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Determining the location of River Dam Group based on set cover Model: A case study of Zambezi River Basin

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ABSTRACT

Taking the Zambezi River Basin as a typical case, this paper studied the location problem of dam group. Based on the topographical and elevation maps of the Zambezi River Basin, we evaluated each region by five indicators (Water head difference elevation, Geological environment, Climatic environment, Population distribution and Biodiversity), and selected the 22 candidate dam sites. Meanwhile, the relative feasibility index of dam construction is calculated by the entropy weight-grey correlation analysis. On this basis, combined with the water management capacity of the dam, a set coverage model of dam selection is established, and the neighborhood adaptive particle swarm optimization algorithm (NAPSO) is used to solve the 12 most suitable dam sites. Comparing with the water management capacity of the original Kariba Dam, the new dams' water storage and flood control capacity, hydroelectric power generation capacity, domestic water supply capacity and other water supply capacity have been increased by 235.92%, 250.62%, 189.66% and 223.61% respectively. Our study can provide some guidance for the site selection project of river dam group.

Keywords: Dam site selection; Set coverage model; NAPSO; Entropy weight-grey correlation analysis

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1. Introduction

The global demand for water, food and energy has seen interest in large dams and their planning and construction continue at a steady pace in many parts of the world [1]. With the increasing demand for new construction, how to scientifically select the location of the dam is very important. Location problem refers to finding a suitable location for special functions or activities, and it has always been a hot issue concerned by geography, operational research, computer science and other disciplines. Reasonable location scheme and decision-making will bring huge economic and social benefits [2]. However, how to allocate different spatial resources reasonably is also a difficult problem.

At present, many scholars have studied the location of the dam to varying degrees. Ren et al. [3] proposed using analytic hierarchy process and hierarchical differentiation method as a means, combined with high-precision satellite images, historical hydrological data and other data to select the site; Liu et al. [4] investigated the surrounding geological environment of the area where the water conservancy project is located for scientific site selection through the use of modern survey technology. With the help of the method of case analysis, Ai et al. [5] put forward the design strategy for the factors to be considered in the location design of reservoir project.

The above scholars have certain reference value and significance for the study of dam location, but most of the location methods mainly evaluate the geological environment, water level drop, population distribution and other conditions of the potential location of the dam to determine the final dam construction site. Therefore, the consideration of location factors is not comprehensive and the location method is not systematic enough. In addition, there is little discussion on the location of multi-dams in large watersheds.

This paper will take the Zambezi River Basin as an example to study the location problem of dam groups in large watersheds. The Zambezi River is the largest river in southern Africa with a total length of 2600 km and a basin area of 1.35 million km^2. The river flows through the plateau and a series of canyon areas, which is rich in hydropower resources. According to the survey, the Kariba Dam, the largest dam in the Zambezi River basin, currently has many hidden dangers due to disrepair. Therefore, under the assumption of demolishing the Kariba dam, this paper intends to establish a dam group location model and determine a better dam group water management capacity system.

In the selection of alternative dam sites, based on the topography and elevation map of the basin, and considering the factors of water head difference elevation, geological environment, climatic environment, population distribution and biodiversity, the candidate dam sites are selected, and the relative feasibility of each candidate dam site is evaluated. On this basis, we introduce the principle of water balance and related constraints, establish a set coverage model and use neighborhood adaptive particle swarm optimization (NAPSO) to solve the problem. In the model, we also consider the special situation such as the short-term shortage of water resources to make the new dam group more reliable. The improvement of water management capacity of the Kariba dam is fully showed its science and superiority. The model can provide guidance and suggestions for scientific location of dams, especially in the case of large watersheds and multiple dams, which has certain research value and practical significance.

2. Selection of the candidate dam sites

The location of the reservoir dam is very important, and the location of the reservoir dam should comprehensively consider the function of the reservoir dam and the characteristics of local physical geography. The reservoir will be generally constructed in the areas with strong flood control effect and rich water energy, which is the locations with large water volume and large drop. The dam site should be built in the river canyon with dense contours, so that the dam body is shorter, the water storage area is wide. And the project quantity should be as small as possible to save the construction investment. There are some other important factors affecting dam site selection, such as population density and precipitation, which also should be considered.

