water

Article

# The Decision of an Eco-Friendly Reservoir Operation Scheme Based on a Variable Set

**Hai-tao Chen, A-long Li, Wen-chuan Wang * and Zhao Zhao**

Henan Key Laboratory of Water Resources Conservation and Intensive Utilization in the Yellow River Basin, School of Water Resources, North China University of Water Resources and Electric Power, Zhengzhou 450011, China; chenghaitao@ncwu.edu.cn (H.-t.C.); lalncwu@stu.ncwu.edu.cn (A.-l.L.); zhaozhao@ncwu.edu.cn (Z.Z.)
* Correspondence: wangwenchuan@ncwu.edu.cn

**Abstract:** The river ecosystem has the characteristics of the coexistence of clarity and ambiguity. The starting point of eco-friendly reservoir operation is to fully consider the ecological water requirements of the lower reaches of the reservoir, so it also has the characteristics of clarity and vagueness. The fuzzy theory is an excellent tool to realize the quantification of fuzzy concepts. In this paper, the variable set theory (VS) is introduced into the decision-making field of eco-friendly reservoir scheduling scheme optimization. Taking Ertan Hydropower Station as an example, the scheduling scheme optimization is carried out. To verify the effectiveness of the evaluation method, this paper compares and analyzes the evaluation results of the fuzzy set evaluation method and the composite fuzzy matter-element method. The results show that the variable fuzzy set method has the advantages of rigorous theory, a concise model, and simple calculation, and the decision result is reasonable and reliable. This research can provide new ideas for the decision-making research of engineering.

**Keywords:** simulation; optimization; eco-friendly reservoir operation; variable sets; decision-making

**Citation:** Chen, H.-t.; Li, A.-l.; Wang, W.-c.; Zhao, Z. The Decision of Eco-friendly Reservoir Operation SchemeBased on Variable Set. *Water* **2021**, *13*, 1694. https://doi.org/10.3390/w13121694

Received: 18 April 2021
Accepted: 16 June 2021
Published: 18 June 2021

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



## 1. Introduction

Reservoir scheduling is an important means for implementing flood control and disaster reduction, unified water resources management, and efficient use. Reservoirs have played enormous economic and social benefits in many aspects, such as water supply, flood control, power generation, and irrigation. However, at the same time, the reservoir has also changed the original hydrological situation of rivers. As a result, a series of river ecological and environmental problems have emerged, such as reducing river runoff, deterioration of water environment quality, a sharp decline in biodiversity, and shrinking of wetlands [1]. Therefore, reservoir operation should fully consider the ecological elements of the lower reaches of the reservoir.

Eco-friendly reservoir dispatching is a reservoir dispatching method adapting to ecological requirements. This satisfies society's primary demand for water resources and, at the same time, takes into account the river ecosystem's demand for water resources. It achieves a win-win result of both ecological and economic benefits through adjusting and changing the reservoir's dispatching mode [2]. Eco-friendly reservoir scheduling needs to focus on solving the following two issues: first, the expression and measurement of ecological goals, and second, the economic and ecological scheduling model. Ecological flow is an important evaluation index of river health [3]. The ecological target in reservoir operation can be set by controlling the ecological flow. Presently, the commonly used methods for setting ecological flow include the Tennant method [4], the Texas method [5], and the natural flow mode method [6].

The current research related to reservoir ecological regulation mainly focus on four aspects. The first is studying the eco-friendly reservoir operation model and solution algorithm [7,8]. The second is the ecological operation of reservoirs focusing on improving the ecological environment of rivers and the operation of eco-friendly reservoirs [9,10]. The third is the evaluation of the current ecological health of the basin [11,12]. The fourth is the evaluation of the reservoir operation plan.

The fourth aspect of the research has also yielded many results. Chen Shouyu proposed the fuzzy optimization model and deeply analyzed the principle and method of the model [13]. After that, the fuzzy comprehensive evaluation method and fuzzy optimization method generated by fuzzy mathematics theory have become popular in recent years. Wang X.J. et al. applied the variable fuzzy set theory and model to the decision-making of reservoir flood control operation, comprehensively considered the changes of the model and its parameters (model changes and target weight changes), and improved the credibility of optimization and decision-making [14]. Li Qiong et al. proposed a composite method of disaster risk assessment based on variable fuzzy sets (VFSs) and information diffusion methods and established a flood risk analysis model with variable fuzzy sets and information diffusion methods. To further analyze the superiority and rationality of the methodology [15], Zou Qiang et al. proposed a set pair analysis-variable fuzzy set model (SPA-VFS) for comprehensive flood risk assessment. The model uses the set pair analysis (SPA) method to obtain the relative membership function of the variable fuzzy set (VFS), which has the advantages of being an intuitive process, having a simple calculation, and having good versatility [16]. Li Q. proposed a flood risk fuzzy analysis method based on VFS and improved information diffusion methods, which overcomes the uncertainty of flood control information and incomplete data [17]. Based on the fuzzy binary comparison method (FBCM) and VFS, Wang Wenchuan et al. proposed a comprehensive variable fuzzy evaluation model (VFEM) to evaluate river water quality [18]. He Guanjie et al. proposed a comprehensive variable fuzzy evaluation model to evaluate the impact of a dam breach on society and the environment [19].

Presently, some commonly used comprehensive evaluation methods still have many problems. For example, the sample information is not fully utilized, the evaluation grade boundary is regarded as definite, the resolution of the evaluation result is not high, and it is difficult to reflect the ambiguity and random uncertainty in the evaluation process. The set pair analysis evaluation method reflects various uncertainties in the evaluation process by establishing the degree of similarity, difference, and opposition between the evaluation plan and the evaluation standard. This method has a clear concept and simple calculation, but it does not consider the ambiguity of the evaluation grade boundary and the weight of the evaluation index [20]. The fuzzy comprehensive evaluation method has certain uncertainty in the evaluation process, and the model is difficult to self-adjust and self-verify [21]. The artificial neural network method repeatedly modifies the network weights through training error feedback. Although it avoids the subjective influence of the evaluator to a certain extent, it easily leads to local extreme points [22]. Most evaluation methods treat the evaluation objects of the water resources system as fuzzy systems, but the many indicators that affect them are definite values. Therefore, the water resources system is essentially a fuzzy and clear hybrid system, and new evaluation principles and methods are needed to evaluate this.

Variable set theory (VS) is developed from Professor Chen Shouyu's variable fuzzy set theory (VFS) in recent years. It is a breakthrough in Zard's fuzzy set theory, and has important theoretical significance. This method not only overcomes the either/or mathematical description of traditional set theory, but also makes up for the defect that fuzzy set theory cannot consider changes in matter. Furthermore, this method can solve the problem of the coexistence of ambiguity and clarity of indicators in a multi-index evaluation and recognition system [23]. Presently, this method has been applied in many fields, and has achieved good results [24–26]. The classification of evaluation indicators for optimizing eco-friendly reservoir operation schemes does not have clear boundaries and is vague, but many indicators that affect these schemes are definite values. Therefore, the evaluation of eco-friendly reservoir operation schemes is essentially variable, fuzzy, explicit, and mixed. The variable set mentioned above can be analyzed and evaluated by the variable set theory.

The purpose of this research is to introduce the optimal decision-making method based on the variable set theory into the field of eco-friendly reservoir operation and evaluate the eco-friendliness of different reservoir operation schemes, taking Ertan Reservoir's operation of an eco-friendly reservoir as an example to verify its practicability.

The structure of the paper is organized as follows. Section 2 presents rules and a mathematical model for the decision of an eco-friendly reservoir operation scheme based on a variable set. Section 3 introduces a studied case, including the study area, used data, and results. Section 4 discusses the evaluation methods used in this article in combination with the two existing evaluation methods. Finally, we provide the conclusions of this work in Section 5.

## 2. Materials and Methods

### *2.1. Eco-Friendly Reservoir Operation Schemes*

There is a certain connection between a river's ecological flow and its biological characteristics [27]. The realization of the health goal of the river ecosystem is mainly achieved by controlling the ecological flow [28]. There are many methods for calculating ecological flow [29], but there is no universal method applicable to all rivers. This paper considers the transformation of the river ecological flow process into a reservoir discharge flow constraint, that is, the discharge flow of the reservoir in a specific period or when each period is greater than the set flow, and the health of the corresponding river ecosystem can be guaranteed.

