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Determination of River Ecological Flow Thresholds and Development of Early Warning Programs Based on Coupled Multiple Hydrological Methods

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Abstract: In order to safeguard the health of river ecosystems and maintain ecological balance, it is essential to rationally allocate water resources. This study utilized continuous runoff data from 1967 to 2020 at the Zhouqu Hydrological Station on the Bailong River. Five hydrological methods, tailored to the hydrological characteristics of the Zhouqu hydrological cross-section, were employed. These methods included the improved dynamic calculation method, the NGPRP method, the improved monthly frequency computation method, the improved RVA method, and the Tennant method. Ecological flow calculations were conducted to determine the ecological flow, with analysis carried out through the degree of satisfaction, economic benefits, and the nonlinear fitting of the GCAS model. We established an ecological flow threshold and early warning program for this specific hydrological cross-section. Ecological flow values calculated using different methods for each month of the year were compared. The improved RVA method and Tennant method resulted in small values ranging from 4.05 to 36.40 m^3/s and 7.65 to 22.94 m^3/s, respectively, with high satisfaction levels and economic benefits, but not conducive to ecologically sound development. In contrast, the dynamic calculation method, NGPRP method, and improved monthly frequency calculation method yielded larger ecological flow values in the ranges of 21.79–97.02 m^3/s, 23.90–137.00 m^3/s, and 28.50–126.00 m^3/s, respectively, with poor fulfillment and economic benefits. Ecological flow thresholds were determined using the GCAS model, with values ranging from 16.72 to 114.58 m^3/s during the abundant water period and from 5.03 to 63.63 m^3/s during the dry water period. A three-level ecological warning system was proposed based on these thresholds, with the orange warning level indicating optimal sustainable development capacity for the Zhouqu Hydrological Station. This study provides valuable insights into the scientific management of water resources in the Bailong River Basin to ensure ecological security and promote sustainable development.

Keywords: ecological flow; hydrological method; terrace hydropower station; threshold; early warning program

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1. Introduction

The maximum carrying capacity of the environment significantly influences the development of human society. Inland rivers and lakes play a crucial role in determining the regional environmental capacity [1]. The volume of water in river channels has a profound impact on the regional ecosystem, affecting downstream pollution levels, aquatic life, agricultural irrigation, vegetation growth, and economic benefits from hydroelectric power [2]. Rainfall-recharging rivers are essential for maintaining regional water and ecological balance, as well as supporting human socio-economic activities [3]. However, with climate change and intensified human activities, the stability of rainfall and ecological flow in these rivers face unprecedented challenges [4,5]. Human water resource projects further impact water availability for river ecosystems. It is crucial to establish precise and

scientific decision-making mechanisms for the ecological protection of rainfall-recharging rivers, considering the balance between climate change, human activities, and ecological preservation. Research on accurately measuring ecological flow thresholds, establishing early warning systems, and implementing prevention and control programs is essential for managing water resources and ecological protection in inland areas [6].

Ecological flow, defined as the minimum flow necessary to sustain the health and biodiversity of river ecosystems, was first introduced by Gleick in the late 20th century [7]. Since then, this concept has been developed and enriched by numerous scholars, government agencies, and environmental organizations worldwide. Key documents shaping the understanding of ecological flow include China's 'Specification for the Calculation of Ecological Flow in Hydropower Projects' (NBT35091-2016), the European Union's Water Framework Directive, and The Nature Conservancy of the United States [8]. Recent research has made significant strides in the field of ecological flow, identifying over 200 calculation methods [9]. These methods are typically categorized into hydrological [10], hydraulic, habitat simulation, and integrated approaches, each offering a unique perspective on determining ecological flow [11,12]. While these methods have laid a foundation for establishing ecological flow requirements, much of the existing literature primarily addresses general river issues, lacking specific research on ecological flow thresholds and early warning systems for rainfall-recharging rivers affected by water diversion and transfer projects [13,14]. Accurately predicting and assessing changes in ecological flow for rainfall-recharging rivers, particularly in the face of increasingly frequent extreme climate events, presents a pressing scientific challenge.

Different categories of ecological flow calculation methods have unique attributes, with the hydrological method being the most practical and widely used due to its basis on continuous multi-year runoff from a river [15]. However, the calculation of ecological flow thresholds may be biased as different methods emphasize varying contexts and calculated ecological flows [16]. To mitigate errors in ecological flow calculation in rainfall-recharging rivers caused by climate, human activities, and calculation methods, this study focuses on the hydrological cycle and ecosystem interactions of these rivers. It considers the unstable runoff changes due to climate change, reduction in river water volume from water diversion projects, and increased ecological protection water demand. This study examines the hydrological characteristics, ecological needs, and human impacts of rainfall-recharging rivers by utilizing five applicable hydrological methods. Nonlinear curve fitting was performed using the Gram–Charlier A Series (GCAS) model in Origin 2021 software to analyze and establish ecological flow thresholds for rainfall-recharging streams. An effective early warning system was developed to monitor and evaluate changes in ecological flows in real time. This research aims to establish a theoretical framework and provide a reference for the conservation of aquatic organisms and the management of water allocation in rivers with intensively stepped hydropower stations built for rainfall recharge.

