Comparative study on the dynamic calculation method of river ecological water demand

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Abstract. In order to maximize the seasonal ecological hydrological demand of the river, this paper introduces three improved dynamic calculation methods. Taking the downstream channel of the Jilintai-I Hydropower Station on the Kashi River in Xinjiang as an example, three methods are applied to calculate the ecological water demand of the channel. Meanwhile, it is compared with the improved classification standard of Tennant method, and a method that is more suitable for the calculation of the ecological water demand of the river in this basin is selected, so that the calculation results can meet the seasonal dynamic demand of runoff while ensuring the basic ecological and hydrological demand of the basin, and benefit to the sustainable development of the river habitat. And reduce the losses caused by hydrological disasters, and achieve the coordinated development of economy and ecology.

1. Introduction

Water resources are the basis for maintaining the stability of river ecosystem. The balance between human water demand and healthy water demand of river ecosystem has become an important challenge for river management in the 21st century [1-2]. In recent years, with the excessive development of water resources, serious imbalance between the distribution of living, production and ecological water, leading to a series of problems such as river channel flow reduction or even cut-off, ecological environment deterioration and so on [3]. In order to restore and maintain river health, it is necessary to scientifically and systematically determine the basic ecological water demand [4]. At the same time, under the background of global warming, the scale and frequency of urban main hydrological disasters increase rapidly [5]. For example, according to the statistics and data of the main hydrological disasters in Urumqi from 1949 to 2015, the main hydrological disasters in Urumqi are caused by flood, snow and drought. Therefore, it is necessary to analyze the allocation proportion of ecological water demand in arid and semi-arid areas, so as to minimize the loss caused by hydrological disasters [6].

The calculation of ecological water demand involves many fields. The conflict between economic and ecological water demand in inland river basin is very serious [7]. At the watershed scale, it is still one of the most important but difficult problems to analyze the environmental flow demand of the basin by coupling hydrological cycle and hydrodynamic process with aquatic ecological process [8]. At the same time, there is a conflict between power generation and ecological demand in hydropower plants. It is necessary to calculate the comprehensive ecological water demand and establish a multi-
objective ecological operation model, so as to achieve the coordinated development of economy and ecology [9]. The calculation of ecological water demand is an important problem to be solved.

In the 1940s, foreign scholars [10] proposed the concept of basic ecological water demand [11], and conducted extensive basic research on its calculation methods. At present, there are more than 200 methods used to study and calculate the ecological water demand of rivers, which can be roughly divided into four categories according to their use conditions and scope of application (Table 1).

**Table 1. Classification of calculation methods of river ecological water demand.**

| Classification       | Representative method                                                                 |
|----------------------|---------------------------------------------------------------------------------------|
| Hydrological method  | Tennant method [12], Tex2 as method [13], NGPRP method [14], Minimum monthly average flow method [15], Estimation algorithm of natural runoff in dry year [16], 7Q10 method [17] etc. |
| Hydraulic method     | Wetted perimeter method [18], R2CROSS method [19], CASMIR method [20-21] etc.         |
| Habitat quota method | IFIM/ PHABSIM method [22-23], RCHARC method [24], Basque method [25] etc.              |
| Comprehensive method | BBM method [26], HEA method [27] etc.                                                 |

In China, the research on basic ecological water demand in river channels started relatively late, and the relevant data may be difficult to support the relevant calculation. The continuous runoff data of rivers required by the hydrological method is easy to obtain, which is easy to calculate and widely used. There are two representative types hydrological methods. One is the dynamic calculation method of annual distribution proposed by Pan et al. in 2012 [28]. The second is that Fan et al. proposed the calculation method of the same-frequency distribution within the year with the "ratios of average flow in the periods" based on the distribution method during the year [29].

This paper introduces three improved new dynamic calculation methods and uses them to calculate the basic ecological flow in the downstream of the Kashi River Jilintai-I Hydropower Station in Xinjiang. Meanwhile, it is compared with the calculation result of the improved Tennant method.