Based on this idea, in accordance with the three types of ecological flow models of do not consider ecological water requirements, meet the minimum ecological water requirements, and try to maintain the natural hydrological characteristics of runoff, six different ecological flow processes were simulated respectively. Correspondingly, six kinds of leakage control schemes can be generated [30]. In this paper, $M_i$ represents the *i*-th leakage control plan. The regardless of ecological water requirement model does not limit the discharge flow of the reservoir to the ecological water demand. It corresponds to the first discharge control scheme ($M_1$), and the discharge flow of the reservoir is greater than zero at this time. The meet the minimum ecological water requirement model requires that the discharge flow of the reservoir must be greater than the ecological water requirement of the river. According to the calculation method of the minimum ecological water requirement, four control schemes ($M_2$, $M_3$, $M_4$, and $M_5$) can be generated. The model of maintain the natural hydrological characteristics of runoff as much as possible starts from the point of view that the natural runoff characteristics are suitable for the ecological water demand of the river, and sets the sixth discharge control plan ($M_6$). The program uses months as the control period. During each control period, the discharge flow of the reservoir should be controlled between the maximum and minimum flow of each month under natural conditions. The reservoir discharge plan is shown in Table 1.

**Table 1.** Eco-friendly reservoir control plan.

| Ecological Flow Patterns | Control Alternatives of Discharge |
|---|---|
| Do not consider ecological water requirements | $M_1$: Reservoir discharge constraint: $Q_t \geq 0$ |
| Meet the minimum ecological water requirements: $Q_t \geq Q_{st}$ | $M_2$: The driest monthly flow estimation method was adopted; $Q_{st}$ takes the annual average of the driest monthly flow |
| | $M_3$: Using the quarterly ecological flow estimation method, referring to the Tennant method, $Q_{st}$ takes 40% of the annual average flow in the non-flood season |

| | |
|---|---|
| | (November to May) and $Q_{st}$ takes 60% of the annual average flow in the flood season (June to October) |
| | $M_4$: Monthly frequency calculation, $Q_{st}$ takes the flow rate at the 95% guaranteed rate for each month |
| | $M_5$: Monthly frequency calculation, $Q_{st}$ takes the flow rate at the 90% guaranteed rate for each month |
| Try to maintain the natural hydrological characteristics of runoff | $M_6$: Reservoir discharge constraint: $Q_{trmin} \leq Q_t \leq Q_{trmax}$. |

$Q_t$ is the discharge flow rate of the reservoir in the t-th period, $Q_{st}$ is the ecological flow rate set in each month, and $Q_{trmax}$ and $Q_{trmin}$ are the monthly maximum and minimum flow rates in natural conditions, respectively.

### 2.2. Evaluation Index System of Eco-Friendly Reservoir Operation Schemes

Based on the recognition that the natural runoff model is most conducive to maintaining the integrity of the river ecosystem, a natural flow model method for reservoir ecological operation is proposed. It is assumed that the natural runoff series before the construction of the reservoir is the most ideal state, and the closer the runoff process after the reservoir adjustment is to the natural flow process, the more favorable the river ecosystem.

With reference to the hydrological characteristic indexes closely related to ecological functions in IHA (Indicators of Hydrologic Alteration) [31], and starting from the availability and completeness of data, this paper selects the six hydrological characteristic values of the dispatched outflow as indexes to establish an eco-friendly reservoir comprehensive evaluation index system for dispatching ecological targets. The six indicators are the average discharge, maximum discharge, minimum discharge, coefficient of variation of runoff, coefficient of uneven distribution of runoff during the year, and concentration of runoff.

The average level of the monthly average flow response sequence is high or low. The monthly maximum and minimum flow, respectively, represent seasonal peak and trough flow. The peak flow has ecological functions, such as promoting the growth and reproduction of fish and other aquatic organisms. Low valley flow has ecological functions, such as enabling plants in certain beach areas to multiply and expel alien species. The coefficient of variation represents, to a certain extent, the size of the inter-annual variation of the flow that the organisms in the river can adapt. The non-uniform coefficient of distribution during the year reflects the fluctuation of the runoff during the year, as well as the relative stability of the biological use of wet and dry water during the year to complete the year's life cycle. The degree of concentration reflects the degree of concentration and dispersion of the data in certain intervals, and it is also a relatively sensitive index to measure changes in runoff.

### 2.3. Optimal Decision-Making Principle Based on Variable Sets

Reservoir operation decision-making has the characteristics of VS, so this paper adopts VS theory to make decisions regarding an eco-friendly reservoir operation plan. The following is a brief introduction to the theory and methods of VS. [23,32–34]

#### 2.3.1. The Fundamental of VS Theory—the Unity of Opposites

Things have the nature of opposites and unity. For example, we usually use rainfall intensity to classify rainfall levels. For example, we stipulate rainfall less than 2.5 mm/h as light rain, greater than or equal to 2.5 mm/h and less than 8 mm/h as moderate rain, greater than or equal to 8 mm/h and less than 16 mm/h as heavy rain, and greater than or equal to 16 mm/h as extra heavy rain. For any rainfall, we can clearly divide the rainfall level according to the abovementioned standards. However, this evaluation also contains arbitrary characteristics. If there is rain, the rainfall is 8 mm/h. According to the standard, we determined it to be heavy rain, which is correct. Normally, we would not define it as light rain or extremely heavy rain, because the gap is large. However, we have this question: as long as the rainfall is slightly less than 8 mm/h, it should be defined as moderate rain, even if it is only a tiny bit less. Is this reasonable? Then 8 mm/h rainfall is the dividing point between moderate rain and heavy rain. Does it have anything to do with moderate rain? The answer is obviously no, because this is not a clear opposite concept. Whether it rains during a certain period of time is a clear opposite concept, that is, an either/or relationship. The above example of rainfall classification belongs to the relationship of unity of opposites. For the rainfall of 8 mm/h, we can think that it has the characteristics of moderate rain and heavy rain at the same time, and it belongs to both moderate rain and heavy rain at the same time. For further analysis, what are the characteristics of rainfall at 9 mm/h, 10 mm/h . . . ? There are many more examples like this. For example, the evaluation of the discharge flow index in the eco-friendly reservoir operation plan has such problems. This type of evaluation is usually to set some flow intervals first, and then determine which level the flow belongs to according to the interval where the actual flow falls. This evaluation will also raise the abovementioned questions. These problems all have the unity of opposites we mentioned.

In order to define the concept of VS, we suppose that $U$ is a set with the unity of opposites; $A$ and $A^c$ represent attractability and repellency, respectively. For any element $u$($u \in U$), the relative membership representing the attractive property is denoted as $\mu_{\hat{A}}(u)$, and the relative membership representing the repulsive property is denoted as $\mu_{\hat{A}^c}(u)$. The determination of the relative membership degree can be reflected by the following mapping:

$$\mu_{\hat{A}}(u)、\mu_{\hat{A}^c}(u):\ U \to [0\ ,1],\ u \mapsto \mu_{\hat{A}}(u)、\mu_{\hat{A}^c}(u) \in [0\ ,1] \tag{1}$$

$$\mu_{\hat{A}}(u) + \mu_{\hat{A}^c}(u) = 1 \tag{2}$$

There must be a gradual change point in the continuum, which has the following properties:

$$\mu_{\hat{A}}(u) = \mu_{\hat{A}^c}(u) = 0.5 \tag{3}$$

For the change of the element $u$ in the domain $U$, mark it as $C(u)$. Regardless of the opposites, phenomena, and concepts of either this or that or either this or that, they still have the following properties after the change:

$$\mu_{\hat{A}}(C(u)) + \mu_{\hat{A}^c}(C(u)) = 1 \tag{4}$$

Equations (1)–(4) are called the unity of opposite polarities of variable sets. It is the theoretical basis for adopting the variable set method for the optimal decision-making of eco-friendly reservoir control and drainage solutions.

### 2.3.2. The Optimal Decision Principle Base on VS

(1) The research object

Set $U$ as the objects consisting of $n$ preferred object:

$$U = \{u_1,\ u_2,\ \ldots,\ u_n\} = \{u_j\} \quad (j = 1,\ 2,\ \ldots,\ n) \tag{5}$$

where $u_j$ is the $j$-th preferred object.

Set that the preferred object includes $m$ evaluation indicators. The indicator feature value matrix of the known object set is as follows:

$$X = (x_{ij}) \quad (i = 1,\ 2,\ \ldots,\ m) \tag{6}$$

where $x_{ij}$ is the $i$-th indicator of the $j$-th preferred object.