2. Materials and Methods

2.1. Overview of the Study Area

The primary focus of this research is the Bailong River Basin, situated at the confluence of the Gansu and Sichuan Provinces. The Bailong River, a major tributary of the Jialing River, spans 576 km in length, covers a basin area of 32,850 km^2, and experiences an average annual runoff of 389 m^3/s. The runoff in the Bailong River Basin is primarily influenced by rainfall, characterized by a significant elevation difference of 3607 m between its source and estuary. Numerous terraced hydroelectric power stations are densely situated along the main river course, with over 180 hydropower stations constructed, mostly being diversion-type. These diversion-type stations alter the flow direction and rate of the original river channel, leading to constraints on aquatic organism survival and posing significant ecological risks to the basin. Figure 1 provides an overview of the geographical location of the Bailong River Basin.

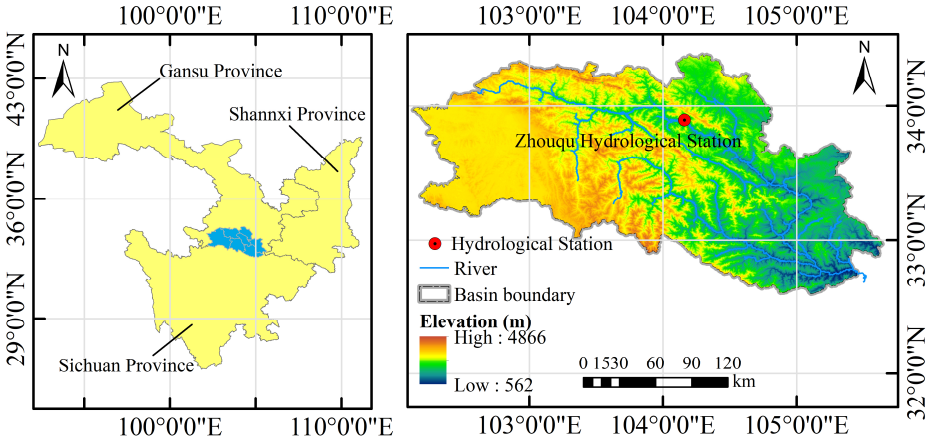


Figure 1. Overview of the geographic location of the Bailong River Basin.

2.2. Data Sources

The dataset utilized in this study comprises monthly runoff data from the Zhouqu Hydrological Station on the Bailong River spanning 54 years from 1967 to 2020, as well as the multi-year average monthly runoff data from 1956 to 2020. These datasets are sourced from the 'Gansu Provincial Water Resources Bulletin' and the measured hydrological data of the Zhouqu Hydrological Station. Positioned near the Xi'ergou Hydropower Station and in close proximity to a densely populated area, the Zhouqu Hydrological Station serves as a crucial hydrological monitoring point, marking the boundary between the upstream and midstream sections of the Bailong River.

2.3. Research Methods

In this study, we reviewed relevant published reports and studies with similar profiles to our study area. Based on the characteristics of our study methods, we identified five suitable ecological flow calculation methods for the area under investigation [17].

2.3.1. Improved Dynamic Calculation Method

The method for calculating ecological flow involves determining the ratio of the sum of the minimum monthly runoff volume of each month to the multi-year average flow [18]. An improved approach includes the use of the P-III curve, with the mean value ratio calculated based on the annual runoff volume corresponding to the P-III curve at a 90% assurance rate. Studies suggest that this method offers a higher level of assurance for ecological flow in rivers. The specific calculation steps are as follows:

① Calculate the average monthly flows for a long series of years $\overline{q}_i$:

$$\overline{q}_i = \frac{1}{n}\sum_{j=1}^{n} q_{ij} \tag{1}$$

② Calculate the annual runoff volume corresponding to the P-III curve at 90% guarantee; the results of the P-III curve alignment are shown in Figure 2.

③ Calculate the mean ratio values for the same period for the improved intra-year spreading method η; using Step ② above, we obtain $q_{90\%}$ = 57.08 m^3/s, and then η = 0.75 here.

$$\eta = q_{90\%}/\overline{q}_i \tag{2}$$

④ Calculate the ecological flows for each month Q_{EF}.

$$Q_{EF} = \overline{q}_i \times \eta \tag{3}$$

where q_{ij} is the runoff volume in month j of year i, m^3/s. n is the total number of years of the long series of historical runoff data. Q_{EF} is the monthly ecological flow at Zhouqu Hydrological Station, m^3/s.

