A Practical Approach for Environmental Flow Calculation to Support Ecosystem Management in Wujiang River, China

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Abstract: To promote ecosystem protection in the Wujiang River, this paper proposes a practical approach for calculating the environmental flow. The proposed approach combines the idea of the “guarantee rate” of the flow duration curve (FDC) method and the grading idea of the Tennant method. A daily flow series of the Wujiang River was compiled from 1956 to 2019 and used to compare the effect of the proposed approach versus the traditional approaches in four selected sections along the river. The results show that the environmental flow of the Wujiang River can be divided into five levels by the T-FDC method, with a level-by-level disparity, and all levels can capture the temporal and spatial variability of river flow. Additionally, the calculated basic environmental flow process ranges between the historical minimum and second minimum monthly average flow, and the threshold width of the optimal flow is more reasonable than the Tennant method. The T-FDC method can provide technical support for Wujiang River ecosystem management and sustainable development.

Keywords: environmental flow; hierarchical target; tennant method; flow duration curve; Wujiang River Basin

1. Introduction

The impact of reservoir development on river ecosystems is of great concern in practice. River hydrological processes have essential ecological effects on river channels and their surrounding organisms [1,2]. While reservoirs regulate runoff for flood control, power generation, and irrigation, they also change the ecological situation of the river to an extent, causing some stress to the ecosystem [3,4]. How to mitigate or eliminate the negative impacts of cascade reservoirs on river ecology is a complex systemic issue [5].

With the global emphasis on ecological protection, hydraulic projects are increasingly required to address and account for river ecological functions in project design and operation. Studies and practices show that one of the essential measures to reduce the ecological impact of hydraulic projects, such as dams and reservoirs in rivers, is to take into account the ecological needs of the river by optimizing the operation of those projects, or the so-called “ecological operation” [6–9]. To formulate ecological operation schemes, a prerequisite is identifying and characterizing the ecological requirement on the amount of river flow, known as environmental flow, so that it can be incorporated in or accounted for in the operation of hydraulic projects and maintain downstream health.

However, the cascade development of the Wujiang River Basin in southwest China started long ago, mainly to generate electricity, and thus limited consideration of river
ecology. Most reservoir projects have no targets for maintaining environmental flow when beginning the design [10]. An easy-to-use and reasonable method for environmental flow calculation is urgently needed to manage ecological operations. Determining rivers’ environmental flow requirement is also a research hotspot in ecology, hydrology, and water resources [11–13].

Depending on their focus, available methods for calculating the environmental flow of rivers can be divided into four main categories: (1) hydrological methods using historical hydrological data, (2) hydraulic methods based on the hydraulic properties of river sections, (3) habitat simulation methods built on habitat suitability analysis, and (4) holistic methods comprehensively considering various factors [14,15]. The hydrological methods are most widely used globally due to their many advantages, such as simple and easy operation, only needing flow data, avoidance of expensive field observations, strong versatility, and quick determination of value. According to some estimates, there are more than 200 calculation methods for environmental flow, and hydrological methods account for about 30% [16,17].

The hydrological methods include the Tennant method [18], the Tessman method [19], the indicators of hydrologic alteration/range of variability approach (IHA/RVA) method [20], the flow duration curve (FDC) method [21] and so on, among which the two most commonly used are the Tennant method and the FDC method. The Tennant method, based on the habits of aquatic organisms, divides a natural year into a fish spawning period and a general water use period [22]. It relates river flow to fish habitat quality, links varying ecological status to different flow levels of rivers, and then sets up the targets of ecological river flow. The FDC is a statistical characteristic curve drawn based on the duration or frequency of the flow equal to or exceeding a particular value during the observation time. As the proportion of time when a specific flow exceeds all historical records, the FDC more adequately reflects the runoff characteristics of the basin under various flow states from low to high [23].

A common problem found for hydrological methods is that they ignore the temporal and spatial variation in river flow and do not capture or reflect the hydrological variation in natural river flow. In addition, the basis of ecological status grading is a fixed percentage, which lacks physical connotation. The methods’ poor spatial transferability and vulnerability to extreme flow events are also issues that need to be solved [16,24,25]. Given these shortcomings of hydrological methods, many scholars proposed improvement strategies from three aspects: characteristic flow, calculation period, and percentage coefficient. Examples include using the annual flow of a typical year or monthly average flow instead of multi-year average flow [26], revising the division of periods based on the seasonal characteristics of the river ecosystem and the activity cycle of the biological population [27], calibrating the relationship between river flow and ecological health based on actual local conditions [28], and so on.

Although factors affecting environmental flow are considered more and more carefully, those improved hydrological methods [29] also make the calculation more complex and lose the essential simplicity of hydrological methods. Furthermore, it is difficult to predict the water regime at the beginning of the year in the actual operation and management of river ecological protection [30]. This makes the improved methods for calculating environmental flow challenging to operate in a practical way that considers the interannual variation in water regimes and distinguishes the wet, normal, and dry years. The technique adopted should not be too complicated from the perspective of practice.

In this paper, we propose and explore an alternative method for calculating the environmental flow of the Wujiang River, called the “Tennant-FDC Method” (T-FDC), to provide technical support for its healthy development. The development of the T-FDC method explicitly considers the annual variation in the river hydrological process combined with the advantage of the FDC method to truly reflect the runoff characteristics under each flow state and the classification idea of the Tennant method. As such, the T-FDC method captures the monthly variability of river flow and is spatially transferable.
The rest of this paper is organized as follows: Section 2 describes the regional situation and requirements of the Wujiang River Basin in southwest China. Section 3 describes the steps of the T-FDC method to calculate multi-level environmental flow. Section 4 shows the results and compares them with other hydrological methods. Section 5 concludes the paper with some discussion.

2. Study Area and Datasets

The Wujiang River Basin is located at 104°18′~109°22′ E and 26°07′~30°22′ N, involving four provinces of Yunnan, Guizhou, Chongqing, and Hubei in China, with a total area of 87,920 km² and mainstream length of 1037 km. It is the largest tributary on the south bank of the upper Yangtze River and a representative river in southwest China. Its runoff is mainly influenced by rainfall, with a clear distinction between wet and dry, with May to September accounting for about 80% of the annual [31].