For the decision-making of the eco-friendly reservoir operation scheme discussed in this article, $U$ represents the set of all possible operation schemes; $u_j$ is the *j-th* feasible operation scheme; and $x_{ij}$ is the *i-th* indicator of the *j-th* operation scheme. For example, the average flow, the maximum flow, etc.

(2) The standard value interval matrix

The standard value interval matrix is the basis for grade division. Set the preferred object's merits to be divided into $c$ levels, and the indicator $x_{ij}$ is optimized based on the standard value interval matrix of $m$ indicators and $c$ levels.

$$I=\left(\left[a_{ih},\ b_{ih}\right]\right)\quad\left(i=1,\ 2,\ \ldots,\ m,\ h=1,\ 2,\ \ldots,\ c\right) \tag{7}$$

where $I$ is the standard value interval matrix and $a_{ih}$, $b_{ih}$ are the upper and lower bounds of the standard value range of the indicator $x_{ij}$ for the *h-th* level, respectively. For indicators for which smaller is better, $a_{ih} > b_{ih}$; for indicators for which bigger is better, $a_{ih} > b_{ih}$. If $x_{ij}$ is in a certain interval, such as $a_{ih} > x_{ij} > b_{ih}$ or $b_{ih} > x_{ij} > a_{ih}$, then it belongs to the *h-th* level.

(3) The definition of key points and their relative degree of membership

There are two types of key points involved in this article. The first category is the demarcation points of the standard value interval matrix, namely $a_{ih}$, $b_{ih}$. The second category is the points where the relative degree of membership is the largest (equal to 1), and there must be one such point in every interval, denoted as $k_{ih}$($k_{ih} \in \left[a_{ih},\ b_{ih}\right]$).

According to the location of the evaluation interval, it can be divided into three different types.

First, for the case where the evaluation level is 1 ($h = 1$, interval of $\left[a_{i1},\ b_{i1}\right]$). Setting level 1 is the priority level. The upper bound $a_{i1}$ is completely subordinate to level 1, so the relative degree of membership to level 1 is 1. At this time, $a_{i1}$ does not belong to level 2 at all, and, according to the unity of opposites theorem, the relative degree of membership to level 2 is 0. That is, $\mu_{i1}\left(a_{i1}\right)=1,\ \ \mu_{i2}\left(a_{i1}\right)=0.$ The lower bound $b_{i1}$ belongs to both level 1 and level 2. We believe that this value has the same relative degree of membership for level 1 and level 2. According to the theorem of the unity of opposites, the relative degree of membership is 0.5. That is, $\mu_{i1}\left(b_{i1}\right)=\mu_{i2}\left(b_{i1}\right)=0.5.$ Since $\mu_{i1}\left(a_{i1}\right)=1$, $k_{i1}$ is certain for this case. That is, $k_{i1}=a_{i1}$.

Second, for the case where the evaluation level is $c$ ($h = c$, interval of $\left[a_{ic},\ b_{ic}\right]$). Setting level $c$ is the inferior level. The lower bound $b_{ic}$ is completely subordinate to level $c$, so the relative degree of membership to level $c$ is 1. At this time, $a_{ic}$ does not belong to level *c-1* at all, and, according to the unity of opposites theorem, the relative degree of membership to level *c-1* is 0. That is, $\mu_{ic}\left(b_{ic}\right)=1,\ \ \mu_{i(c-1)}\left(b_{ic}\right)=0.$ The upper bound $a_{ic}$ belongs to both level $c$ and level *c-1*. We believe that this value has the same relative degree of membership for level $c$ and level *c-1*. According to the theorem of the unity of opposites, the relative degree of membership is 0.5. That is, $\mu_{ic}\left(a_{ic}\right)=\mu_{i(c-1)}\left(a_{ic}\right)=0.5.$ Since $\mu_{ic}\left(b_{ic}\right)=1$, $k_{i1}$ is certain for this case. That is, $k_{ic}=b_{ic}$.

Third, other grades $l$, except for the evaluation grades *1* and $c$($h$ = $l$, interval of $\left[a_{il},\ b_{il}\right]$). The upper bound $a_{il}$ belongs to both level $l$ and level *l-1*. We believe that this value has the same relative degree of membership for level $l$ and level *l-1*. According to the theorem of the unity of opposites, the relative degree of membership is 0.5. That is, $\mu_{ic}\left(a_{ic}\right)=\mu_{i(c-1)}\left(a_{ic}\right)=0.5.$ The lower bound $b_{il}$ belongs to both level $l$ and level *l+1*. We believe that this value has the same relative degree of membership for level $l$ and level *l+1*. According to the theorem of the unity of opposites, the relative degree of membership is 0.5. That is, $\mu_{ic}\left(b_{ic}\right)=\mu_{i(c+1)}\left(b_{ic}\right)=0.5.$ In this case, let the relative membership degree of the midpoint value of the interval be the largest (equal to 1). That is, $\mu_{il}\left(\left(a_{il}+b_{il}\right)/2\right)=1$, $k_{il}=\left(a_{il}+b_{il}\right)/2$.

Therefore, the relative membership degree of each key point is as follows:

$$\begin{cases}\mu_{i1}(a_{i1})=1,\mu_{i2}(a_{i1})=0,\mu_{i1}(b_{i1})=\mu_{i2}(b_{i1})=0.5\\ \mu_{i(l-1)}(a_{il})=\mu_{il}(a_{il})=\mu_{il}(b_{il})=\mu_{i(l+1)}(b_{il})=0.5,\mu_{il}((a_{il}+b_{il})/2),\left(l=2,\ 3,\ \ldots,\ c-1\right)\\ \mu_{i(c-1)}(a_{ic})=\mu_{ic}(a_{ic})=0.5,\mu_{i(c-1)}(b_{ic})=0,\mu_{ic}(b_{ic})=1\end{cases} \tag{8}$$

At the same time, the point with the largest relative membership degree to each level can be expressed as:

$$\begin{cases}k_{i1}=a_{i1}\\ k_{ih}=\left(a_{ih}+b_{ih}\right)/2,\quad \left(h=2,3,\ \ldots,\ c-1\right)\left(i=1,2,\ldots,\ m\right)\\ k_{ic}=b_{ic}\end{cases} \tag{9}$$

where $a_{ih}$, $b_{ih}$ are defined by (7). We can get the matrix *K*, which is composed of the points with the largest relative membership degree to each evaluation level. The largest relative membership degree is 1 for each interval.

$$K=\left(k_{ih}\right),\quad \left(h=1,2,\ \ldots,\ c\right)\left(i=1,2,\ \ldots,\ m\right) \tag{10}$$

Any point $k_{ih}$ in the matrix is satisfied by $\mu_{ih}\left(k_{ih}\right)=1$.

In order to facilitate the calculation, a matrix *T* is constructed:

$$T=\left(k_{i1},\ b_{i1},\ k_{i2},\ b_{i2},\ k_{i3},\ \ldots,\ k_{i(c-1)},\ b_{i(c-1)},\ k_{ic}\right),\left(i=1,2,\ \ldots,\ m\right) \tag{11}$$

The matrix *T* is formed by inserting the matrix *K* into the demarcation point $b_{ih}$ mentioned in (7).

(4) The calculation of relative degree of membership

For the *j-th* operation ($u_j$) scheme defined in (5), each plan includes *m* indicators. The *j-th* operation scheme can be represented by the following vector:

$$x_j=\left(x_{1j},\ x_{2j},\ \ldots,\ x_{mj}\right)=\left(x_{ij}\right),\ i=1,\ 2,\ \ldots,\ m \tag{12}$$

For any element $x_{ij}$, which is the *i-th* indicator of the *j-th* operation scheme, compare it with the element in the *i-th* row of the matrix *T*. The element $x_{ij}$ may be located in a certain interval, or it may not be included in the matrix. The two cases are explained separately below.