### 2. Overview of the study area

![Figure 1. Location map of Kashi River watershed.](image)

Kashi River, the second largest tributary of Ili River, is a seasonal river. The total length of Kashi River is 304km, and the basin area above the Tuohai River in Yining County is 8656 square kilometers. The Jilintai-I Hydropower Station is located in the middle of the Jilintai Gorge section in...
the middle reaches of the Kashi River. At the dam site, the average annual flow is 112 m$^3$/s, and the average annual runoff is 3.461 billion m$^3$. The location of Kashi River watershed is shown in Figure 1.

### Table 2. Annual average monthly runoff.

| Month | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Q$^i$ (m$^3$/s) | 33.8 | 31.8 | 34.6 | 85.3 | 180.1 | 275.5 | 284.1 | 219.3 | 116.3 | 68.8 | 48.3 | 38.9 |

The river runoff fluctuates to a certain extent during the year, showing the characteristics of some northern rivers. Among them, the inflow from May to August is more in the flood season (wet period), and the inflow from September to April of the next year is less than Non-flood season (normal river flow period and dry period). Based on the monthly runoff data of the station from 1958 to 2014 (Table 2), the basic ecological water demand of the river is calculated.

### 3. Calculation methods and application examples

#### 3.1. Definition of related concepts

1. River ecological water demand. River ecological water demand is a general term of water demand to meet various functions of river ecosystem under specific time and space conditions [28].

2. The mean ratio of the same period is the ratio of the mean value of the river runoff in a certain period of time (such as month) and the mean value of the history in the same period, expressed by $\eta$ [28].

#### 3.2. Dynamic calculation method

**3.2.1. Dynamic calculation method of instream basic ecological water demand.** The dynamic calculation method is based on the long series of runoff data of the hydrological section of the river. The percent of the average flow in the same periods is determined by the ratio of the minimum annual average runoff to the annual average runoff, and the monthly basic ecological water demand of the river is calculated based on the annual process of the multi-year monthly average flow data [28]. The calculation formula is as follows:

$$Q = \frac{1}{12} \sum_{i=1}^{12} q_i_q; \quad q_i = \frac{1}{n} \sum_{j=1}^{n} q_{ij}$$  \hspace{1cm} (1)

$$Q_{\text{min}} = \frac{1}{12} \sum_{i=1}^{12} q_{\text{min}(i)}; \quad q_{\text{min}(i)} = \min(q_{ij}), j = 1, 2, \ldots, n$$  \hspace{1cm} (2)

$$\eta = \frac{Q_{\text{min}}}{Q}$$  \hspace{1cm} (3)

$$Q_i = \bar{q}_i \times \eta$$  \hspace{1cm} (4)

In the formula: $Q$ is the annual average runoff (m$^3$/s); $\bar{q}_i$ is the average monthly runoff in month $i$ (m$^3$/s); $q_{ij}$ is the monthly average runoff in month $i$ of the year $j$ (m$^3$/s); $Q_{\text{min}}$ is the minimum annual average runoff (m$^3$/s); $q_{\text{min}(i)}$ is the annual minimum monthly runoff in month $i$ (m$^3$/s); $Q_i$ is the monthly basic ecological water demand of river (m$^3$/s); $\eta$ is the percent of the average flow in the same periods; $n$ is the statistical year.

**3.2.2. The limitation of the dynamic calculation method.** The dynamic calculation method is suitable for large and medium-sized continuous rivers with continuous runoff data, which makes up for the empiricism and subjectivity of the traditional hydrological method, which takes the specific percentage of the annual average runoff or the specific guarantee rate on the natural runoff frequency curve as the hydrological index. The mean value ratio of the same period is more representative of the
to a certain extent, it compensates for the lack of hydrological method to calculate the ecological base flow of the river based on a specific percentage of the average runoff for many years [28]. However, due to the percent of the average flow in the same periods, it weakens the extreme runoff such as extremely abundant and extremely dry in each month, which can not reflect the annual variation of seasonal rivers and is difficult to meet the seasonal ecological hydrological demand of rivers to the maximum [30].