The Wujiang River Basin has a natural drop of 2124 m and an average channel gradient of 0.205%, rich in hydropower resources. Since the 1970s, China carried out large-scale hydropower development in the Wujiang River Basin and planned a 12-level development scheme in the mainstream. Except for the Baima navigation and hydropower project at the most downstream area, all the planned hydraulic engineering projects are completed, and the impact on the ecological environment is gradually emerging. The geographical location and water system distribution of the Wujiang River Basin are shown in Figure 1.

In this study, the daily runoff data of critical hydrological stations in the Wujiang River Basin (Figure 1) from the past 64 years (1956~2019) were referenced from the Hydrological Yearbook of the People’s Republic of China [32]. The environmental flow was calculated using the collected data.

Considering the spatial variability of environmental flow, comprehensively evaluated from the aspects of hydraulic connection, representativeness, monitoring degree and adjustment degree, this study identified four critical cross sections located downstream of the corresponding reservoir for ecological protection along the mainstream of the Wujiang River, as shown in Table 1, the name of which is marked as red in Figure 1.

| Cross Section Name | Section Type |
|--------------------|--------------|
| Hongjiadu (HJD)    | Upstream/midstream boundary section |
| Wujiangdu (WJD)    | Controlled hydraulic engineering section |
| Sinan (SN)         | Midstream/downstream boundary section |
| Wulong (WL)        | Basin outlet section |
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### Table 1. Critical sections for ecological protection on the Wujiang River.

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### 3. Methodology

The T-FDC method proposed in this paper is characterized by drawing on the classification idea of the Tennant method to obtain multi-level environmental flows. Figure 2 presents the design framework for the proposed T-FDC method.

![Figure 2. Technical route of the T-FDC method.](image-url)

Figure 1. Map of the Wujiang River Basin.

**3.1. Monthly FDC**

Generally, the T-FDC method prioritizes daily flow series and constructs FDCs month by month based on the total period method, provided that data are available to improve the time variability and accuracy of the method. Weekly and monthly flow series can also be used in case of poor data availability, making the method flexible.

To address the deficit of the calculated environmental flow, which is a single value within or between years. The specific guarantee rate has greater empirical and regional applicability from constructing curves on an annual scale [12]. This paper groups flow data on a monthly basis (e.g., “all the Mays” within a range of years) and constructs the FDC on a month-by-month basis [33] to enhance the representation of the temporal variability of the flow regime.

Depending on the different processing of runoff data, major approaches to constructing FDC include the total period approach, the calendar year approach, and the median annual approach [34]. The total period approach can comprehensively describe the basin’s historical runoff changes. The calendar year approach and the median annual approach have advantages in describing the interannual variation in runoff and reducing the impact of extreme flow events. However, they significantly shorten the daily average flow series length, resulting in increased uncertainty in the description of the monthly variation characteristics of runoff by the FDC [35].

The time scale of flow points for constructing the FDC is self-defined according to management requirements, which can be daily, weekly, or longer. However, the larger the time scale is, the easier it is to blur the details of flow changes, especially in small flow areas, such as sources and tributaries. The difference between FDCs constructed based on daily flow versus monthly flow may be as high as 35% [36].

There are many methods for calculating curves. Some classical ones include the technique based on the empirical frequency and the method based on information entropy theory proposed by V. P. Singh [37], and so on. These methods have their statistical basis, and the results are consistent. The FDC based on entropy theory can resist the influence of extreme values, but its estimation method is more complex. Therefore, considering the simplicity of the technique, this paper selects the empirical frequency to construct a monthly FDC:

\[
p_i = \frac{1}{j} \sum_{j=1}^{n} f_j 
\]
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\[ P_i = \frac{i}{j+1} \]  

where \( P_i \) is the empirical frequency of a measured daily flow in a specific month, \( i \) is the descending number of all daily flows of the month in all years, and \( j \) is the sample size (i.e., the number of days of the month in all years).

For the FDC of each month, different distributions, such as polynomial function, rational function, power function [38,39] and others, are used to fit the data and estimate corresponding parameters. The reliability and practicability of the fitting results are evaluated by the coefficient of determination (R²) to get the best estimates of the parameters.

3.2. Basic Environmental Flow

The basic environmental flow refers to the minimum value of discharge that needs to be maintained in a river to ensure basic conditions for existing ecosystems [40], according to appropriate criteria based on hydrological and environmental conditions.

The flow \( Q_{90} \) or \( Q_{95} \) at 90% or 95% of the period of record is often selected as the basic environmental flow in the FDC method [41,42]. However, the specific positioning of \( Q_{90} \) and \( Q_{95} \) in terms of river ecosystem function is ambiguous in existing studies, and their adaptability varies across rivers. Therefore, to improve the transferability of the basic environmental flow index, the T-FDC method selects the mean value of \( Q_{90} \) and \( Q_{95} \) as the basic environmental flow. For a specific month, the basic environmental flow is:

\[ E_{min} = \frac{Q_{90} + Q_{95}}{2} \]
where $E_{\text{min}}$ is the basic environmental flow, $Q_{90}$ and $Q_{95}$ are the flow at the 90% and 95% period of the record on the FDC of the corresponding month, respectively.

### 3.3. Optimal Environmental Flow

The optimal environmental flow refers to the runoff process of maintaining a sound ecological condition of the water body, which is the control index for developing and utilizing water resources.

Using predetermined percentages of average annual flow as environmental flow criteria (Table 2), the Tennant method divides the ecological status into ten levels based on arithmetic progression. It takes the 6th~10th level as the optimal ecological state. This idea of grading is a bright spot in all environmental flow calculation methods.

| Narrative Description of Flows | Recommended Base Flow Regimens of the Average Flow (%) |
|-------------------------------|-------------------------------------------------------|
| General Water Use Period      | Fish Spawning Period                                  |
| Optimum range                 | (60, 100)                                             |
| Outstanding                   | (60, 100)                                             |
| Excellent                     | (50, 60)                                              |
| Good                          | (40, 50)                                              |
| Fair or degrading              | (30, 40)                                              |
| Poor or minimum               | (20, 30)                                              |
| Severe degradation            | (10, 20)                                              |

Table 2. The ecological status grading system of the Tennant method [18].