First, if it is in a certain interval of the matrix *T* (e.g. $x_{ij}\in\left[k_{ih},\ k_{i(h+1)}\right]$; this interval must include the qualitative change point $b_{ih}$), it is calculated by (13) and (14).

$$\mu_{ih}\left(x_{ij}\right)=0.5\left(1+\frac{b_{ih}-x_{ij}}{b_{ih}-k_{ih}}\right),\quad x_{ij}\in\left[k_{ih},\ b_{ih}\right],\ h=1,\ 2,\ \ldots,c \tag{13}$$

$$\mu_{i(h+1)}\left(x_{ij}\right)=0.5\left(1+\frac{b_{ih}-x_{ij}}{b_{ih}-k_{i(h+1)}}\right),\quad x_{ij}\in\left[b_{ih},\ k_{i(h+1)}\right],\ h=1,\ 2,\ \ldots,\ \left(c-1\right) \tag{14}$$

In the formula, $\mu_{ih}\left(x_{ij}\right)$ is the relative membership degree of indicator $x_{ij}$ to the *h-th* level, $\mu_{i(h+1)}\left(x_{ij}\right)$ is the relative membership degree of indicator $x_{ij}$ to the (*h+1)-th* level. The meaning of the other variables is the same as before. However, according to the principle of the unity of opposites, when $x_{ij} \in [b_{ih}, \ k_{i(h+1)}]$, although it belongs to the *(h+1)-th* level according to the classification, it still has a subordination relationship to the *h-th* level. The degree of relative membership can be determined by (2). So, the relative membership degree of $x_{ij}$ to the *h-th* level is as follows:

$$\mu_{ih}(x_{ij}) = \begin{cases} 0.5\left(1+\dfrac{b_{ih}-x_{ij}}{b_{ih}-k_{ih}}\right); & x_{ij} \in [k_{ih}, \ b_{ih}], \ h=1, \ 2, \ \ldots, c \\ 0.5\left(1-\dfrac{b_{ih}-x_{ij}}{b_{ih}-k_{i(h+1)}}\right); & x_{ij} \in [b_{ih}, \ k_{i(h+1)}], \ h=1, \ 2, \ \ldots, \ (c-1) \end{cases} \tag{15}$$

If $x_{ij} \in [k_{ih}, \ k_{i(h+1)}]$, then $x_{ij}$ can only belong to the *h-th* and *(h+1)-th* levels, and the relative degree of membership for other levels is zero.

$$\begin{cases} \mu_{i\ (<h)}(x_{ij}) = 0 \\ \mu_{i\ (>(h+1))}(x_{ij}) = 0 \end{cases} \tag{16}$$

In the formula, $\mu_{i(<h)}(x_{ij})$ is the relative membership degree of indicator $x_{ij}$ to the level less then *h*, and $\mu_{i\ (>(h+1))}(x_{ij})$ is the relative membership degree of indicator $x_{ij}$ to the level more than *h+1*.

Second, if $x_{ij}$ falls outside the range of the *i-th* row the matrix *T*, the relative degree of membership of $x_{ij}$ for level *1* and level *c* is determined by Equations (17) and (18), respectively.

Indicator that the smaller, the better:

$$\begin{cases} \mu_{i1}(x_{ij}) = 1, & x_{ij} < k_{i1} \\ \mu_{ic}(x_{ij}) = 1, & x_{ij} > k_{ic} \end{cases} \tag{17}$$

Indicator that the bigger, the better:

$$\begin{cases} \mu_{i1}(x_{ij}) = 1, & x_{ij} > k_{i1} \\ \mu_{ic}(x_{ij}) = 1, & x_{ij} < k_{ic} \end{cases} \tag{18}$$

At this situation, the relative degree of membership for other levels is zero.

(5) The calculation of comprehensive relative membership degree

Equations (15)–(18) are index relative membership models. The comprehensive relative membership model is shown as follows [34]:

$$v_h(u_j) = \frac{1}{1+\left(\dfrac{\sum_{i=1}^{m}\left[w_i\left(1-\mu_{ih}(x_{ij})\right)\right]^p}{\sum_{i=1}^{m}\left[w_i \ \mu_{ih}(x_{ij})\right]^p}\right)^{\frac{\alpha}{p}}}, \quad h=1, \ 2, \ \ldots, \ c \tag{19}$$

In the formula, $u_j$ represents the *j-th* preferred object in (5). $v_h(u_j)$ is the comprehensive relative membership degree of $u_j$ to the *j-th level.* $w_i$ is the weights of indicator $x_{ij}$, $\sum_{i=1}^{m} w_i = 1$. $\alpha$ is optimization criteria parameters, $\alpha = 1$ equals the least squares rule, and $\alpha=2$ equals the least squares criterion. *p* is the distance parameters, *p = 1* is the Hamming distance, and *p = 2* is the Euclidean distance. If parameter $\alpha=1$ and $p=1$, then formula (19) is a linear model:

$$v_h\left(u_j\right)=\sum_{i=1}^{m} w_i\ \mu_{ih}\left(x_{ij}\right),\quad h=1,\ 2,\ \ldots,\ c \tag{20}$$

The meaning of variables is the same as before.

According to formula (19) or (20), the comprehensive relative membership degree of the evaluation object $u_j$ to each level can be obtained:

$$\vec{v}\left(u_j\right)=\left(v_1\left(u_j\right),\ v_2\left(u_j\right),\ \ldots,\ v_c\left(u_j\right)\right) \tag{21}$$

The meaning of variables is the same as before.

(6) The calculation of the grade characteristic values

Grade characteristic values can be calculated as follows:

$$H\left(u_j\right)=\sum_{h=1}^{c} v_h^{\circ}\left(u_j\right)\times h,\quad h=1,\ 2,\ \ldots,\ c \tag{22}$$

In the formula, $H\left(u_j\right)$ is the grade characteristic values to the *j-th* preferred object, and $v_h^{\circ}\left(u_j\right)$ is the normalized vector values of $v_h\left(u_j\right)$.

If similar calculations are performed for each decision plan $u_j\left(j=1,\ 2,\ \ldots,\ n\right)$, the level feature value of *n* projects are as follows: $H\left(u_1\right)$, $H\left(u_2\right)$, …, $H\left(u_n\right)$. The scheme with the smallest level feature value is the preferred decision scheme.

## 3. Case Study

### 3.1. Study Area

Ertan Hydropower Station is located at Panzhihua City, southwestern Sichuan Province, China, on the lower reaches of the Yalong River. The dam site is 33 km away from the intersection of Yalong River and Jinsha River, and 46 km away from Panzhihua City. The basin area above the dam site of Ertan Hydropower Station is 116,400 km$^2$, accounting for about 90% of the entire basin area of the Yalong River. The maximum dam height of the hydropower station is 240 m, the normal storage level of the reservoir is 1200 m above sea level, the total storage capacity is 5.8 billion m$^3$, the regulating storage capacity is 3.37 billion m$^3$, and the total installed capacity is 3.3 million kw. The project is mainly for power generation, with other comprehensive utilization benefits. The project started in September 1991, and the first unit generated power in July 1998. It was completed in 2000. It was the largest power station completed and put into operation in the twentieth century in China. The development of the Yalong River implements an environmental protection strategy. As the first hydropower station developed on the Yalong River cascades, the ecological dispatch of Ertan is of great significance to the subsequent operation of the power station and the capacity of power generation, flood control, water supply, and ecological dispatch in the basin. The water system diagram of the Ertan Hydropower Project area is shown in Figure 1.