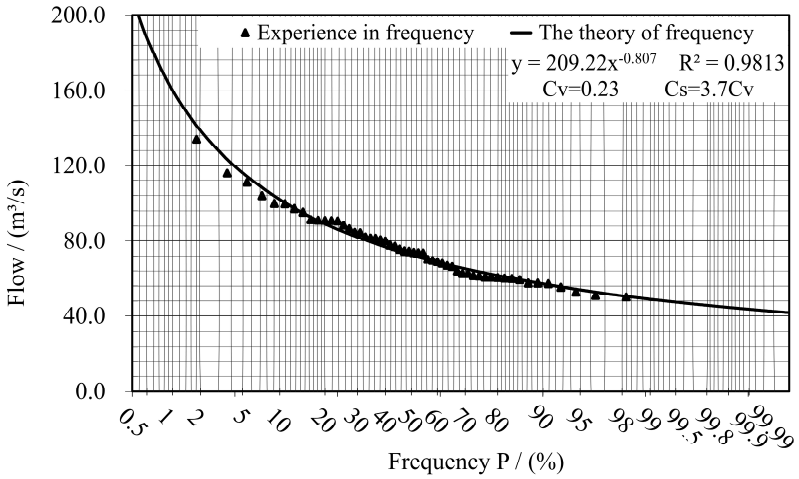


Figure 2. Wiring results of historical flow P-III curves at Zhouqu Hydrological Station. Here, C_v is the coefficient of variation, and C_s is the coefficient of bias.

2.3.2. NGPRP Method

The NGPRP (Northern Great Plains Resource Program) method classifies historical years as flat water, wet years, or dry years. It calculates ecological flow for each month by using runoff data from the 90% guarantee rate in a flat water year [19,20]. This study utilized the method outlined in GB/T22482-2008 Specification for Hydrological Intelligence Forecasting to calculate the distance from the flat percentage (E_i) using a specific formula [17]. The criteria for categorizing annual types are shown in Table 1.

$$E_i = \frac{(Q_i - Q_n)}{Q_n} \times 100\% \quad (4)$$

where Q_i is the average annual flow in year i, m^3/s. Q_n represents multi-year average annual runoff, m^3/s.

Table 1. Criteria for the classification of chronotypes.

Model Year	Dry Year	Flat Water Year	Wet Year
Percentage anomaly	$E_i < -10\%$	$-10\% \leq E_i \leq 10\%$	$E_i > 10\%$

2.3.3. Improved Monthly Frequency Calculation Method

The improved monthly frequency calculation method based on the NGPRP method categorizes ecological flows into the dry year, flat water year, and wet year with varying guarantee rates. A refinement to this approach involves establishing a consistent 50% guarantee rate for each period within a wet year, flat water year, and dry years to maintain stability in runoff and flow continuity. As a result, ecological flow is calculated on a monthly basis.

2.3.4. Improved RVA Method

The Range of Variability Approach (RVA) method, introduced by Richter et al. [21] in 1997, builds upon the Indicators of Hydrological Change (IHA) method [22]. This method is commonly used to assess the impact of human activities on a river's hydrological conditions. A crucial aspect of the methodology is the RVA threshold, which determines the upper and lower limits of ecological flow in a channel at 25% and 75% of the frequency of incoming

water from the upstream channel. The improved RVA method classifies incoming water into different periods such as pre-flood, post-flood, main-flood, and non-flood periods to reduce the impact of small RVA thresholds calculated during dry periods. Formula (5) is applied to calculate ecological flow during the main flood season, while Formula (6) is used for the remaining period.

$$Q_{EF} = (Q_u - Q_d) \cdot 50\% \quad (5)$$

$$Q_{EF} = (Q_u - Q_d) \cdot 75\% \quad (6)$$

where Q_u is the upper RVA threshold runoff volume corresponding to when the frequency of incoming water is 50%. Q_d is the lower RVA threshold runoff volume corresponding to when the frequency of incoming water is 75%.

2.3.5. Tennant Method

The Tennant method, also known as the Montana method, establishes empirical relationships between runoff and river ecosystems using measured runoff data from rivers [23]. Previous research [24] has revealed that when the minimum instantaneous flow reaches 10% of the average annual flow, it can support the survival of aquatic organisms in the habitat for a shorter duration. A minimum instantaneous flow of 30% of the average annual flow is sufficient to create a favorable survival environment for most aquatic organisms in the habitat. Furthermore, a minimum instantaneous flow of 60% of the average annual flow provides an excellent survival environment for aquatic organisms during the main growth and recuperation periods [25]. The calculation steps of the Tennant method are outlined below.