For the deficiency that the specific guarantee rate has a greater degree of empirical and regional applicability to the traditional FDC method, the grading idea of the Tennant method is borrowed and combined with the concept of guarantee rate of the FDC method. Taking the flow at 50% of the period of record on the FDC as the upper limit of the optimal environmental flow [16,43] divides the range from the basic environmental flow to the upper limit into ten levels, and 6th–10th levels are taken as the optimal ecological range, of which the 6th level is the lower limit, that is:

$$
E_{\text{opt}} = \left[ E_{\text{opt,lower}}, E_{\text{opt,upper}} \right] = \left[ E_{\text{opt,lower}}, Q_{50} \right]
$$

$$
E_{\text{opt,lower}} = \frac{Q_{50} - E_{\text{min}}}{0.1Q_{50}} \times 5 + E_{\text{min}} = \frac{5}{9} Q_{50} + \frac{4}{9} E_{\text{min}}
$$

$$
E_{\text{opt,upper}} = Q_{50}
$$

where $E_{\text{opt}}$ is the optimal environmental flow range, $E_{\text{opt,lower}}$ and $E_{\text{opt,upper}}$ are the lower and upper limits of the range, respectively, $Q_{50}$ is the flow at the 50% period of the record on the FDC of the corresponding month, and $E_{\text{min}}$ is the basic environmental flow defined by Equation (2).

### 3.4. Multi-Level Environmental Flow

As shown in Table 2, the arithmetic progression of the Tennant method is based on the percentage of the river flow in the natural multi-year average. To avoid the impact of extreme wet or dry events, modify the difference value between the basic environmental flow and the lower limit of optimal environmental flow to 10% of the monthly $Q_{50}$. Then, the number of levels from basic environmental flow to the lower bound of the optimal range in a specific month of any particular section is:

$$
n = \left\lceil \frac{E_{\text{opt,lower}} - E_{\text{min}}}{0.1Q_{50}} \right\rceil + 1 = \left\lceil \frac{5}{9} \times \frac{Q_{50} - E_{\text{min}}}{0.1Q_{50}} \right\rceil + 1
$$

where $n$ is the number of levels, $\lceil \rceil$ represents the rounding operation.

To facilitate the actual engineering operation, the number of environmental flow levels in each month of the same section should preferably be a fixed value. For taking one from...
different values, there can be options for taking the minimum, the maximum, the average, and the mode. In practical engineering, a smaller number of grades is more convenient for operation, so the maximum value is unsuitable. Whereas the minimum does not cater for the rest of the months in statistical significance, and the mode is a better indicator of the most demand, rather than the average. Therefore, take the mode of each month’s level number as the final environmental flow level number of the corresponding section. If the mode is not unique, then take the smallest integer greater than or equal to the average of these modes, that is:

\[ N = \lceil \text{mode}(n) \rceil \] (5)

where \( N \) is the final level number from the basic to lower bound of a specific section; \([n]\) is the set of level numbers for each month of the section; and \( \text{mode} \) and \( \lceil \rceil \) represent the mode and ceiling operations, respectively.

Ultimately, based on the grading idea of the Tennant method, the environmental flow at all levels from basic to lower bound in a particular month is:

\[ E_m = E_{\min} + \frac{5}{9} \times \frac{m-1}{N-1} \times (Q_{50} - E_{\min})(m = 1, 2, \ldots, N) \] (6)

where \( E_m \) is the \( m \)-th level environmental flow. \( E_1 \) is the basic environmental flow, \( E_N \) is the lower limit of the optimal environmental flow range, and \( Q_{50} \) is the upper limit of the range.

4. Results and Discussion

4.1. Calculation Results of Multi-Level Environmental Flow

Based on the historical daily runoff data, the monthly FDCs of each critical section were fitted, respectively, (regarding Appendices A–D for details). Then the environmental flow with different levels at separate sections was calculated and compared. More specifically, in terms of the calculated multi-level environmental flow, there are five environmental flow levels at each section (HJD, WJD, SN, and WL, four sections in total), respectively, \( E_1 \)~\( E_5 \), of which are recorded in Table 3, and vividly shown in Figure 3. Where \( E_1 \) is the basic environmental flow, \( E_2 \) and \( E_3 \) are the second and third levels of environmental flow representing, respectively, fair and good ecological status, and \( E_4 \) and \( E_5 \) are the lower and upper limit of the optimal environmental flow, respectively.

![Figure 3. Multi-level environmental flow processes of Wujiang River.](image-url)
Table 3. Environmental flows of Wujiang River calculated by the T-FDC method.