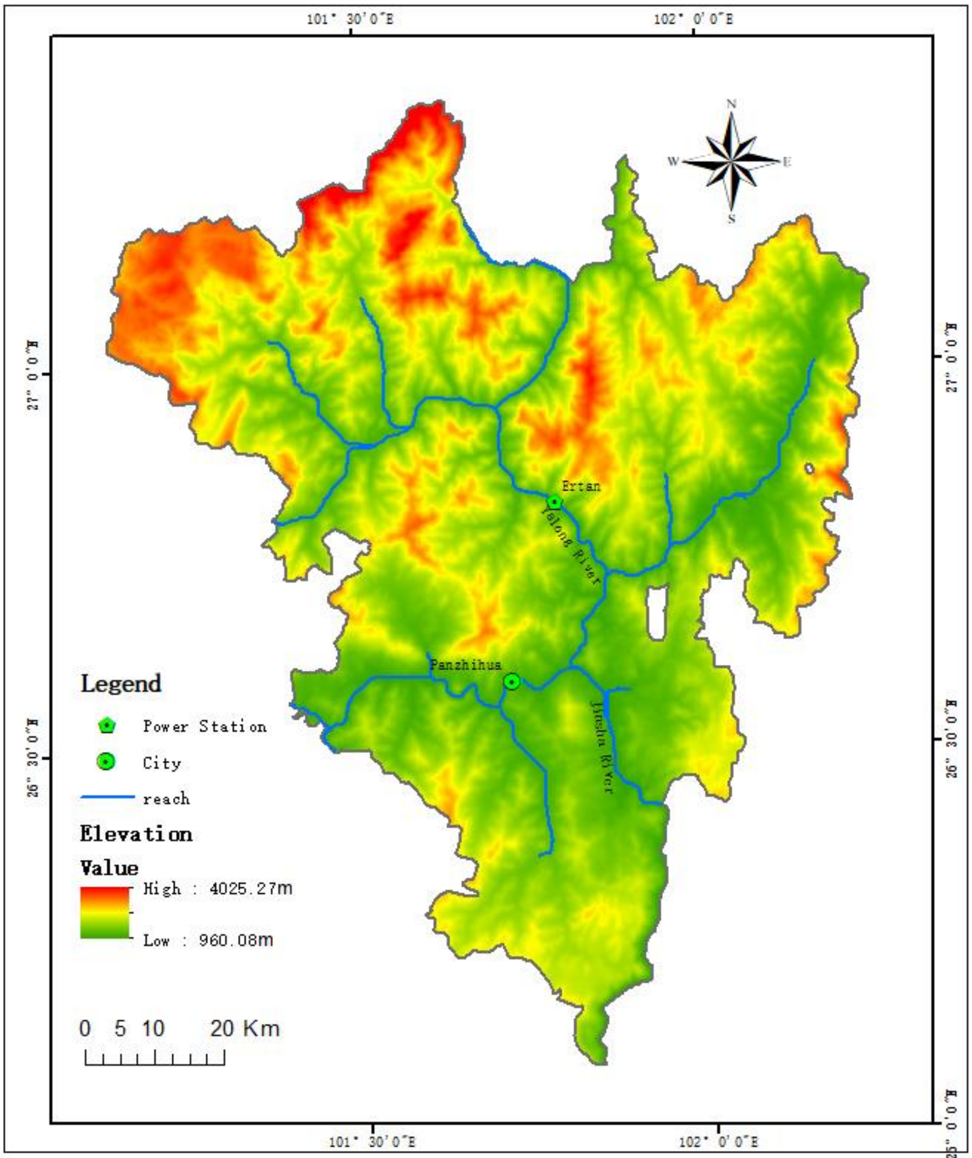


**Figure 1.** The water system diagram of the Ertan Hydropower Project area.

### *3.2. Eco-Friendly Reservoir Operation*

Mei yadong et al. [30] used 41 years of measured runoff data at Ertan Hydropower Station as the dispatch control period and months as the calculation period, and adopted the method of combining simulation and optimization to formulate the six leakage control schemes described in Table 1. A reservoir optimal dispatch model with the maximum power generation as the objective function was constructed, the dynamic programming method was used to solve the problem, and the optimal dispatch result was obtained. The dispatching results of Ertan Hydropower Station based on the eco-friendly reservoir dispatching plan are shown in Table 2. In the table, $M_i$ is the *i-th* leakage control scheme.

**Table 2.** Scheduling results table based on an eco-friendly reservoir scheduling scheme.

| Schemes | Multi-Year Average Power Generation ($10^8$ kW·h) | The Average Amount of Water Discarded over the Years ($10^8$ $m^3$) | Power Generation Guarantee Rate (%) |
|---|---|---|---|
| $M_1$ | 164.6769 | 59.5775 | 92 |
| $M_2$ | 164.6769 | 59.5775 | 92 |
| $M_3$ | 164.6374 | 59.5852 | 92 |
| $M_4$ | 164.4720 | 59.5253 | 92 |
| $M_5$ | 163.3475 | 59.9587 | 92 |
| $M_6$ | 164.3399 | 59.2941 | 92 |

According to the evaluation indicators selected in Section 2.2, the original indicator attribute matrix was constructed by the difference between the calculated value of each indicator under the leakage control plan and the actual measured value of each indicator under natural conditions, as shown in Table 3. In the table, $M_i$ is the *i-th* leakage control scheme, and $x_1$ to $x_6$ represent evaluation indicators, representing the average flow, maximum flow, minimum flow, coefficient of variation, non-uniform coefficient of distribution during the year, and the degree of concentration.

**Table 3.** Optimal operation results of Ertan Reservoir under all kinds of control schemes of the release discharge.

| Schemes | Evaluation Index | | | | | |
|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ |
| $M_1$ | 822.04 | 1096.70 | 722.39 | 0.2747 | 0.0161 | 0.8872 |
| $M_2$ | 822.04 | 1096.70 | 722.39 | 0.2747 | 0.0161 | 0.8872 |
| $M_3$ | 822.98 | 1096.70 | 738.76 | 0.2750 | 0.0125 | 0.8904 |
| $M_4$ | 821.30 | 1098.29 | 786.94 | 0.2740 | 0.0156 | 0.8831 |
| $M_5$ | 772.81 | 1097.89 | 1005.42 | 0.2553 | 0.0093 | 0.8305 |
| $M_6$ | 793.76 | 426.66 | 725.62 | 0.2369 | 0.0164 | 0.8956 |

*3.3. Optimization of Scheduling Schemes Based on Variable Fuzzy Sets*

The scheme sets $M_1$ to $M_1$ constitute the domain *U* mentioned in Section 2.3. That is:

$$U = \{M_1,\ M_2,\ \ldots,\ M_6\} \quad (23)$$

From Table 3, the feature matrix *X* based on the variable set evaluation described in Section 2.3.2 can be obtained.

$$X = \begin{bmatrix} 822.04 & 822.04 & 822.98 & 821.30 & 772.81 & 793.76 \\ 1096.70 & 1096.70 & 1096.70 & 1098.29 & 1097.89 & 426.66 \\ 722.39 & 722.39 & 738.76 & 786.94 & 1005.42 & 725.62 \\ 0.2747 & 0.2747 & 0.2750 & 0.2740 & 0.2553 & 0.2369 \\ 0.0161 & 0.0161 & 0.0125 & 0.0156 & 0.0093 & 0.0164 \\ 0.8872 & 0.8872 & 0.8904 & 0.8831 & 0.8305 & 0.8956 \end{bmatrix} = (x_{ij}) \quad (24)$$

The control solution is optimized according to level 3 criteria. The standard value interval matrix *I* is:

$$I = \begin{bmatrix} [328.81,\ 647.32] & [647.32,\ 970.99] & [970.99,\ 1294.65] \\ [394.20,\ 788.39] & [788.39,\ 1182.59] & [1182.59,1576.78] \\ [313.43,\ 626.87] & [626.87,\ 940.30] & [940.30,\ 1253.74] \\ [0.1060,\ 0.2121] & [0.2121,\ 0.3181] & [0.3181,\ 0.4242] \\ [0.0057,\ 0.0115] & [0.0115,\ 0.0172] & [0.0172,\ 0.0229] \\ [0.3516,\ 0.7032] & [0.7032,\ 1.0548] & [1.0548,\ 1.4064] \end{bmatrix} = [a_{ih},\ b_{ih}] \tag{25}$$

The preferred method steps are as follows.

From formula (9), the matrix *K* can be calculated.

$$K = \begin{bmatrix} 323.66 & 809.16 & 1294.65 \\ 394.20 & 985.49 & 1576.78 \\ 313.43 & 783.59 & 1253.74 \\ 0.1060 & 0.2651 & 0.4242 \\ 0.0057 & 0.0144 & 0.0229 \\ 0.3516 & 0.8790 & 1.4064 \end{bmatrix} = (k_{ih}) \tag{26}$$

Determining matrix *T* according to matrix *K* and the graded qualitative change point $b_{ih}$:

$$T = \begin{array}{c} \begin{array}{ccccc} (k_{i1}) & (b_{i1}) & (k_{i2}) & (b_{i2}) & (k_{i3}) \end{array} \\ \begin{bmatrix} 323.66 & 647.32 & 809.16 & 970.99 & 1294.65 \\ 394.20 & 788.39 & 985.49 & 1182.59 & 1576.78 \\ 313.43 & 626.87 & 783.59 & 940.30 & 1253.74 \\ 0.1060 & 0.2121 & 0.2651 & 0.3181 & 0.4242 \\ 0.0057 & 0.0115 & 0.0144 & 0.0172 & 0.0229 \\ 0.3516 & 0.7032 & 0.8790 & 1.0548 & 1.4064 \end{bmatrix} \end{array} \tag{27}$$

Using Formula (15)—(18), the relative membership degree of each indicator of the *j-th* scheme can be calculated. Now take the program scheme 1 ($M_1$) as an example for illustration. Knowing that the characteristic value of the first indicator of scheme 1 is 822.04 from matrix *X*, calculated by formula (15), $\mu_{12}(x_1) = 0.5\left(1 + \frac{970.99 - 822.04}{970.99 - 809.16}\right) = 0.9602$. According to the theorem of the unity of opposites, calculated by formula (8), $\mu_{13}(x_1) = 0.0398$. According to formula (16), $\mu_{11}(x_1) = 0$. That is, $\vec{\mu}_1(\mathrm{x}_1) = (0,\ 0.9602,\ 0.0398)$.