① The amount of water in the river throughout the year was categorized into dry and wet periods.

In the watershed under investigation, the dry period spans from November to April of the following year, while the abundant water period is from May to October.

② Calculations were conducted to ascertain the ecological flow of the river for each month of the year using the assessment criteria outlined in Table 2, following the Tennant method for calculating ecological flow.

Table 2. Tennant method for calculating ecological flow assessment criteria.

Narrative Description of Flow	Recommended Base Flow Regimens (Percentages of Average Annual Flow)/%	
	Wet Season	**Dry Season**
Flushing or Maximum	200	200
Optimal Range	60~100	60~100
Outatanding	60	40
Excellent	50	30
Good	40	20
Fair	30	10
Minimum	10	10
Severe Degradation	0~10	0~10

2.3.6. Gram–Charlier A Series Model

The Gram–Charlier A Series (GCAS) kurtosis function is a mathematical model commonly utilized in chromatographic analysis. This function is derived from the Gram–Charlier Series, which is a technique employed to enhance Gaussian distributions for better representation of distributions exhibiting skewed and tailed characteristics. In the context of chromatographic analysis, this series enables a more precise modeling of peak shapes, particularly in cases of asymmetric peaks [26]. It has a wider range of applications in fields such as thermodynamics [27] and aerodynamics [28]. In this research, the GCAS peak function was ultimately chosen to determine the threshold value of ecological flow at a hydrological section. This decision was based on a comparison between the variations in

average monthly runoff over the years at the hydrological section in the study area and the fitting accuracy of the GCAS peak function.

3. Results

3.1. Ecological Flows Calculated by Each Hydrological Method

This study utilized five hydrological methods to calculate the ecological flow at Zhouqu Hydrological Station on a monthly basis throughout the year. The results, depicted in Figure 3, show a consistent pattern where ecological flow is higher during the wet season (main flood season) and lower during the dry season (non-main flood season). Overall, there is a single-peak change pattern, starting with an increase and then a decrease. The ecological flow values calculated by the different methods ranged from 4.05 to 137.00 m^3/s annually. The improved dynamic calculation method (21.79–97.02 m^3/s), NGPRP method (23.90–137.00 m^3/s), and improved monthly frequency calculation method (28.50–126.00 m^3/s) provided results closest to the average monthly runoff, with lower dispersion and standard deviations of 21.41, 15.82, and 4.67, respectively. On the other hand, the improved RVA method (4.05–36.40 m^3/s) and the Tennant method (7.65–22.94 m^3/s) also had results closer to the average monthly runoff but with larger standard deviations of 64.81 and 68.81, respectively. Further analysis and verification are necessary to determine if these methods meet the lower ecological flow limit of the river. During the hydrological method calculation process, the ecological flow values for individual months exhibited abrupt changes. In Figure 3b, the results of the improved dynamic calculation method, the NGPRP method, and the improved monthly frequency calculation method all show a lower inflection point in August, followed by an increase in September, aligning with the overall trend of average monthly runoff over the years. However, the NGPRP method displayed a more significant sudden change. Upon analyzing the calculation principles of the method, it was determined that this discrepancy may be attributed to an extreme dry spell in August during the year corresponding to the 90% guarantee rate in the selected flat water year, resulting in reduced river runoff and a larger mutation value in the calculated ecological flow for that month. Furthermore, the improved RVA method and the Tennant method did not exhibit noticeable sudden changes in ecological flow values throughout the year. This can be attributed to the fact that these two methods calculate ecological flow by adjusting the baseline value of ecological flow through a percentage-based approach, which accounts for the variability in runoff volume corresponding to the frequency of upstream water inflow and the historical average monthly runoff volume. This adjustment minimizes the error potential stemming from unstable runoff variations across different months of the year, thereby enhancing the stability of ecological flow calculation outcomes.