| Region          | January | February | March  | April  | May    | June   | July   | August | September | October | November | December |
|-----------------|---------|----------|--------|--------|--------|--------|--------|--------|-----------|---------|----------|----------|
| Hangjiang       | E₁      | 40.82    | 35.68  | 29.03  | 26.85  | 44.92  | 122.15 | 145.02 | 89.53     | 90.78   | 73.68    | 61.88    | 45.56    |
|                 | E₂      | 42.49    | 37.61  | 31.20  | 32.57  | 63.36  | 153.59 | 167.63 | 115.73    | 116.59  | 87.10    | 68.44    | 48.42    |
|                 | E₃      | 44.16    | 39.54  | 33.38  | 38.30  | 81.79  | 185.02 | 190.24 | 141.94    | 142.40  | 100.51   | 71.81    | 51.27    |
|                 | E₄      | 45.83    | 41.47  | 35.55  | 44.02  | 100.23 | 216.46 | 212.85 | 168.15    | 168.21  | 113.93   | 76.77    | 54.13    |
|                 | E₅      | 49.84    | 46.11  | 40.77  | 57.76  | 144.48 | 291.91 | 267.12 | 231.05    | 230.15  | 146.13   | 88.69    | 60.99    |
| Wujiangdu       | E₁      | 109.79   | 111.56 | 103.30 | 111.31 | 244.82 | 522.44 | 439.91 | 284.56    | 293.53  | 247.58   | 149.98   | 104.22   |
|                 | E₂      | 120.52   | 119.90 | 110.51 | 132.04 | 301.56 | 630.82 | 539.70 | 357.23    | 357.28  | 298.74   | 180.73   | 123.18   |
|                 | E₃      | 131.25   | 128.25 | 117.73 | 152.77 | 358.31 | 739.21 | 639.49 | 459.90    | 459.90  | 349.89   | 211.49   | 142.15   |
|                 | E₄      | 141.98   | 136.60 | 124.94 | 173.50 | 415.05 | 847.59 | 739.28 | 541.57    | 541.57  | 401.05   | 242.24   | 161.11   |
|                 | E₅      | 167.74   | 156.63 | 142.26 | 223.25 | 551.24 | 1107.71| 978.78 | 747.18    | 747.18  | 523.82   | 316.05   | 206.63   |
| Sinan           | E₁      | 183.74   | 184.69 | 171.06 | 234.04 | 594.67 | 1010.28| 721.70 | 381.39    | 468.37  | 400.17   | 269.10   | 153.63   |
|                 | E₂      | 200.93   | 198.97 | 189.69 | 300.52 | 705.70 | 1213.71| 894.73 | 526.61    | 562.10  | 478.82   | 334.40   | 187.87   |
|                 | E₃      | 218.11   | 213.26 | 208.33 | 367.00 | 816.73 | 1417.14| 1067.77| 671.83    | 655.83  | 557.48   | 399.70   | 222.12   |
|                 | E₄      | 235.30   | 227.55 | 226.97 | 433.48 | 927.76 | 1620.57| 1240.81| 817.05    | 749.56  | 636.14   | 464.99   | 256.36   |
|                 | E₅      | 276.55   | 261.85 | 271.70 | 593.03 | 1194.24| 2108.80| 1656.11| 1165.57   | 974.51  | 824.92   | 621.71   | 338.55   |
| Wubang          | E₁      | 277.43   | 304.44 | 327.20 | 588.73 | 1340.95| 2190.71| 1201.19| 689.37    | 673.46  | 565.66   | 385.66   | 285.55   |
|                 | E₂      | 302.84   | 323.65 | 357.60 | 724.55 | 1559.16| 2488.50| 1543.55| 852.14    | 942.09  | 936.91   | 735.23   | 329.41   |
|                 | E₃      | 328.26   | 342.86 | 388.00 | 860.37 | 1777.36| 2786.30| 1885.92| 1014.91   | 1210.73 | 1068.64 | 689.83   | 373.26   |
|                 | E₄      | 353.67   | 362.08 | 418.41 | 996.20 | 1995.57| 3084.09| 2228.29| 1777.68   | 1479.36 | 1200.38 | 806.42   | 417.12   |
|                 | E₅      | 414.67   | 408.19 | 491.38 | 1322.17| 3798.80| 3049.97| 1568.34| 2124.09   | 1516.55 | 1086.22 | 522.38   | 222.12   |

It turns out that the results of the multi-level environmental flow calculated through the T-FDC method proposed in this paper present pronounced monthly variability and level-by-level disparity. The variation shows a reasonable correlation with the wet and dry seasons of the Wujiang River Basin, which is abundant from May to September, and preliminarily proves the feasibility of the calculation method.

In addition, concerning the multi-level environmental flow of the Wujiang River calculated through the T-FDC method, there are five levels for each section, while there are seven levels for each region with the Tennant method applied. As a matter of fact, during actual management operation, the more environmental flow levels are taken into consideration, the more difficult it becomes for the actual reservoir operation and water resource allocation. Therefore, the T-FDC method gained an edge over the other in this case.

Figure 4 shows the values of basic environmental flow and the upper and lower limits of optimal environmental flow at different sections. In addition to the apparent monthly variability shown in the figure, the values of environmental flow calculated by the T-FDC method from upstream to downstream of the Wujiang River vary considerably, which exhibits good spatial variability. Furthermore, the similar pattern (enclosing shape) of the environmental flow radar plots for different levels at each section obtained through the T-FDC method reflects its stability.
4.2. Comparison in Terms of Basic Environmental Flow

To further assess the validity of the T-FDC method in the Wujiang River Basin, some typical hydrological methods were selected for comparison. Among the existing methods, only the environmental flow obtained through the Tennant method has multiple levels, while the rest merely focus on the basic environmental flow. In addition, with the common methods implemented, including the traditional Tennant method, basic environmental flows of constant value within the year are obtained, lacking monthly variation. Therefore, for the basic environmental flow calculation, the improved monthly Tennant method \[25\] and the dynamic calculation method (DC) \[44\], which is widely used in China and recommended by the Chinese National Standard (SL/T 712-2021), were chosen for comparison with the T-FDC proposed in this paper. The improved monthly Tennant method was selected for comparison for the optimal environmental flow calculation.

Together with the historical minimum and second minimum monthly average flow process (MMAF and MMAF-II) in the measured runoff of the Wujiang River, the obtained results of the basic environmental flow calculation with the T-FDC method, the monthly Tennant method, and the DC method, respectively, applied were plotted as in Figure 5.

![Figure 5](Image)

**Figure 5.** Basic environmental flow calculated by various methods and measured small flow.

The basic environmental flow process by the T-FDC method is relatively stable, ranging between the historical MMAF and MMAF-II. In contrast, the basic environmental flow by the Tennant method turns out to be much lower than the natural MMAF, which is very unfavourable to the maintenance of river ecological health. This variability from low natural flows is due to the vulnerability of the Tennant method to the extremes of the natural hydrological situation, showing its poor spatial portability, which is not suitable for the Wu River.