In this paper, the research route of the dam groups location problem in the Zambezi River Basin is as follows:

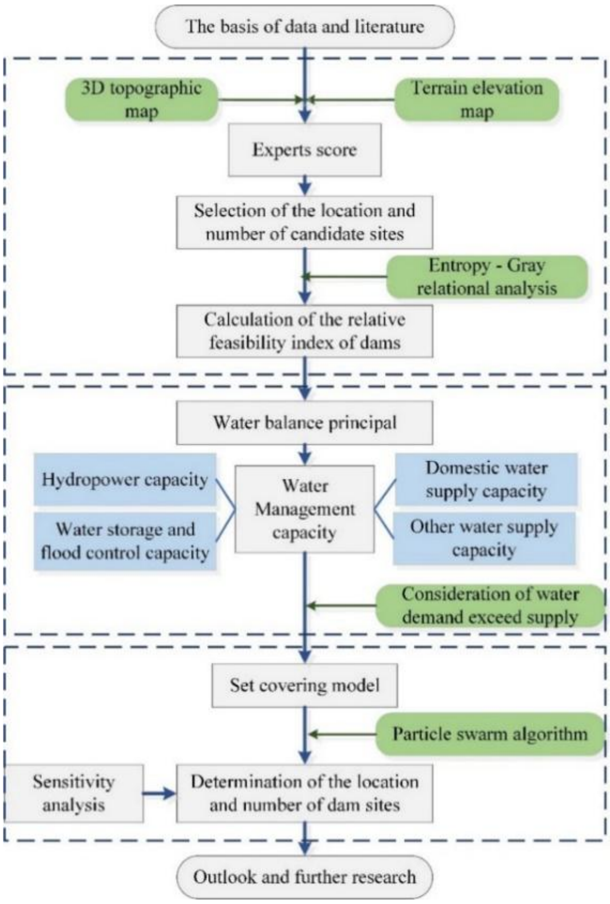

Fig. 1 The research route of this paper

To select the candidate dam sites, we firstly use MATLAB to construct the three-dimensional topographic map and topographic elevation map of the Zambezi River Basin as a preliminary basis for judging its geographical environment (Fig. 2).

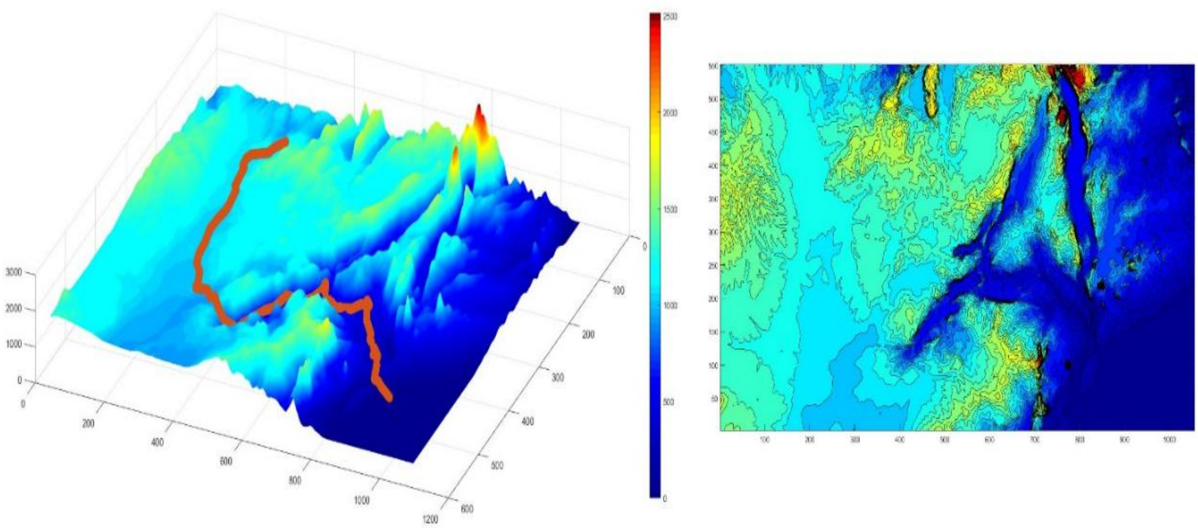

Fig. 2 The three-dimensional topography and elevation map of the Zambezi River Basin

By studying a large number of related literatures [7, 8] and combined with five indicators of water head difference elevation, geological environment, climatic environment, population distribution and biodiversity, the 22 candidate dam sites in the Zambezi River basin were selected (Fig. 3).