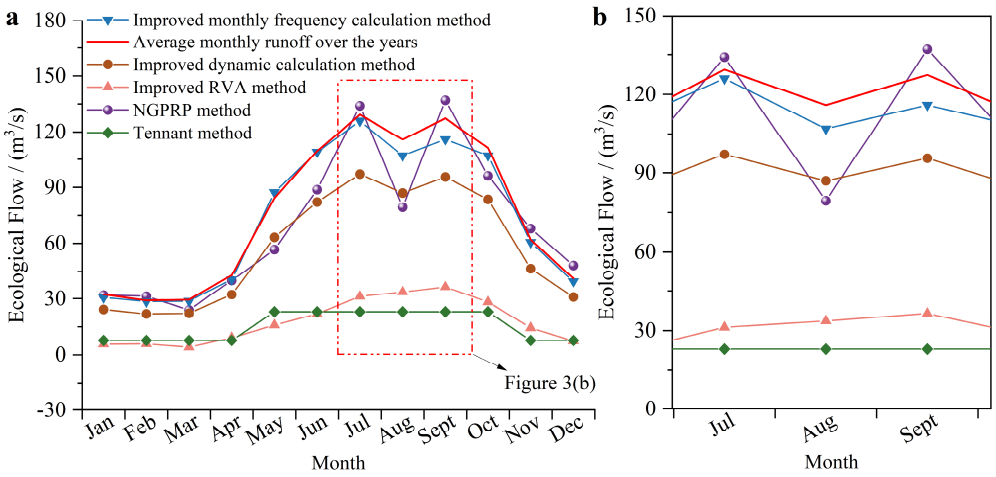


Figure 3. Results of ecological flow calculations for each hydrological method. Here, (**a**) overall trends in ecological flows.; (**b**) shows a partial enlargement.

3.2. Analysis of the Level of Satisfaction

The degree of ecological flow satisfaction is defined as the proportion of years in which river runoff exceeds the ecological flow threshold relative to the total number of years in a long series. This ratio provides insight into the relationship between ecological flow and river runoff in terms of water quantity, indicating the reasonableness and reliability of the ecological flow threshold. This study utilized historical runoff data from 1967 to 2020 to assess the degree of ecological flow satisfaction using various hydrological methods. The results, depicted in Figure 4, reveal that the improved RVA method and the Tennant method consistently achieved a high degree of satisfaction, reaching 100% throughout the year. This suggests that the ecological flow values calculated by these methods meet the water requirements of aquatic organisms in the river channel. The improved dynamic calculation method followed with a satisfaction rate ranging from 61.11% to 100.00%, with lower levels in August and September (61.11%) and higher levels in other months. The two methods for calculating ecological flows with lower satisfaction levels, the improved monthly frequency calculation method and the NGPRP method, had satisfaction levels ranging from 46.30% to 50.00% and 16.67% to 90.74%, respectively. The improved monthly frequency calculation method showed a more uniform distribution of satisfaction levels with less dispersion throughout the year, while the NGPRP method exhibited a maximum difference of 74.07% in satisfaction levels and a larger degree of dispersion annually. The fluctuating water quantity in the river poses a significant risk to the normal activities of aquatic organisms. Based on the analysis, the ecological flow values derived from the improved RVA method, the Tennant method, and the improved dynamic calculation method demonstrated higher satisfaction levels and were deemed more appropriate for calculating ecological flows in the study area.

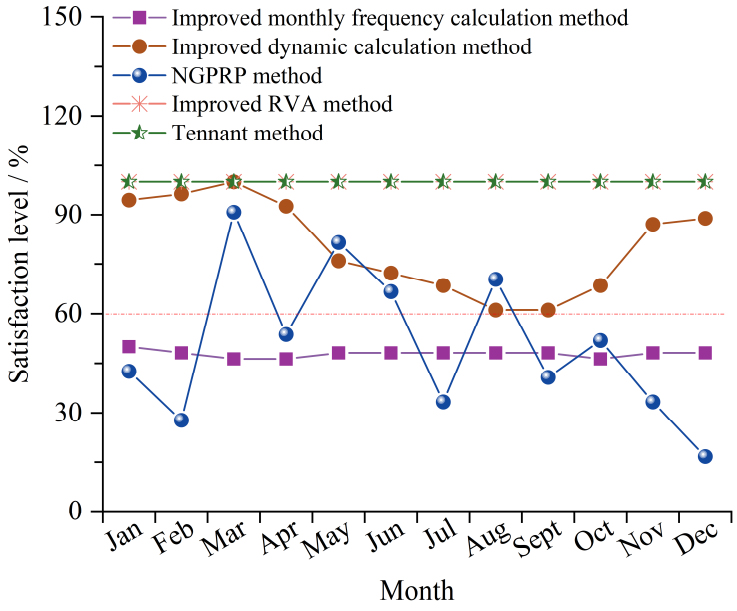


Figure 4. Analysis of ecological flow satisfaction.