Compared with the Tennant method, the environmental flow process calculated by the DC method shows better monthly variability, with values closer to the natural small flow process. Notwithstanding, compared with the T-FDC method, the values obtained by the DC method are generally smaller. Additionally, the values through such methods are significantly lower than the natural MMAF during the dry months of the year and higher than those by the T-FDC method and the natural MMAF-II at the end of the flood season. For the actual reservoir operation management, this is not conducive to ecological protection during the dry season and the realization of power generation benefits at the end of the flood season. Therefore, in comparison, the basic environmental flow process by the T-FDC method is more feasible and reasonable.
4.3. Comparison in Terms of Optimal Environmental Flow

The optimal environmental flow results by the T-FDC method and the improved Tennant method are shown in Figure 6.

![Figure 6. Optimal environmental flow calculated by two methods.](image)

Overall, in the Wujiang River Basin, the T-FDC method’s optimal flow range covers that of the Tennant method. In addition, the ranges of optimal flow by the two methods are similar in the dry season, but the lower limit by the Tennant method is much lower than that by the T-FDC method in flood season. This is because the water volume changes drastically in flood season, which is prone to inducing extreme flow events, causing the mean value to deviate from the overall distribution and thus leading to a wide range of variations in the optimal environmental flow through applying the Tennant method. Thus, the T-FDC method proves more scientific and reasonable than the Tennant method for the ecosystem management in the Wujiang River.

5. Conclusions

This paper studied the development of environmental flow management objectives in the Wujiang River, with the most fundamental problems of the traditional hydrological methods pertinent to the subject analyzed. In an effort to address the problems thereof, a T-FDC method was proposed by combining the FDC method’s guarantee rate idea with the Tennant method’s grading idea. The results show its effectiveness and feasibility:

1. The T-FDC method is well applicable in the Wujiang River, showing monthly variability and spatial transferability, excluding the influence of extreme wet or dry events. Furthermore, the basic environmental flow process obtained through this method is stable, ranging between the historical minimum and the second minimum monthly average flow. In contrast, the threshold width of the optimal environmental flow is more reasonable than the Tennant method.
2. Only the measured runoff data, which can be on any time scale, is needed as the input required for the T-FDC method, which helps the handling of shortage for daily runoff processes and eliminates errors caused by interpolation, effectively improving the method’s adaptability.
3. Regarding practical engineering management, the proposed T-FDC method improved operability by reducing the number of environmental flow levels taken into consideration.
Several improvements can be incorporated into our proposed method. First, although the T-FDC method achieved successful application in the Wujiang River Basin, it is still necessary to further explore the applicability to rivers with different hydraulic conditions other than the Wujiang River and to evaluate the robustness, reproducibility, and spatial portability of the method. In addition, the T-FDC method proposes not to distinguish the interannual variation in wet and dry from the point of view of the operational simplicity of practical management. It can potentially result in too high a standard in dry years, which is challenging to operate in actuality and can moderately enhance the method’s adaptability to synchronous wet/dry events.

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**Conflicts of Interest:** The authors declare no conflict of interest.

**Appendix A. Fitted FDC of Hongjiadu**

Figure A1. Cont.
Figure A1. Monthly fitted FDC of Hongjiadu section.

Table A1. Fit type and equation form of Hongjiadu section.

| Month      | Fit Type | Degree | Equation Form                                      |
|------------|----------|--------|---------------------------------------------------|
|            |          | Numerator | Denominator |                                                                 |
| January    | Polynomial | 3              | $f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4$       |
| February   | Power    | -                | $f(x) = a_1 x^2 + a_3$                           |
| March      | Power    | -                | $f(x) = a_1 x^3 + a_3$                           |
| April      | Rational | 1, 3           | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |
| May        | Polynomial | 5              | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |
| June       | Rational | 3, 3           | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |
| July       | Rational | 4, 2           | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |
| August     | Rational | 0, 3           | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |
| September  | Polynomial | 4              | $f(x) = a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5$   |
| October    | Polynomial | 4              | $f(x) = a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5$   |
| November   | Polynomial | 3              | $f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4$           |
| December   | Polynomial | 5              | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |

Table A2. Specific parameters of Hongjiadu section.

| Month      | $a_1$  | $a_2$  | $a_3$  | $a_4$  | $a_5$  | $a_6$  | $a_7$  | $R^2$  |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|
| January    | -66.96 | 134    | -107.1 | 78.25  | -      | -      | -      | 0.981  |
| February   | 82.21  | -0.1915| -47.76 | -      | -      | -      | -      | 0.988  |
| March      | -43.62 | 0.5355 | 70.87  | -      | -      | -      | -      | 0.991  |
| April      | 19.39  | 9.285  | -0.2621| 0.42   | 0.05906| -      | -      | 0.982  |
| May        | -4990  | 11,720 | -9801  | 3562   | -811.8 | 308.4  | -      | 0.993  |
| June       | -83.85 | 269    | -154.4 | 30.21  | -0.4225| -0.05657| 0.04252| 0.995  |
| July       | 112.7  | -488.5 | 599    | -137.6 | 13.11  | -0.2484| 0.02413| 0.992  |
| August     | 39.36  | -1.019 | 0.5199 | 0.04017| -      | -      | -      | 0.974  |
| September  | 3608   | -9135  | 7943   | -3007  | 664.3  | -      | -      | 0.973  |
| October    | -360.1 | 575.9  | -219.9 | -192.2 | 247.7  | -      | -      | 0.993  |
| November   | -285.8 | 453.8  | -261.1 | 141.5  | -      | -      | -      | 0.976  |
| December   | -1.284 | 1.546  | -2.555 | -0.1121| -2.637 | 61     | -      | 0.980  |
Appendix B. Fitted FDC of Wujiangdu

Figure A2. Monthly fitted FDC of Wujiangdu section.