Similar calculations are carried out on indicators 2 to 6 of scheme (1), and the relative membership degree matrix of the indicators of the scheme is obtained.

$$\mu(M_1) = \begin{bmatrix} 0 & 0.9602 & 0.0398 \\ 0 & 0.7179 & 0.2821 \\ 0.1952 & 0.8048 & 0 \\ 0 & 0.9094 & 0.0906 \\ 0 & 0.6930 & 0.3070 \\ 0 & 0.9767 & 0.0233 \end{bmatrix} \tag{28}$$

This matrix reflects the relative membership degrees of different indicators in scheme (1) for different evaluation levels.

For the convenience of comparison, the indicator weight vector proposed in the literature [35] is used for calculation. That is, $\vec{w}$ = (0.1733, 0.1554, 0.1817, 0.1566, 0.1659, 0.1671). The comprehensive relative membership degree is calculated using the linear model formula (see Equation (20)). The membership vector of scheme (1) can be obtained.

$$\vec{v}\left(M_1\right)=\left(0.0355,\ 0.8448,\ 0.1197\right) \tag{29}$$

From Formula (22), the level feature value of scheme 1 is obtained. Similar calculations were performed on the remaining schemes to obtain the evaluation level characteristic values of each scheme. The optimal results of the scheme are shown in Table 4. Among them, the order of scheme 6 is NO.1, and scheme 6 can be selected as the decision scheme.

**Table 4.** Optimal decision results.

| Comprehensive Relative Membership | Grade | | | Grade Characteristic Values | Ranking |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | | |
| $M_1$ | **0.0355** | 0.8448 | 0.1197 | 2.0843 | 4 |
| $M_2$ | 0.0355 | 0.8448 | 0.1197 | 2.0843 | 4 |
| $M_3$ | 0.0798 | 0.8489 | 0.0713 | 1.9914 | 3 |
| $M_4$ | 0 | 0.8956 | 0.1044 | 2.1044 | 5 |
| $M_5$ | 0.1714 | 0.6746 | 0.1540 | 1.9826 | 2 |
| $M_6$ | 0.2325 | 0.7000 | 0.0675 | 1.8350 | 1 |

Since Ertan is a water conservancy project dominated by power generation, its social and economic benefits under the same guaranteed output are mainly reflected in power generation, so the impact on power generation should be fully considered when comparing plans. However, it can be seen from Table 1 that scheme 6 is only 0.21% less than scheme 1 and scheme 2, which have the largest average power generation in many years. Therefore, scheme 6 is the optimal solution that takes into account both ecological and economic goals. At the same time, the calculation results also show that, for the mid- and long-term reservoir dispatching with a monthly calculation period, different ecological water needs have little effect on the average power generation for many years. The main reason is that the outflow of the reservoir has a basic lower limit due to the limitation of the guaranteed output of the power station.

## 4. Discussions

### *4.1. Comparison and Analysis of the Results of Evaluation Methods with Fuzzy Sets*

Wang Jinlong et al. [35] applied a fuzzy set comprehensive evaluation method to evaluate the ecological dispatching scheme of Ertan Hydropower Station. This article uses the same index weight as Wang Jinlong for evaluation, namely, $\vec{w}$ = (0.1659, 0.1692, 0.1661, 0.1660, 0.1668, 0.1659). The comparison of the evaluation results is shown in Table 5. It can be seen from the table that scheme 6 is the optimal scheme, scheme 4 is the worst scheme, and the optimal results of the two methods are basically the same. The results show that it is feasible to apply the variable set theory to the optimal decision-making of the eco-friendly reservoir control plan. At the same time, it can be found that the difference between the two evaluation methods lies in scheme 3 and scheme 5. However, from the perspective of its level feature value and connection number, there is little difference between scheme 3 and scheme 5, indicating that the degree of eco-friendliness is equivalent. From Table 2, it can be seen that scheme 3 has 0.79% more power generation than scheme 5. Therefore, from the perspective of taking into account economic benefits, the evaluation results obtained by the method used in this article are better.

**Table 5.** Comparison with the result of the fuzzy sets method.

| | Fuzzy Set Pair Comprehensive Evaluation Method | | Variable Sets Method | |
|---|---|---|---|---|
| | **Contact number** | **Ranking** | **Grade Characteristic Value** | **Ranking** |
| $M_1$ | −0.1547 | 4 | 2.0843 | 4 |
| $M_2$ | −0.1547 | 4 | 2.0843 | 4 |
| $M_3$ | 0.0308 | 2 | 1.9914 | 3 |
| $M_4$ | −0.1950 | 5 | 2.1044 | 5 |
| $M_5$ | 0.0225 | 3 | 1.9826 | 2 |
| $M_6$ | 0.2006 | 1 | 1.8350 | 1 |

*4.2. Comparison and Analysis of Composite Fuzzy Matter Element Methods*

Mei Yadong et al. also applied the compound fuzzy matter-element method to evaluate the ecological dispatching scheme of Ertan Hydropower Station [30]. This article uses the same index weight as Mei Yadong for evaluation, namely, $\vec{W}$ = (0.1733, 0.1554, 0.1817, 0.1566, 0.1659, 0.1671). The comparison of the evaluation results is shown in Table 6. For both options, scheme 6 is the recommended decision-making option, and scheme 5 is ranked second. The difference between the two evaluation methods lies in the ranking of the last two levels.

**Table 6.** Comparison with the results of the fuzzy matter element method.

| Schemes | Compound Fuzzy Matter Method | | Variable Sets Method | |
|---|---|---|---|---|
| | **Euclidean Closeness** | **Ranking** | **Grade Characteristic Values** | **Ranking** |
| $M_1$ | 0.6880 | 5 | 2.0920 | 4 |
| $M_2$ | 0.6880 | 5 | 2.0920 | 4 |
| $M_3$ | 0.7194 | 3 | 1.9978 | 3 |
| $M_4$ | 0.6904 | 4 | 2.1089 | 5 |
| $M_5$ | 0.7220 | 2 | 1.9766 | 2 |
| $M_6$ | 0.8204 | 1 | 1.8228 | 1 |

The difference between the last two levels can be analyzed through the membership matrix of each scheme. The degree of the relative membership matrix of scheme 1, 2, and 4 is as follows.

$$\mu(\boldsymbol{M}_1)=\mu(\boldsymbol{M}_2)=\begin{bmatrix} 0 & 0.9602 & 0.0398 \\ 0 & 0.7179 & 0.2821 \\ \mathbf{0.1952} & \mathbf{0.8048} & \mathbf{0} \\ 0 & 0.9094 & 0.0906 \\ 0 & 0.6930 & 0.3070 \\ 0 & 0.9767 & 0.0233 \end{bmatrix};\ \mu(M_4)=\begin{bmatrix} 0 & 0.9625 & 0.0375 \\ 0 & 0.7139 & 0.2821 \\ \mathbf{0} & \mathbf{0.9893} & \mathbf{0.0107} \\ 0 & 0.9160 & 0.0840 \\ 0 & 0.7807 & 0.2193 \\ 0 & 0.9883 & 0.0117 \end{bmatrix} \tag{30}$$

It can be seen from the above two matrices that the main factor for the difference lies in the third evaluation factor (the distance between the minimum flow and the minimum flow of natural runoff). In scheme 1 and scheme 2, the probability of this factor belonging to "excellent" is 0.1952, the probability of belonging to "medium" is 0.8048, and the probability of belonging to "bad" is 0. In scheme 4, the probability of this factor belonging to "excellent" is 0, the probability of belonging to "medium" is 0.9893, and the probability of belonging to "bad" is 0.0107. The minimum flow and the minimum flow of natural runoff are critical indicators to measure the degree of satisfaction of the ecological water demand of the river. From this perspective, the analysis of scheme 1 and scheme 2 is better than scheme 4.