3.3. Economic Benefit Analysis

Xi'ergou Hydropower Station is situated in Hanban Township, Zhouqu County, along the main stream of the Bailong River, approximately 34 km downstream from Zhouqu County and upstream of the Lijie Hydropower Station. As a gate-dam runoff-diversion-type hydropower station, its primary objective is electricity generation, with a designated flow rate of 141.00 m^3/s. Given its diversion-type nature, it is crucial to maintain discharge flow during the dry season to support the growth, reproduction, habitat, and overwintering of aquatic organisms, particularly during fish breeding and overwintering seasons. This creates a conflict between maximizing economic benefits through power generation and

meeting the water needs of aquatic life. While increased water usage enhances power generation benefits, it reduces the discharge flow essential for aquatic life behind the dam, potentially jeopardizing the ecosystem's stability. Evaluating the ecological flow threshold involves comparing the ecological flow discharged from behind the dam with the diversion and power generation flow of the station, serving as a key indicator of the calculation's scientific rigor and validity. Analysis depicted in Figure 5 reveals that the ecological flow represents a smaller proportion of the power generation flow calculated by the improved RVA method and the Tennant method, indicating superior power generation and economic benefits in this scenario. The ecological flow share of the improved dynamic calculation method ranged from 15.45% to 68.81% for all months of the year. Meanwhile, the improved monthly frequency calculation method showed an ecological flow share ranging from 20.21% to 89.36%. In contrast, the NGPRP method presented the lowest economic benefit evaluation, indicating a poor economic benefit for the hydropower station under this ecological flow discharge mode. Therefore, when considering the economic benefits for Zhouqu Hydrological Station, we recommend the ecological flow calculated by the improved RVA method and the Tennant method as they offer better economic benefits.

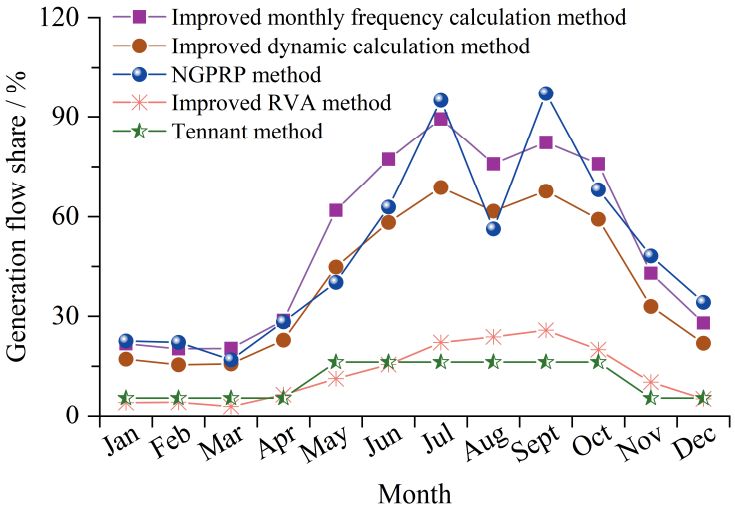


Figure 5. Analysis of the economic benefits of ecological flows.

3.4. Determination of Ecological Flow Thresholds

Based on the characteristics of ecological flow determined through hydrological methods and the runoff variations in the Bailong River Basin throughout the year, the authors propose a novel approach to defining ecological flow thresholds. Instead of assigning a fixed numerical value, this study established monthly ecological flow thresholds by considering the specific water conditions and the water demand of aquatic organisms in the river channel for each month. The results indicate that methods like the improved dynamic calculation method, the NGPRP method, and the improved monthly frequency calculation method yielded higher ecological flow values, which can be considered the maximum desirable range at Zhouqu Hydrological Station. Conversely, the RVA method and Tennant method produced lower ecological flow values, which can also be set as the maximum desirable range at Zhouqu Hydrological Station. A nonlinear fitting method was employed in this study to compare model fitting effects and determine the most suitable method for determining ecological flow thresholds in the study area. By comparing the model analyses such as Lorentz, Voigt, and BiHill, it was found that the GCAS model yielded the best results with larger R^2 values for fitting the desired range of ecological flow thresholds at Zhouqu Hydrological Station. The fitting results for the maximum and minimum ecological flow thresholds are illustrated in Figure 6a,b.

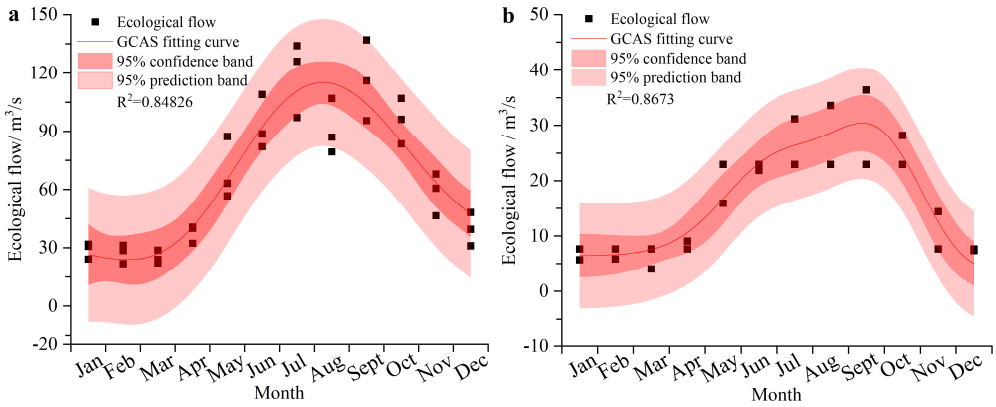


Figure 6. Nonlinear fitting to solve for ecological flow thresholds. Here, (**a**) shows the fitted results for the maximum ecological flow; (**b**) shows the fitting results of the minimum ecological flow.