Table A3. Fit type and equation form of Wujiangdu section.

| Month    | Fit Type   | Degree | Numerator | Denominator |
|----------|------------|--------|-----------|-------------|
| January  | Polynomial | 4      | 5         |             |
| February | Rational   | 1      | 5         |             |
| March    | Power      | -      | -         |             |
| April    | Polynomial | 6      |           |             |
| May      | Polynomial | 4      |           |             |
| June     | Polynomial | 5      |           |             |
| July     | Polynomial | 4      |           |             |
| August   | Polynomial | 5      |           |             |
| September| Polynomial | 4      |           |             |
| October  | Polynomial | 5      |           |             |
| November | Polynomial | 4      |           |             |
| December | Polynomial | 4      |           |             |

The equation forms are:

- \( f(x) = a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5 \)
- \( f(x) = \frac{a_2 x^3 + a_3 x^2 + a_4 x + a_5}{a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5} \)
- \( f(x) = a_1 x^6 + a_2 x^5 + a_3 x^4 + a_4 x^3 + a_5 x^2 + a_6 x + a_7 \)
- \( f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6 \)
- \( f(x) = a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5 \)
- \( f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4 \)
- \( f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4 \)
- \( f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4 \)
- \( f(x) = a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5 \)
- \( f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4 \)
Table A4. Specific parameters of Wujiangdu section.

| Month   | $a_1$  | $a_2$  | $a_3$  | $a_4$  | $a_5$  | $a_6$ | $a_7$ | $R^2$   |
|---------|--------|--------|--------|--------|--------|-------|-------|---------|
| January | -667.7 | 1212   | -679.2 | -16.14 | 235.8  | -     | -     | 0.996   |
| February| -4.157 | 5.794  | -2.738 | 2.771  | -1.279 | 0.2573| 0.00839| 0.997   |
| March   | 678.8  | -0.09016| -580.3 | -     | -     | -     | -     | 0.985   |
| April   | 35,450 | -126,600| 175,600| -118,600| 40,140| -6766 | 820.6 | 0.997   |
| May     | 4667   | -11,000| 8890   | -3498  | 1161   | -     | -     | 0.984   |
| June    | -58,890| 158,000| -152,900| 64,400| -12,720| 2448  | -     | 0.983   |
| July    | -1131  | 2057   | -865.1 | -1479  | 1748   | -     | -     | 0.991   |
| August  | -22,210| 71,200 | -84,760| 46,120 | -12,310| 2209  | -     | 0.986   |
| September| 203.2  | -4012  | 6658   | -4322  | 1623   | -     | -     | 0.950   |
| October | -3179  | 10,900 | -12,690| 6022   | -1683  | 863.9 | -     | 0.990   |
| November| 1796   | -4439  | 3435   | -1155  | 477.3  | -     | -     | 0.987   |
| December| 986.5  | -3174  | 3176   | -1342  | 418.7  | -     | -     | 0.978   |

Appendix C. Fitted FDC of Sinan

Figure A3. Monthly fitted FDC of Sinan section.
| Month     | Fit Type | Degree | Numerator | Denominator | Equation Form                                                                 |
|-----------|----------|--------|-----------|-------------|-------------------------------------------------------------------------------|
| January   | Rational | 2      | 5         |             | \[ f(x) = \frac{a_1 x^7 + a_2 x^6 + a_3 x^5 + a_4 x^4 + a_5 x^3 + a_6 x^2 + a_7 x + a_8}{b_1 x^7 + b_2 x^6 + b_3 x^5 + b_4 x^4 + b_5 x^3 + b_6 x^2 + b_7 x + b_8} \] |
| February  | Polynomial | 4      |           |             | \[ f(x) = a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5 \] |
| March     | Polynomial | 5      |           |             | \[ f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6 \] |
| April     | Rational  | 0      | 3         |             | \[ f(x) = \frac{a_1 x^3}{b_1 x^3 + b_2 x^2 + b_3 x + b_4} \] |
| May       | Polynomial | 5      |           |             | \[ f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6 \] |
| June      | Polynomial | 6      |           |             | \[ f(x) = a_1 x^6 + a_2 x^5 + a_3 x^4 + a_4 x^3 + a_5 x^2 + a_6 x + a_7 \] |
| July      | Polynomial | 3      |           |             | \[ f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4 \] |
| August    | Polynomial | 5      |           |             | \[ f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6 \] |
| September | Polynomial | 5      |           |             | \[ f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6 \] |
| October   | Polynomial | 3      |           |             | \[ f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4 \] |
| November  | Power     | -      |           |             | \[ f(x) = a_1 x^i + a_2 \] |
| December  | Polynomial | 5      |           |             | \[ f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6 \] |

Table A6. Specific parameters of Sinan section.

| Month     | \(a_1\) | \(a_2\) | \(a_3\) | \(a_4\) | \(a_5\) | \(a_6\) | \(a_7\) | \(a_8\) | \(R^2\) |
|-----------|----------|----------|----------|----------|----------|----------|----------|----------|--------|
| January   | -0.2816  | 8.041    | 1.938    | -2.172   | 1.72     | -0.5942  | 0.1184   | 0.00016  | 0.997  |
| February  | 424.3    | -1850    | 2446     | -1434    | 572.1    | -        | -        | -        | 0.964  |
| March     | -16,530  | 45,480   | -46,880  | 22,300   | -5048    | 752.7    | -        | -        | 0.973  |
| April     | 82.98    | -1,086   | 0.4871   | 0.04298  | -        | -        | -        | -        | 0.992  |
| May       | -40,600  | 95,210   | -79,690  | 28,900   | -5878    | 2189     | -        | -        | 0.992  |
| June      | 82,660   | -337,800 | 535,300  | -411,700 | 157,400  | -29,970  | 5020     | -        | 0.988  |
| July      | 2342     | -3297    | -1178    | 2777     | -        | -        | -        | -        | 0.986  |
| August    | -27,420  | 70,330   | -65,500  | 26,930   | -6627    | 2396     | -        | -        | 0.982  |
| September | -49,260  | 122,600  | -115,100 | 52,050   | -13,160  | 2802     | -        | -        | 0.994  |
| October   | -1890    | 3371     | -2837    | 1637     | -        | -        | -        | -        | 0.987  |
| November  | -673.4   | 1.43     | 871.6    | -        | -        | -        | -        | -        | 0.996  |
| December  | -13,120  | 32,160   | -30,790  | 14,670   | -3779    | 808.4    | -        | -        | 0.989  |

Appendix D. Fitted FDC of Wulong

Figure A4. Cont.
Figure A4. Monthly fitted FDC of Wulong section.