### *4.3. Stability Analysis of the Optimal Decision Model*

For the multi-index optimization decision-making model, when the optimization method and index system are certain, the optimization result is largely affected by the weight of the evaluation index. In this paper, two sets of weights are used to analyze the optimal decision-making of the leakage control program, and the same decision-making results and program ranking are obtained. It shows that the variable decision-making model based on variable sets for optimal selection of reservoir-controlled reservoirs has a certain degree of stability, effectively avoiding the situation where the corresponding decision results change drastically when the indicator weights change slightly. It can be seen from Figure 2 that the evaluation result based on the variable set method is stable when the weights obtained by different methods have small changes.

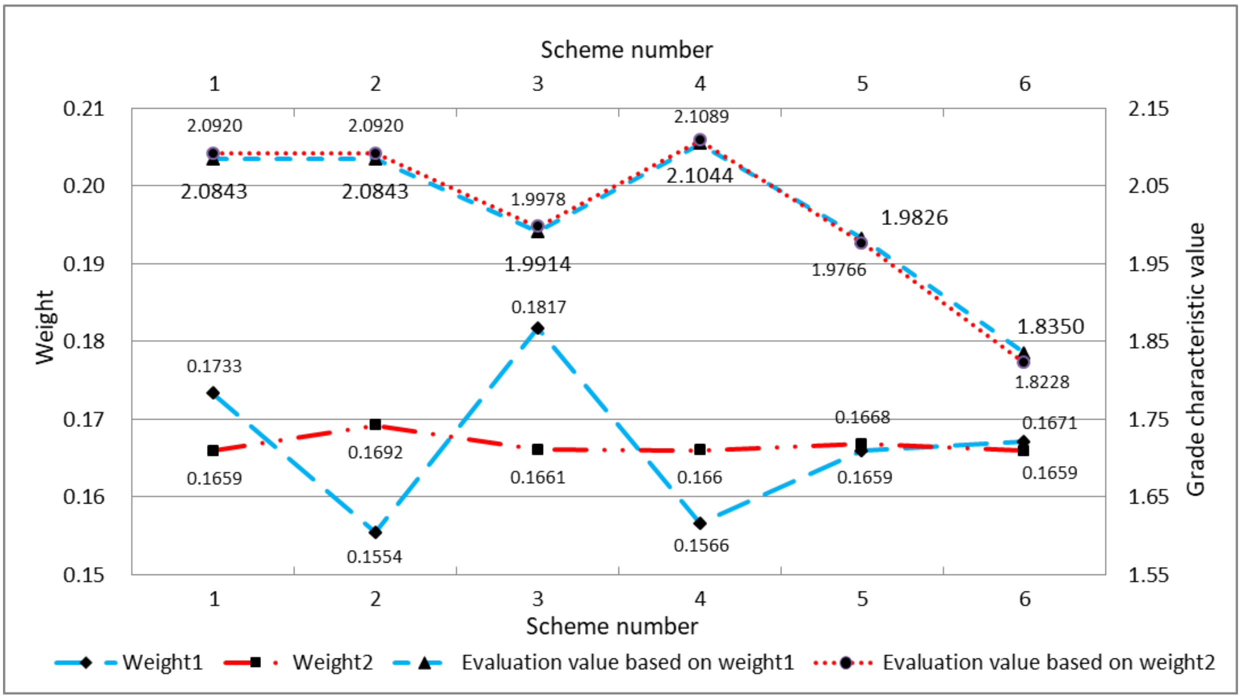


**Figure 2.** Comparison of the optimal calculation results for two weighted schemes.

### *4.4. Scope of Application*

The hydrological characteristics of rivers vary greatly. Some rivers have water all year round, and their runoff changes little during the year. Some rivers have runoff only in the rainy season, and dry up for a long time in the non-rainy season. Some rivers have a larger average flow, while others have a smaller average flow. These characteristics are related to various factors, such as the size, geographic location, and underlying surface of the research basin. This also determines that the ecological characteristics of different rivers are very different. This study is suitable for the situation where the watershed area is relatively large and the water flow in the river is constant year-round. For smaller watersheds, due to seasonal dry-off conditions, the method of determining ecological flow needs to be revised, so the method of this study should be adjusted accordingly.

### *4.5. Engineering Application Prospects*

The decision-making of an eco-friendly reservoir operation plan has the characteristics of the unity of opposites, so VS can be used as a tool for evaluation. Most of the evaluation problems involved in the engineering field have this characteristic. Therefore, the VS method can be widely used in project evaluation in the engineering field. This research can provide new ideas for the decision-making research of engineering.

## **5. Conclusions**

This paper simulates six different ecological flow processes and converts them into constraints that control the discharge of reservoirs. Through the combination of simulation and optimization methods, an ecologically friendly reservoir optimal operation model was constructed, and six types of reservoir control schemes based on different ecological flow processes were proposed. Taking the natural runoff model as the ideal state, an evaluation index system was used to evaluate the outflow of rivers and the degree of river ecosystem friendliness under different reservoir control schemes. The VS was introduced into the optimal decision-making field of an eco-friendly reservoir operation plan. For the first time, the philosophy of dialectic and mathematical thinking are used to study the optimal decision-making of eco-friendly reservoir scheduling. Taking Ertan Hydropower Station as an example, the research results show that:

(1) The comparison with the evaluation results of the two evaluation methods shows that the method proposed in this paper is feasible, and has the characteristics of simple calculation and stable evaluation results. This method provides a new idea for the study of the decision of an eco-friendly reservoir operation scheme.

(2) The method proposed in this paper is suitable for the decision-making study of eco-friendly reservoir scheduling under the condition that the basin area is relatively large and the water flow in the river is continuous all year. For smaller watersheds, the research methods proposed in this article need to be improved.

(3) The research can provide new ideas for the decision-making research of engineering.

(4) Ertan Hydropower Station should use the maximum and minimum values in the natural flow sequence at each period as the discharge constraints of the reservoir. Maintaining the natural characteristics of runoff as much as possible in controlling discharge can effectively take into account the needs of both power generation and the river's ecological health.

**Author Contributions:** H.-t.C. were responsible for the original concept and writing the paper. A.-l.L. and Z.Z. processed the data and conducted the program design. W.-c. W. revised the manuscript and shared numerous comments and suggestions to improve the study quality. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the project of key science and technology of the Henan province (No: 202102310259), and the Henan province university scientific and technological innovation team (No: 18IRTSTHN009).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not Applicable.

**Acknowledgments:** The authors are grateful to the project of key science and technology of the Henan province (No: 202102310259), and the Henan province university scientific and technological innovation team (No: 18IRTSTHN009).