3.3. Improved dynamic calculation method

3.3.1. Improved dynamic calculation method and its application. Fan et al. proposed the improved dynamic calculation method (hereinafter referred to as the new method 1) in 2018 [30]. Based on the original method, the three calculation periods are divided according to the characteristics of seasonal rivers. The curve is adapted to the average annual runoff in the past years, and the annual average flow under different guarantee rates is obtained, and the runoff data corresponding to the year with the guarantee rate between 5% and 95% is selected from the monthly data with the 95% guarantee rate. The ratio of the average flow rate to the average annual flow rate in the wet period, normal river flow period and dry period, redefine the ratio in the same periods [30]. At the same time, this method reviews the runoff data to ensure its reliability and rationality, and to a certain extent avoid the impact of extreme conditions on the overall results.

According to the seasonal characteristics of the Kashi River runoff, the period from May to August, April and September to November, and December to March of the following year are divided into three periods: wet period, normal river flow period and dry period. According to the P-III curve, the average annual flow rate of Jilintai-I Hydropower Station from 1958 to 2014 is fit. Excluding four years (1992, 2005, 2010, 2014) with annual flow guarantee rate not between 5% and 95%.

Zhao et al. proposed the improved dynamic calculation method (hereinafter referred to as the new method 2) in 2018 [31]. On the basis of the original method, the percent of the average flow in the same periods is redefined from the ratio of annual runoff to average annual runoff in extremely dry year (P = 90%) to calculate the basic ecological water demand.

According to the 1958-2014 runoff data of Jilintai-I Hydropower Station, P-III curve is used to fit the annual average flow. The wiring results are shown in Table 3.

Table 3. Wiring results.

| Average (m³/s) | Cv | Cs/Cv | 90% annual runoff (m³/s) |
|---------------|----|-------|-------------------------|
| 118.08        | 0.18| 4.44  | 93.30                   |

Deng proposed the improved dynamic calculation method (hereinafter referred to as the new method 3) in 2019 [32]. Based on the original method, the extreme values of each month’s runoff are eliminated, and it is proposed to quantify the "average ratio of the same period of the same period" in the two periods of flood season and non-flood season. According to the seasonal characteristics of Kashi River, may to August is divided into flood season, January to April and September to December are divided into non-flood season, so as to maximize the seasonal hydrological demand of the river [32]. See Table 4 for the ecological basic flow of the river channel calculated by the three methods.

Table 4. Results of improved dynamic calculation method.

| Month | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Instream ecological water demand (m³/s) | New method 1 | 125.3 | 23.6 | 25.5 | 57.5 | 126.4 | 191.1 | 199.1 | 152.4 | 77.546.232.4 | 28.9 |
|       | New method 2 | 226.7 | 255.1 | 127.3 | 67.4 | 142.3 | 217.8 | 224.5 | 173.3 | 91.954.438.1 | 30.7 |
|       | New method 3 | 222.7 | 213.3 | 232.2 | 56.9 | 115.6 | 176.0 | 182.6 | 140.2 | 77.746.132.3 | 26.1 |
3.3.2. Analysis of the results of the improved dynamic calculation method. Based on the multi-year runoff data of Jilintai-I Hydropower Station from 1958 to 2014, the ecological flow of the river is calculated by using the same frequency distribution calculation method within the year [29], the dynamic calculation method [28] and three improved dynamic calculation methods, respectively, which are plotted together with the minimum monthly average runoff process of each month of the station over the years (Figure 2).

![Figure 2. Comparison of calculation results.](image)

From the above figure, it can be seen that the new dynamic calculation method 1 and 2 can better meet the ecological water demand in the river channel. The ecological flow calculated by the new dynamic calculation method 2 is basically the same as that calculated by the dynamic calculation method before the improvement. Even in the flood season, the ecological flow calculated by the improved method is slightly smaller than that before the improvement. The calculated value of the ecological flow distribution within a year decreases in the order of 2,1,3 of the new dynamic calculation method and the same frequency distribution method within the year.