Table A7. Fit type and equation form of Wulong section.

| Month     | Fit Type   | Degree | Equation Form |
|-----------|------------|--------|---------------|
| January   | Rational   | 0      | $f(x) = \frac{a_1}{x^{a_2} + 3}$ |
| February  | Polynomial | 3      | $f(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4$ |
| March     | Polynomial | 4      | $f(x) = a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5$ |
| April     | Polynomial | 5      | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |
| May       | Polynomial | 5      | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |
| June      | Rational   | 2      | $f(x) = a_1 x^2 + a_2 x + a_3$ |
| July      | Power      | -      | $f(x) = a_1 x^{0.5} + a_2$ |
| August    | Polynomial | 6      | $f(x) = a_1 x^6 + a_2 x^5 + a_3 x^4 + a_4 x^3 + a_5 x^2 + a_6 x + a_7$ |
| September | Polynomial | 5      | $f(x) = a_1 x^5 + a_2 x^4 + a_3 x^3 + a_4 x^2 + a_5 x + a_6$ |
| October   | Power      | 4      | $f(x) = a_1 x^{0.5} + a_2$ |
| November  | Rational   | 0      | $f(x) = a_1 x^2 + a_2 x + a_3$ |
| December  | Polynomial | 4      | $f(x) = a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5$ |

Table A8. Specific parameters of Wulong section.

| Month    | $a_1$   | $a_2$   | $a_3$   | $a_4$   | $a_5$ | $a_6$ | $a_7$ | $R^2$ |
|----------|---------|---------|---------|---------|-------|-------|-------|-------|
| January  | 142.2   | -1.399  | 0.8248  | 0.1555  | -     | -     | -     | 0.978 |
| February | -1413   | 2721    | -1904   | 856.6   | -     | -     | -     | 0.987 |
| March    | 5427    | -14,370 | 13,500  | -5629   | 1390  | -     | -     | 0.984 |
| April    | -118,500| 317,500 | -320,100| 150,100 | -33,660| 4504  | -     | 0.992 |
| May      | -24,740 | 44,050  | -25,890 | 7044    | -3954 | 3992  | -     | 0.997 |
| June     | 3239    | -3426   | 960.5   | -0.5323 | -0.2408| 0.1435| -     | 0.995 |
| July     | -5084   | 0.7955  | 5980    | -       | -     | -     | -     | 0.993 |
| August   | -107,600| 274,200 | -262,600| 121,300 | -31,520| 6044  | -     | 0.988 |
| September| -198,300| 547,900 | -541,700| 214,700 | -16,700| -10,460| 4526  | 0.997 |
| October  | -2962   | 0.4657  | 3661    | -       | -     | -     | -     | 0.986 |
| November | 312.7   | -0.6969 | 0.3614  | 0.1564  | -     | -     | -     | 0.993 |
| December | 2364    | -7650   | 8070    | -3784   | 1206  | -     | -     | 0.976 |

References
1. Poff, N.L.; Zimmerman, J.K.H. Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows. *Freshw. Biol.* **2010**, *55*, 194–205. [CrossRef]
2. Zeiring, B.; Seliger, C.; Greimel, F.; Schmutz, S. River Hydrology, Flow Alteration, and Environmental Flow. In *Riverine Ecosystem Management: Science for Governing towards a Sustainable Future*; Schmutz, S., Sendzimir, J., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 67–89. ISBN 978-3-319-73250-3.
3. Vörösmarty, C.J.; McIntyre, P.B.; Gessner, M.O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Liernur, C.R.; et al. Global Threats to Human Water Security and River Biodiversity. *Nature* **2010**, *467*, 555–561. [CrossRef] [PubMed]

4. Karimi, S.; Salarijazi, M.; Ghorbani, K.; Heydari, M. Comparative Assessment of Environmental Flow Using Hydrological Alteration and Reliability of Water Demands. *Sci. Total Environ.* **2022**, *810*, 151630. [CrossRef]

5. Babaei, S.H.; Soltani, S.; Saffari, A. Evaluating Dam Re-Operation for Freshwater Conservation in the Sustainable Rivers Project. *River Res. Appl.* **2012**, *28*, 777–792. [CrossRef]

6. Lu, X.; Wang, X.; Ban, X.; Singh, V.P. Considering Ecological Flow in Multi-Objective Operation of Cascade Reservoir Systems under Climate Variability with Different Hydrological Periods. *J. Environ. Manag.* **2022**, *309*, 114690. [CrossRef]

7. Richter, B.; Thomas, G. Restoring Environmental Flows by Modifying Dam Operations. *Ecol. Soc.* **2007**, *12*, 12. [CrossRef]

8. Konrad, C.P.; Warner, A.; Higgins, J.V. Evaluating Dam Re-Operation for Freshwater Conservation in the Sustainable Rivers Project. *River Res. Appl.* **2012**, *28*, 777–792. [CrossRef]

9. Palmer, M.A.; Bernhardt, E.S. Hydroecology and River Restoration: Ripe for Research and Synthesis. *Ecol. Appl.* **2005**, *15*, 997–1008. [CrossRef]

10. Atieh, M.; Taylor, G.; Sattar, M.A.; Gharabaghi, B. Prediction of Flow Duration Curves for Ungauged Basins. *J. Hydrol.* **2018**, *559*, 383–394. [CrossRef]

11. Lu, X.; Wang, X.; Ban, X.; Singh, V.P. Considering Ecological Flow in Multi-Objective Operation of Cascade Reservoir Systems under Climate Variability with Different Hydrological Periods. *J. Environ. Manag.* **2022**, *309*, 114690. [CrossRef]

12. Kannan, N.; Anandhi, A.; Jeong, J. Estimation of Stream Health Using Flow-Based Indices. *Hydrology* **2018**, *5*, 20. [CrossRef]

13. Min et al. The Environmental Flows Implementation Challenge: Insights and Recommendations across Water-Limited Systems. *Wires Water* **2022**, *9*, e1565. [CrossRef]

14. Smakhtin, V.U. Low Flow Hydrology: A Review. *J. Hydrol.* **2001**, *240*, 147–186. [CrossRef]

15. Yao, T.; He, L.M.; Niu, C.W.; Jia, Y.W. A Review of Environmental Flow Assessment: Methodologies and Application in the Qianhe River. *IOP Conf. Ser. Earth Environ. Sci.* **2016**, *39*, 012067. [CrossRef]