Fig. 3 The distribution map of the candidate dam sites

The suitable dam locations in the Zambezi River basin are mainly concentrated on the west side of Victoria Falls in the upper reaches, the middle section of the Kalaba and Calabasas reservoirs, and part of the lower reaches of the Calabasas reservoir (Fig. 3). These areas generally have the characteristics of being close to natural reservoirs, wide hinterland and stable geological conditions, which meet the basic natural conditions of dam construction. The longitude, latitude, rainfall and scores of indexes of the 22 candidate sites are shown in Table 1.

Table 1 The information of the 22 candidate sites.

No.	Latitude(°S)	Longitude(°E)	Rainfall(mm)	Elevation	Geology	Biodiversity	Population
1	-13.5493	23.1262	1110	1	2	4	2
2	-15.5663	23.1262	705	3	4	2	2
3	-15.9151	23.2471	727	3	4	2	2
4	-17.8788	25.3345	703	2	3	3	1
5	-17.5863	25.0057	721	2	3	4	2
6	-17.8062	25.2894	726	3	3	4	2
7	-17.8546	25.3937	729	4	3	3	2
8	-17.8506	25.5448	731	4	2	3	3
9	-17.8071	25.6902	734	4	3	3	4
10	-16.5223	28.7612	672	5	5	2	2

11	-16.1878	28.8399	664	2	4	3	3
12	-15.9476	28.9339	693	3	3	4	3
13	-15.6562	29.6429	791	3	4	3	2
14	-15.6157	29.9277	786	3	4	4	2
15	-15.6562	30.1978	783	4	4	3	2
16	-15.6239	30.4194	779	4	3	4	2
17	-15.6271	30.5686	784	3	4	3	2
18	-15.6536	30.7994	803	3	4	4	2
19	-15.5937	32.6871	865	5	5	3	3
20	-15.6477	33.0131	812	4	3	3	2
21	-15.5838	33.2713	765	3	3	4	3
22	-16.4089	33.8101	681	3	4	4	2

3. Relative feasibility of dam construction

Among the 22 candidate dam sites, each site has its advantages and disadvantages. Thus, we need to make screening work combined with the relative feasibility of dam construction to determine the final number and location of dams.

3.1 Grey correlation analysis

To analyze the relative feasibility of dam construction, we can combine the expert scores of five indicators (water head difference elevation, geological environment, climatic environment, population distribution and biodiversity) of each site, and establish the entropy weight-grey correlation analysis model to obtain the relative feasibility index ϵ_j of the j-th dam site. The basic idea of grey correlation analysis is to judge whether the sequence curve is closely related according to the similarity of the geometric shape of the sequence curve. The closer the curve is, the greater the correlation degree between the corresponding sequences is, and vice versa is smaller [9]. The steps are as follows:

3.1.1 Determining subsequence and parent sequence

Set U as the subsequence, which is the set of indicators. Where u_i is the i-th index, and there are 5 indicators in the sequence, that is:

$$U=\{u_1, u_2, u_3, \cdots, u_m\}, \text{ Where } i=1, 2, 3, \cdots, m \quad (1)$$

Set V as the parent sequence, which is the new dam site set. Where v_j is the j-th dam site, and there are 22 evaluation objects in the sequence, that is:

$$V=\{v_1, v_2, v_3, \cdots, v_n\}, \text{ Where } j=1, 2, 3, \cdots, n \quad (2)$$

3.1.2 Establishing evaluation matrix *R*

The evaluation matrix R is established as follows:

$$R=\{r_{ij}\}=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \quad (3)$$

Where r_{ij} is the data of the i-th index at the j-th dam site.