The ecological flow fitting results, with R^2 values in Figure 6 all exceeding 0.84, indicate good fitting and high credibility. The final ecological flow thresholds for Zhouqu Hydrological Station are presented in Figure 7, showing maximum values ranging from 23.87 to 114.58 m^3/s and minimum values ranging from 5.03 to 30.34 m^3/s for each month of the year.

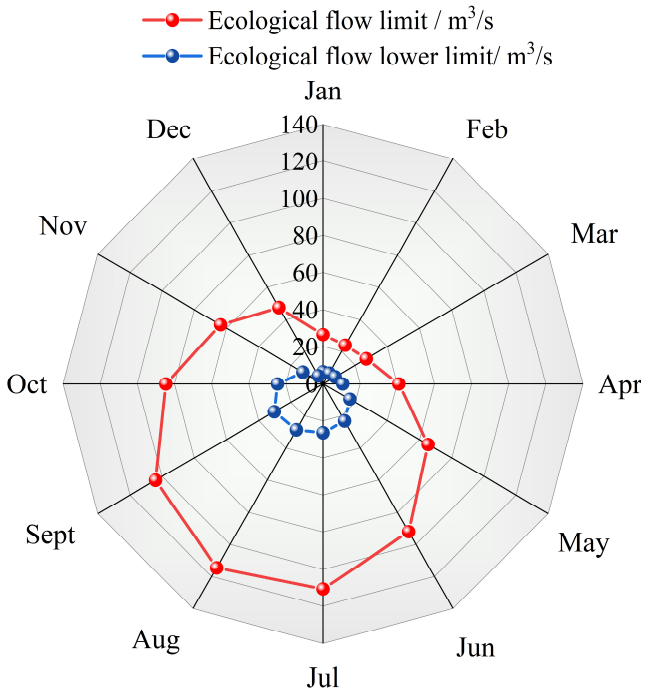


Figure 7. Ecological flow thresholds for each month of the year at Zhouqu Hydrological Station.

3.5. Ecological Flow Early Warning Program

Water resource management and the implementation of an ecological flow early warning system in the Bailong River Basin are crucial for maintaining the health of the river ecosystem and ensuring the sustainable use of water resources. In accordance with the "Technical Requirements for the Preparation and Implementation of Ecological Flow Guarantee Plans for Key Rivers and Lakes", issued in 2019 by the General Institute of Water Resources and Hydropower Planning and Design of the Ministry of Water Resources, the ecological flow warning levels in the Bailong River Basin were categorized into three levels: blue warning, orange warning, and red warning. Each level corresponds to specific ecological flow conditions and appropriate response measures. The blue warning level aims

to maintain an ecological flow target value within the upper one-third range between the maximum and minimum ecological flows, indicating good ecological flow conditions. The orange warning level targets an ecological flow value within the middle one-third range, signaling mild damage to the ecosystem. The red warning level sets the ecological flow target value within the lower one-third range, indicating significant ecological damage. The ecological flow early warning program at the Zhouqu Hydrological Station is illustrated in Figure 8.

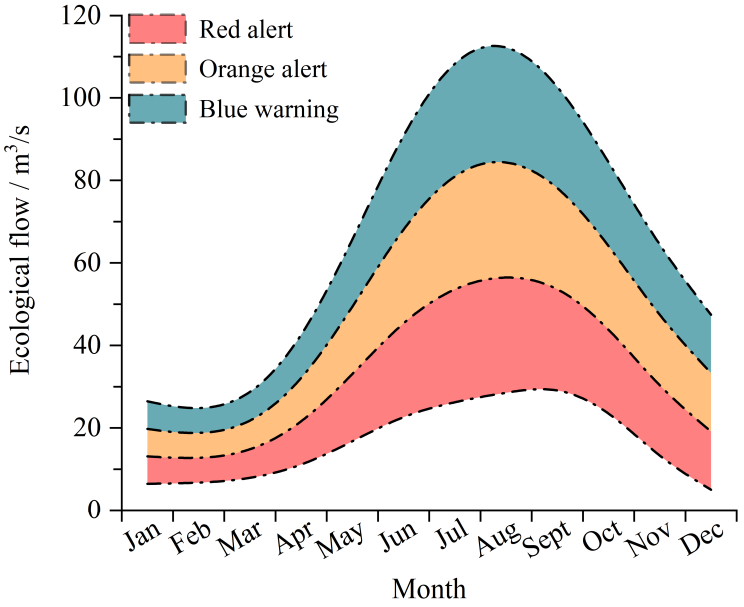


Figure 8. Early warning program setting for ecological flow at Zhouqu Hydrological Station.