3.4. Comparison with Tennant method

Tennant method was proposed by Tennant D.L. in 1976 [12]. This method is to use the percentage flow of the annual average runoff of the river as the ecological water demand of the river. Tian et al. divided the year into two calculation periods: flood season and non-flood season. The improved Tennant method is more suitable for the calculation of ecological flow of seasonal rivers [33].

| Runoff and habitat suitability | Percentage of recommended runoff to annual average/% |
|-------------------------------|-----------------------------------------------|
|                               | Flood season | Non-flood season |
| Maximum                       | 200          | 200               |
| Best range                    | 60~100       | 60~100            |
| Excellent                     | 40           | 60                |
| Very good                     | 30           | 50                |
| Good                          | 20           | 40                |
| General                       | 10           | 30                |
| Poor                          | 10           | 10                |
| Very poor                     | 0~10         | 0~10              |

Tennant method is a commonly used method to calculate ecological flow in water conservancy projects. Generally, 30% and 10% of annual average runoff are used as flood season and non-flood
season respectively [32]. Based on the seasonal characteristics of the Kashi River Basin, the evaluation period of the Tennant method is revised (Table 5).

Because the division of the calculation period of the wet period, the normal river flow period and the dry period in the Kashi River Basin of the study area coincides with the flood season and the non-flood season, the same Tennant classification standard can be used for the flood season and the wet period, the non-flood season and the normal river flow period and the dry period.

Compare the evaluation results of the river ecological flow processes obtained by the three improved dynamic calculation methods and the same frequency method with the revised Tennant method (Table 6).

Table 6. Comparison between the calculation results of river ecological flow and the revised evaluation results of Tennant method.

| Method                      | Percentage of annual average runoff/% | Evaluation result of revised Tennant method |
|-----------------------------|---------------------------------------|------------------------------------------|
|                             | Flood season  | Non-flood season | Annual | Flood season | Non-flood season | Annual |
| New method 1                | 69.8          | 69.2             | 69.6   | Best range   | Best range       | Best range |
| New method 2                | 79.0          | 79.0             | 79.0   | Best range   | Best range       | Best range |
| New method 3                | 64.1          | 66.9             | 65.0   | Best range   | Best range       | Best range |
| The method of equal frequency within one year | 58.2          | 59.6             | 58.6   | Excellent    | Very good to excellent | Very good |

It can be seen from Table 6 that the revised Tennant method is consistent with the evaluation results of the three years of the New Year's distribution calculation method in the flood season, non-flood season and year-round river ecological flow as a percentage of its annual average runoff value. The later Tennant method for the same-frequency distribution calculation method during the year during the flood season, non-flood season and year-round ecological flow is slightly worse than the three new-year distribution methods. It can be seen that the new distribution calculation method is more conducive to the sustainable development of the river ecosystem [32].

4. Conclusion
The three improved dynamic calculation methods introduced in this paper can meet the ecological water demand of the Kashi River to a certain extent. The calculation method of the annual distribution of ecological runoff obtained by the dynamic calculation method 3 and the method before the improvement is not much different, and even smaller in the flood season. The distribution of ecological water in the improved dynamic calculation method 2 is too large, which may have a certain impact on the demand for power generation and irrigation of rivers. In contrast, the improved dynamic calculation method 1 is more suitable for ecological flow calculation in the Kashi River Basin. According to the seasonality of the river, this method uses different mean value ratios for different calculation periods, which improves to a certain extent the shortcomings of the ecological flow obtained by the original method and the shortcomings that affect biological reproduction. And on the basis of the original method, a series of review of runoff data was added to ensure the reliability and rationality of runoff data.

The practical application shows that river ecological water demand not only includes the ecological environment water demand, but also reflects the change law of annual distribution of ecological water demand according to seasonal characteristics. The three improved dynamic calculation methods have some ecological significance, which can be used for reference in the calculation of ecological water demand of seasonal rivers. However, further comparative analysis is needed to select a more suitable calculation method for each basin. In this paper, the calculation method of ecological water demand
more suitable for similar seasonal rivers is preliminarily obtained. However, the ecological water demand of the basin is always restricted by the demand of economic development and other aspects. Therefore, the next research should consider the comprehensive water use regulation of the basin, and seek the optimal water allocation scheme to balance the economic and ecological water demand.

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