3.1.3 Standardized processing

In order to eliminate the influence of different index dimensions, it is necessary to standardize the evaluation matrix. If r_{ij} is set as the data of the i-th index of the j-th dam site, $R^{(1)}$ is the standardized evaluation matrix, and each element in $R^{(1)}$ is $r_{ij}^{(1)}$, which is the data of the i-th index of the j-th dam site after standardized processing.

$$r_{ij}^{(1)}=\frac{r_{ij}}{\sqrt[2]{\sum_{j=1}^{n} r_{ij}^{2}}} \tag{4}$$

Where i=1, 2, 3,⋯, m; j=1, 2, 3,⋯, n

3.1.4 The establishment of virtual parent sequence

Take out the maximum value r_i of each column in the positive standardized $R^{(1)}$ matrix to form a virtual parent sequence R', that is:

$$R'=\{r_i', r_i', r_i',\cdots, r_i'\},\ \text{Where } i=1, 2, 3,\cdots, m \tag{5}$$

3.1.5 The establishment of weighted absolute range matrix

The absolute difference matrix $R^{(2)}$ is formed by calculating and comparing the absolute difference of the corresponding elements of the subsequence and the virtual parent sequence, and its elements are:

$$r_{ij}^{(2)}=|r_{ij}^{(1)}-r_i'|,\ \text{Where } i=1, 2, 3,\cdots, m;\ j=1, 2, 3,\cdots, n \tag{6}$$

Set W as the weight matrix given to each index by using entropy weight method, that is:

$$W=[w_1, w_2, w_3,\cdots, w_m],\ \text{Where } i=1,2,3,\cdots,m \tag{7}$$

The weighted absolute difference matrix $R^{(3)}$ is formed by multiplying the weight matrix and the absolute difference matrix, where the element is $r_{ij}^{(3)}$, that is:

$$r_{ij}^{(3)}=w_i r_{ij}^{(2)},\ \text{Where } i=1, 2, 3,\cdots, m;\ j=1, 2, 3,\cdots, n \tag{8}$$

3.1.6 The calculation of the grey correlation degree

Set the correlation coefficient of the j-th value of the i-th index to the j-th dam site as ξ_{ij}^{j}, that is:

$$\xi_{ij}^{j}=\frac{\min\limits_{i=1}^{m}\left[\min\limits_{j=1}^{n} r_{ij}^{(3)}\right]+\eta\max\limits_{i=1}^{m}\left[\max\limits_{j=1}^{n} r_{ij}^{(3)}\right]}{r_{ij}^{(3)}+\eta\max\limits_{i=1}^{m}\left[\max\limits_{j=1}^{n} r_{ij}^{(3)}\right]} \tag{9}$$

Where η is the resolution coefficient, its value is between 0 and 1, usually is set as 0.5. The value of η can affect the difference of correlation coefficient ξ_{ij}^{j}, which is the correlation degree of the j-th value of the i-th index to the j-th dam site.

The correlation coefficient is normalized, that is:

$$S_{ij}^{j}=\frac{1}{n}\sum_{j=1}^{n}\xi_{ij}^{j} \tag{10}$$

Where i=1, 2, 3,⋯, m; j=1, 2, 3,⋯, n. S_{ij}^{j} is the correlation value of the j-th value of the i-th index to the j-th dam site. Considering the very small data ϵ_j, which means the smaller the value, the more relevant, and the relative feasibility index of the j-th dam site is:

$$\epsilon_j=\sum_{j=1}^{n}\left(S_{ij}^{j}\right)_{max}-S_{ij}^{j} \tag{11}$$

Where $\left(S_{ij}^{j}\right)_{max}$ is the largest correlation value among n alternative dam sites.

3.2 Entropy weight method

In view of the influence of each index on the relative feasibility of dam construction at each dam site, this paper weighs each index by introducing entropy weight method. Entropy weight method is an objective weighting method. The principle is that the greater the degree of variation of the index, the less the amount of information reflected, and the lower the corresponding weight. The steps are as follows:

Construct probability matrix P, and the formula for each element p_{ij} in P is:

$$p_{\mathrm{ij}}=\frac{r_{\mathrm{ij}}{}^{(1)}}{\sum_{\mathrm{j=1}}^{\mathrm{n}} r_{\mathrm{ij}}{}^{(1)}} \quad (1)$$

Where $i=1, 2, 3,\cdots, \mathrm{m}; j=1,2,3,\cdots, \mathrm{n}$

The information entropy e_{j} of each index and the information utility value d_{j} is calculated, and the entropy weight w_{j} of each index is normalized. Taking into account the possible occurrence of $p_{\mathrm{ij}}=0$, in which $\ln\left(p_{\mathrm{ij}}\right)$ does not exist, then $p_{\mathrm{ij}}\ln\left(p_{\mathrm{ij}}\right)=0$ is defined, and the calculation formulas are:

$$e_{\mathrm{j}}=-\frac{1}{\ln \mathrm{n}}\sum_{\mathrm{j=1}}^{\mathrm{n}} p_{\mathrm{ij}}\ln\left(p_{\mathrm{ij}}\right) \quad (2)$$

$$d_{\mathrm{j}}=1-e_{\mathrm{j}} \quad (3)$$

$$w_{\mathrm{j}}=\frac{d_{\mathrm{j}}}{\sum_{\mathrm{i=1}}^{\mathrm{m}} d_{\mathrm{j}}} \quad (4)$$