16. Pastor, A.V.; Ludwig, F.; Biemans, H.; Hoff, H.; Kabat, P. Accounting for Environmental Flow Requirements in Global Water Assessments. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 5041–5059. [CrossRef]

17. Baghel, D.S.; Gaur, A.; Karthik, M.; Dohare, D. Global Trends in Environmental Flow Assessment: An Overview. *J. Inst. Eng. India Ser. A* **2019**, *100*, 191–197. [CrossRef]

18. Tennant, D.L. Instream Flow Regimens for Fish, Wildlife, Recreation and Related Environmental Resources. *Fisheries* **1976**, *1*, 6–10. [CrossRef]

19. Tessmann, S.A.; South Dakota State University; Water Resources Institute. *Environmental Use Sector: Reconnaissance Elements of the Western Dakotas Region of South Dakota Study*, Water Resources Institute, South Dakota State University: Brookings, SD, USA, 1979.

20. Zhao, Q.; Liang, S. Effects of Dams on River Flow Regime Based on IHA/RVA. In *Proceedings of IAHS*; Copernicus GmbH: Göttingen, Germany, 2015; pp. 275–280.

21. Sugiyama, H.; Vudhivanich, V.; Whitaker, A.C.; Lorsirirat, K. Stochastic Flow Duration Curves for Evaluation of Flow Regimes in Meandering Rivers. *Energy Convers. Manag.* **2022**, *240*, 285–293. [CrossRef]

22. Lin, C.; Kang, L. A New Modified Tennant Method with Spatial-Temporal Variability. *Water Resour. Manag.* **2014**, *28*, 4911–4926. [CrossRef]

23. Zhang, C.; Wan, Z.; Jing, Z.; Zhang, S.; Zhao, Y. Calculation of Ecological Water Requirements of Urban Rivers Using a Hydrological Model: A Case Study of Beiyun River. *J. Clean. Prod.* **2020**, *262*, 121368. [CrossRef]

24. Zhang, H.; Chang, J.; Gao, C.; Wu, H.; Wang, Y.; Lei, K.; Long, R.; Zhang, L. Cascade Hydropower Plants Operation Considering Comprehensive Ecological Water Demands. *Energy Convers. Manag.* **2019**, *180*, 119–133. [CrossRef]

25. Yu, Z.; Zhang, J.; Wang, H.; Zhao, J.; Dong, Z.; Peng, W.; Zhao, X. Quantitative Analysis of Ecological Suitability and Stability of Meandering Rivers. *Front. Biosci.* **2022**, *27*, 42. [CrossRef]

26. Elhawi, N.; Vörösmarty, C.J.; Fekete, B.M.; Stakhiv, E.Z. Reservoir Operations under Climate Change: Storage Capacity Options to Mitigate Risk. *J. Hydrol.* **2017**, *555*, 435–446. [CrossRef]

27. Feng, Z.; Liu, S.; Niu, W.; Li, S.; Wu, H.; Wang, J. Ecological Operation of Cascade Hydropower Reservoirs by Elite-Guide Gravitational Search Algorithm with Lévy Flight Local Search and Mutation. *J. Hydrol.* **2020**, *581*, 124425. [CrossRef]
32. Department of Hydrology, Ministry of Water Resources. *Hydrological Yearbook of the People’s Republic of China (1956–2019)*; No. 10; Bureau of Hydrology: Beijing, China, 1960; Volume 6.

33. Burgan, H.I.; Aksoy, H. Monthly Flow Duration Curve Model for Ungauged River Basins. *Water* 2020, 12, 338. [CrossRef]

34. McMillan, H.K. A Review of Hydrologic Signatures and Their Applications. *Wires Water* 2021, 8, e1499. [CrossRef]

35. Gnann, S.J.; Coxon, G.; Woods, R.A.; Howden, N.J.K.; McMillan, H.K. TOSSH: A Toolbox for Streamflow Signatures in Hydrology. *Environ. Model. Softw.* 2021, 138, 104983. [CrossRef]

36. Zhang, Y.; Singh, V.P.; Byrd, A.R. Entropy Parameter M in Modeling a Flow Duration Curve. *Entropy* 2017, 19, 654. [CrossRef]

37. Singh, V.P.; Byrd, A.; Cui, H. Flow Duration Curve Using Entropy Theory. *J. Hydrol. Eng.* 2014, 19, 1340–1348. [CrossRef]

38. Quimpo, R.G.; Alejandrino, A.A.; McNally, T.A. Regionalized Flow Duration for Philippines. *J. Water Res. Plan. Manag.* 1983, 109, 320–330. [CrossRef]

39. Mimikou, M.; Kaemaki, S. Regionalization of Flow Duration Characteristics. *J. Hydrol.* 1985, 82, 77–91. [CrossRef]

40. Greco, M.; Arbia, F.; Giampietro, R. Definition of Ecological Flow Using IHA and IARI as an Operative Procedure for Water Management. *Environments* 2021, 8, 77. [CrossRef]

41. World Meteorological Organization. *Operational Hydrology Report (OHR), 50. Manual on Low-Flow Estimation and Prediction*; WMO: Geneva, Switzerland, 2008; ISBN 978-92-63-11029-9.

42. Singh, A.; Mitra, S. Assessment of Environmental Flow Requirements of Damodar River Basins by Using Flow Duration Indices Method—A Case Study. *Int. J. Hydrol.* 2018, 2, 281–283. [CrossRef]

43. Men, B.; Yu, T.; Kong, F.; Yin, H. Study on the Minimum and Appropriate Instream Ecological Flow in Yitong River Based on Tennant Method. *Nat. Environ. Pollut. Technol.* 2014, 13, 6.

44. Pan, Z.; Ruan, X.; Xu, J. A New Calculation Method of Instream Basic Ecological Water Demand. *J. Hydraul. Eng. (ShuiLiXueBao Chin.)* 2013, 44, 119–126. [CrossRef]