4. Discussion

The concept of ecological flow and its calculation methods, both domestically and internationally, are not solely based on the level of ecological restoration or protection efforts by researchers. They also take into account natural elements such as geographic location, climatic conditions, and hydrological characteristics of the study area [29]. Therefore, when determining the ecological flow of rivers in various basins, research methods should be chosen based on the specific characteristics of each [30]. In the case of the Bailong River Basin, where runoff is primarily dependent on rainfall recharge and minimally influenced by iceberg snowmelt, and with a lack of biological data, five hydrological methods were selected for calculating ecological flow thresholds at the Zhuoqu hydrological cross-section. These methods included the improved dynamic calculation method, the NGPRP method, the improved monthly frequency calculation method, the improved RVA method, and the Tennant method. They were chosen for their suitability for low-priority river segments [31], consideration of climatic conditions and frequency factors [32], and ability to determine required flows based on changing river conditions [33]. The study findings demonstrated that the ecological flow results at the Zhouqu hydrological cross-section, determined through the improved dynamic calculation method, the NGPRP method, and the improved monthly frequency calculation method, were consistently higher than the ecological flow calculations derived from the improved RVA method and the Tennant method across all months of the year. These results align with the conclusions drawn by Qu et al. [34]. The dynamic calculation method was found to be highly suitable for calculating ecological flow downstream of small hydropower dams. The recommended ecological flow threshold in the river was established by dividing the flood period and dry period, enhancing the scientific rigor of ecological flow calculations. Furthermore, three ecological flow warning levels (blue, orange, and red) were defined, along with corresponding response measures, to effectively monitor and manage water resources in the Bailong River Basin,

ensuring ecological flow stability and river ecosystem health [35]. The delineation of these warning thresholds offers clear guidance for the scientific management and allocation of water resources in the Bailong River Basin. Establishing an ecological flow monitoring and early warning system can enhance flow monitoring accuracy, optimize reservoir scheduling, and facilitate the timely implementation of ecological and environmental protection measures to preserve the ecological environment. This is crucial for achieving sustainable development and safeguarding water resources [36]. Future research on river ecological flows should focus on enhancing existing hydrological methods for more precise simulation and prediction of river flows. This study delves into the parameterization of existing models, data assimilation techniques, and uncertainty assessment of model outputs in the context of hydrology. It suggests exploring modern technological tools like remote sensing technology and Internet of Things (IoT) devices for the real-time monitoring and analysis of hydrological data [37]. Furthermore, the determination of ecological flow thresholds should consider seasonal variations, climate change, and human activities' impacts [38]. Future research should focus on developing dynamic models that can adapt ecological flow thresholds based on real-time environmental changes to meet ecological needs at various temporal and spatial scales. Our study emphasizes the importance of continuous in-depth exploration to provide robust theoretical and technical support for the scientific management and protection of river ecological flow. This research is crucial for maintaining biodiversity, sustainable water resource use, and fostering a harmonious coexistence between humans and nature in the long term.

5. Conclusions

Based on an extensive analysis of historical runoff data from the Bailong River Zhouqu Hydrological Station, five hydrological methods tailored to the characteristics of the Bailong River Basin were employed to compute the ecological flow rate. The key findings indicate that the ecological flow values derived from the improved RVA method and the Tennant method were generally lower, resulting in a higher level of satisfaction and enhanced economic benefits for the hydropower station. However, this approach only meets the minimum survival water requirements of aquatic organisms in the river, posing a limitation on the river's ecological sustainable development. Conversely, the ecological flow calculations using the improved dynamic calculation method, the NGPRP method, and the improved monthly frequency calculation method yielded higher values. Although these methods may lead to poorer economic benefits for diversion-type hydropower stations and lower satisfaction levels, they offer significant advantages for aquatic organism survival and ecological enhancement in the river channel. The ecological flow threshold established through the nonlinear fitting of the GCAS model at Zhouqu Hydrological Station ranged from 5.03 to 114.58 m^3/s, with a high level of credibility in the fitting results. The ecological flow threshold for Zhouqu Hydrological Station was used to establish an ecological early warning scheme, which was divided into three warning levels: blue, orange, and red. Taking into account both ecological satisfaction and economic benefits, the orange warning level indicates that the ecological flow at Zhouqu Hydrological Station is in a relatively good state and can also contribute to the sustainable development of the ecological health of the Bailong River Basin.

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