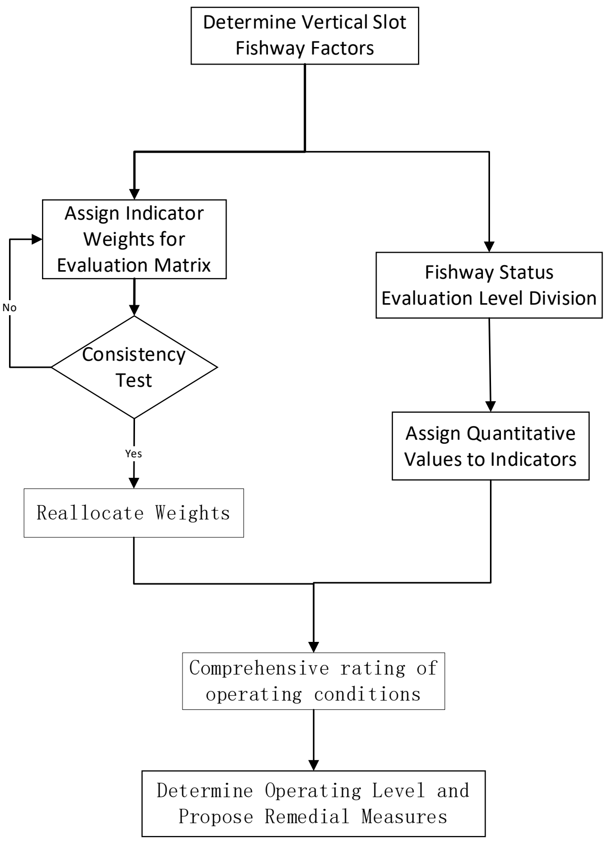


*Fig.2 - Vertical Slot Fishway: Operation Evaluation & Calculation Flowchart*

## CASE ANALYSIS

### *Basic parameters*

The fish passage project for the Laolongkou Hydro-junction is situated in the middle and lower reaches of the Hunchun River. The highest water level for fish in the reservoir is 109 m; the highest normal tailwater level downstream from the reservoir is 82 m, resulting in a design water level difference of 27 m. The main migratory fish species in the Hunchun River include masu salmon, common salmon, humpback salmon, and Japanese lamprey. There are also anadromous species such as the ridge head fish, Asian smelt, and dace. The period from mid-August to mid-October marks the upstream migration season for spawning adult fish, while mid-April to mid-May is the season for juvenile fish to descend to the sea, following the current [23,24].

*Fig.3 - Site View of the Fishway Project at Laolongkou*

### *Indicator Weight Reassignment and Scoring*

Based on the basic parameters and monitoring values described in the data for the case, the weight coefficients for parameters or indicators that are unlisted or cannot be quantified are set to zero, and the weights of the indicators are redistributed. The coefficients for D4, D6, D7, D9, D10, D11, D12, D13, D14, D26, and D27 are zero. Consequently, the weights for C9, D5, and D8 are set to one. The weights for D15 and D16 undergo redistribution. After calculation, the weight ratio of the two sub-indices is:

$$[0.6818 \quad 0.3182] \tag{17}$$

Next, each sub-indicator is individually scored. The scores are detailed in Table15.

*Tab.17 - Table of Comprehensive Scores for Sub-indicators [23-27]*

| Indicator level | Sub-indicator level | Parameters & Data | Score |
|---|---|---|---|
| C1 | D1 | The normal operating water depth is between 2.9 and 3.9 m. | 4 |
| | D2 | The maximum water level difference is 27m. | 2 |
| | D3 | The water depth of the fishway ranges from 0.6 to 2.2 m. | 5 |
| C2 | D5 | The maximum flow rate is 2.35 m/s. | 3 |
| C3 | D8 | The maximum discharge is 1.65 $m^3/s$. | 5 |
| C4 | D15 | The turbulent kinetic energy range is from 0.01 to 0.12 $m^2/s^2$. | 5 |
| | D16 | There are no obvious vortices. | 5 |
| C5 | D17 | The fishway is arranged within the spillway. | 4 |
| | D18 | There is one fish inlet. | 4 |
| | D19 | There are no obvious water jumps in the channel. | 5 |
| C6 | D20 | The bottom slope of the fishway is 1:10. | 3 |
| | D21 | The total length of the fishway is 281.6m. | 4 |
| | D22 | The spacing between partitions in the fishway is 3.2 m. | 4 |
| | D23 | The width of the vertical slots in the fishway is 0.32 m. | 5 |
| C7 | D24 | The fishway has five outlets at varying heights. | 5 |
| | D25 | The exit is equipped with gates, trash racks, protective fences, and an auxiliary water supply system. | 5 |
| C9 | D28 | The main migratory fish species include salmon, lamprey, and beachhead fish. | 4 |
| | D29 | The theoretical maximum capacity of the fishway is 7,000 fish per day. | 5 |
| | D30 | The main fishing season occurs from August to October each year. | 4 |

### *Comprehensive ratings and reviews*

According to formula (2), the comprehensive score of the fishway operation assessment for the project is calculated as:

$$S_{sum}=\sum_{i=1}^{n}\sum_{j=1}^{m_i} W_i \times W_{ij} \times S_{ij} = 4.12 \tag{18}$$

Referring to Tab.5, the comprehensive score table for fishway operation evaluation, it is determined that the operation level of the fishway project is 'Operating Excellently.' The actual operating conditions meet the design requirements, and all data monitoring is normal.

## CONCLUSION

(1) This study references assessment theory and draws on existing methods to establish for the first time an operational evaluation analysis based on the Analytic Hierarchy Process for vertical slot

fishways. This method encompasses three main categories - hydraulic characteristics, engineering layout, operational management, and monitoring - including a total of 30 factors.

(2) Based on the literature of numerous fishway studies, the study adopted a five-level classification method to divide the operational efficiency grades of vertical slot fishways, providing a qualitative description for each corresponding grade. Using a scale of 1 to 9, the weights of each indicator were evaluated, criteria were established, and a comprehensive score was given to the performance of each indicator for the vertical slot fishway operation.

(3) After presenting a method for assessing the operation of vertical slot fish passages, the passageway project at the Laolongkou Hydraulic Junction was examined as a case study. Using actual measured data from the project and applying it to the evaluation system for the efficiency of vertical slot fishway operation, the project was rated as ' Operating Excellently ' in its operation, which confirmed the validity and reliability of the proposed assessment system.

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