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

## References

1. Magilligan, F.J.; Nislow, K.H. Changes in hydrologic regime by dams. *Geomorphology* **2005**, *71*, 61–78, doi:10.1016/j.geomorph.2004.08.017.
2. Xu, Z.; Yin, X.; Sun, T.; Cai, Y.; Ding, Y.; Yang, W.; Yang, Z. Labyrinths in large reservoirs: An invisible barrier to fish migration and the solution through reservoir operation. *Water Resour. Res.* **2017**, *53*, 817–831, doi:10.1002/2016wr019485.
3. Ma, D.; Luo, W.; Yang, G.; Lu, J.; Fan, Y. A study on a river health assessment method based on ecological flow. *Ecol. Model.* **2019**, *401*, 144–154, doi:10.1016/j.ecolmodel.2018.11.023.
4. Karimi, S.; Salarijazi, M.; Ghorbani, K.; Heydari, M. Comparative assessment of environmental flow using hydrological methods of low flow indexes, Smakhtin, Tennant and flow duration curve. *Acta Geophys.* **2021**, *69*, 285–293, doi:10.1007/s11600-021-00539-z.
5. Poff, N.L. Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world. *Freshw. Biol.* **2017**, *63*, 1011–1021, doi:10.1111/fwb.13038.
6. Poff, N.L.; Allan, J.D.; Bain, M.B.; Karr, J.R.; Prestegaard, K.L.; Richter, B.D.; Sparks, R.E.; Stromberg, J.C. The Natural Flow Regime a paradigm for river conservation and restoration. *Bioscience* **1997**, *47*, 769–784, doi:10.2307/1313099.
7. Wang, X.; Zhou, J.; Ou, Y.; Zhang, Y. TGC eco-friendly feneration multi-objective optimal dispatch modeland its solution algorithm. *J. Hydraul. Eng.* **2013**, *44*, 154–163, doi:10.13243/j.cnki.slxb.2013.02.013.11.
8. Kuriqi, A.; Pinheiro, A.N.; Sordo-Ward, A.; Bejarano, M.D.; Garrote, L. Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition. *Renew. Sustain. Energy Rev.* **2021**, *142*, 110833, doi:10.1016/j.rser.2021.110833.
9. Zhou, T.; Dong, Z.; Wang, W.; Shi, R.; Gao, X.; Huang, Z. Study on Multi-Scale Coupled Ecological Dispatching Model Based on the Decomposition-Coordination Principle. *Water* **2019**, *11*, 1443, doi:10.3390/w11071443.
10. Shen, Q.; Mo, L.; Liu, G. Multi-objective Ecological Dispatching of Reservoir Based on MOCEA/D Algorithm. *J. Coast. Res.* **2019**, *93*, 460–465, doi:10.2112/si93-060.1.
11. Ihunwo, O.C.; Ibezim-Ezeani, M.U. Distribution, Source Appropriation, and Human Health Risk Assessment of Polycyclic Aromatic Hydrocarbons due to Consumption of Callinectes amnicola from Woji Creek in Sambreiro River. *Turk. J. Fish. Aquat. Sci.* **2021**, *21*, 245–253, doi:10.4194/1303-27142-v21_05_04.
12. Alric, B.; Dézerald, O.; Meyer, A.; Billoir, E.; Coulaud, R.; Larras, F.; Mondy, C.P.; Usseglio-Polatera, P. How diatom-, invertebrate- and fish-based diagnostic tools can support the ecological assessment of rivers in a multi-pressure context: Temporal trends over the past two decades in France. *Sci. Total Environ.* **2021**, *762*, 143915, doi:10.1016/j.scitotenv.2020.143915.
13. Shouyu, C.; Yu, G. Variable Fuzzy Sets and its Application in Comprehensive Risk Evaluation for Flood-control Engineering System. *Fuzzy Optim. Decis. Mak.* **2006**, *5*, 153–162, doi:10.1007/s10700-006-7333-y.
14. Wang, X.J.; Zhao, R.H.; Hao, Y.W. Flood Control Operations Based on the Theory of Variable Fuzzy Sets. *Water Resour. Manag.* **2011**, *25*, 777–792, doi:10.1007/s11269-010-9726-5.
15. Li, Q.; Zhou, J.; Liu, D.; Jiang, X. Research on flood risk analysis and evaluation method based on variable fuzzy sets and information diffusion. *Saf. Sci.* **2012**, *50*, 1275–1283, doi:10.1016/j.ssci.2012.01.007.
16. Zou, Q.; Zhou, J.; Zhou, C.; Song, L.; Guo, J. Comprehensive flood risk assessment based on set pair analysis-variable fuzzy sets model and fuzzy AHP. *Stoch. Environ. Res. Risk Assess.* **2012**, *27*, 525–546, doi:10.1007/s00477-012-0598-5.
17. Li, Q. Fuzzy approach to analysis of flood risk based on variable fuzzy sets and improved information diffusion methods. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 239–249, doi:10.5194/nhess-13-239-2013.
18. Wang, W.-C.; Xu, D.-M.; Chau, K.-W.; Lei, G.-J. Assessment of River Water Quality Based on Theory of Variable Fuzzy Sets and Fuzzy Binary Comparison Method. *Water Resour. Manag.* **2014**, *28*, 4183–4200, doi:10.1007/s11269-014-0738-4.
19. He, G.; Chai, J.; Qin, Y.; Xu, Z.; Li, S. Coupled Model of Variable Fuzzy Sets and the Analytic Hierarchy Process and its Application to the Social and Environmental Impact Evaluation of Dam Breaks. *Water Resour. Manag.* **2020**, *34*, 2677–2697, doi:10.1007/s11269-020-02556-x.
20. Kumar, K.; Garg, H. TOPSIS method based on the connection number of set pair analysis under interval-valued intuitionistic fuzzy set environment. *Comput. Appl. Math.* **2016**, *37*, 1319–1329, doi:10.1007/s40314-016-0402-0.
21. Su, L.; Li, H.; Li, Z.; Cao, Y. Identification of unbalanced bids based on grey-fuzzy evaluation method. *Can. J. Civ. Eng.* **2020**, *47*, 272–278, doi:10.1139/cjce-2018-0778.

22. Herzog, S.; Tetzlaff, C.; Wörgötter, F. Evolving artificial neural networks with feedback. *Neural Netw.* **2020**, *123*, 153–162, doi:10.1016/j.neunet.2019.12.004.
23. Chen, S.; Xue, Z.; Li, M. Variable Sets principle and method for flood classification. *Sci. China Ser. E Technol. Sci.* **2013**, *56*, 2343–2348, doi:10.1007/s11431-013-5304-4.
24. Ke, L.; Wang, Q.; Sun, X.; Sun, C.; Zhou, H.; Wang, F. The seawater environment quality evaluation research base on variable fuzzy pattern recognition model. *Acta Ecol. Sin.* **2013**, *33*, 1889–1899, doi:10.5846/stxb201208251203.
25. Peng, Y.; Chu, J.; Xue, Z. Basin flood control system risk evaluation based on variable sets. *Sci. China Ser. E Technol. Sci.* **2017**, *60*, 153–165, doi:10.1007/s11431-016-0234-0.
26. Wan, X.-Y.; Zhong, P.-A.; Appiah-Adjei, E.K. Variable Sets and Fuzzy Rating Interval for Water Allocation Options Assessment. *Water Resour. Manag.* **2014**, *28*, 2833–2849, doi:10.1007/s11269-014-0640-0.
27. Dong, Z.; Zhang, J.; Zhao, J. Comments upon progress of environmental flows assessments. *J. Hydraul. Eng.* **2017**, *48*, 670–677, doi:10.13243/j.cnki.slxb.20161056.11.
28. Vogel, R.M.; Sieber, J.; Archfield, S.A.; Smith, M.P.; Apse, C.D.; Huber-Lee, A. Relations among storage, yield, and instream flow. *Water Resour. Res.* **2007**, *43*, doi:10.1029/2006wr005226.
29. Braun-Cruz, C.C.; Tritico, H.M.; Beregula, R.L.; Girard, P.; Zeilhofer, P.; Ribeiro, L.D.S.; Fantin-Cruz, I. Evaluation of Hydrological Alterations at the Sub-Daily Scale Caused by a Small Hydroelectric Facility. *Water* **2021**, *13*, 206, doi:10.3390/w13020206.
30. Mei, Y.; Zhai, L.; Yang, N. Evaluation of control alternatives of release discharge for eco-friendly reservoir operation. *Eng. J. Wuhan Univ.* **2008**, *41*, 10–13.
31. Richter, B.; Baumgartner, J.V.; Wigington, R.; Braun, D.P. How much water does a river need? *Freshw. Biol.* **1997**, *37*, 231–249, doi:10.1046/j.1365-2427.1997.00153.x.
32. Chen, S. Variable sets and the theorem and method of optimal decision- making for water resource system. *J. Hydraul. Eng.* **2012**, *43*, 1066–1074, doi:10.13243/j.cnki.slxb.2012.09.008.11.
33. Chen, S.; Xue, Z.; Li, M.; Zhu, X. Variable sets method for urban flood vulnerability assessment. *Sci. China Ser. E Technol. Sci.* **2013**, *56*, 3129–3136, doi:10.1007/s11431-013-5393-0.
34. Chen, S. Variable sets assessment theory and method of water resource system. *J. Hydraul. Eng.* **2013**, *44*, 134–142, doi:10.13243/j.cnki.slxb.2013.02.011.11.
35. Wang, J.; Huang, W.; Ma, G.; Liu, G.; Guo, L. Evaluation of control alternatives of discharge for eco-friendly reservoir operation based on fuzzy set pair analysis and entropy weight fuzzy iteration method. *J. Sichuan Univ. Eng. Sci. Ed.* **2015**, *47*, 1–8, doi:10.15961/j.jsuese.2015.s2.001.11.