Where $i=1, 2, 3,\cdots, \mathrm{m}; j=1, 2, 3,\cdots, \mathrm{n}$

Then the weight matrix W is:

$W=[w_1, w_2, w_3,\cdots, w_{\mathrm{m}}]$, Where $i=1, 2, 3,\cdots, \mathrm{m}; j=1, 2, 3,\cdots, \mathrm{n}$ (5)

3.3 Analysis of relative feasibility index of dam construction

Based on the above analysis, the relative feasibility indexes of the 22 candidate dam sites are obtained by MATLAB, which are shown in the following Table 2:

Table 2 The relative feasibility index of each candidate dam sites

Serial number	Relative feasibility index of dam construction	Serial number	Relative feasibility index of dam construction
1	2.629	12	2.782
2	2.506	13	2.640
3	2.511	14	2.812
4	2.411	15	2.733
5	2.640	16	2.805
6	2.698	17	2.639
7	2.621	18	2.816
8	2.642	19	3.185
9	2.902	20	2.640
10	2.935	21	2.798
11	2.646	22	2.788

The feasibility indexes of dam construction in the upper reaches are significantly higher than that in the middle and lower reaches (Table 2), which may be the result of the differences of hydropower resources and high-level potential in the upper reaches. In addition, the low population distribution caused by the marshes near the Kalene Mountains in Zambia in the upper reaches may also be an important influencing factor.

4. Water management capacity of multi-dam system

In view of the water management capacity of the dam group, we should elaborate and analyze the water storage and flood control capacity, hydropower capacity, domestic water supply capacity and other water supply capacity respectively (Fig. 4).

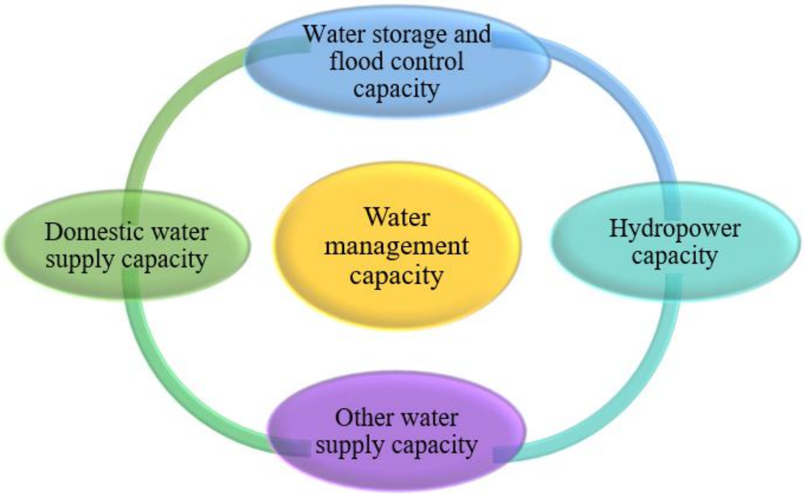

Fig. 4 The Composition of water management capacity

4.1 Water storage and flood control capacity

The main function of the dam is to block the high and fill the low, which means to store water in the flood season to avoid flood disasters, and release water in the dry season to supplement and keep flows. Therefore, the water storage and flood control capacity are important for water management, and we will consider it from the principle of water balance of the dam reservoir.

4.1.1 The principle of water balance

If $W_{\mathrm{in}}(\mathrm{t,j})$ is set as the input water of the j-th dam reservoir at t time, the input is the runoff, in which the natural consumption of water has been considered in the runoff. $W_{\mathrm{s}}(\mathrm{t,j})$ is set as the water storage capacity of the j-th dam reservoir at t time, then the water storage capacity should not only consider domestic water supply and other water supply, but also meet the minimum storage capacity requirements (Fig. 5).

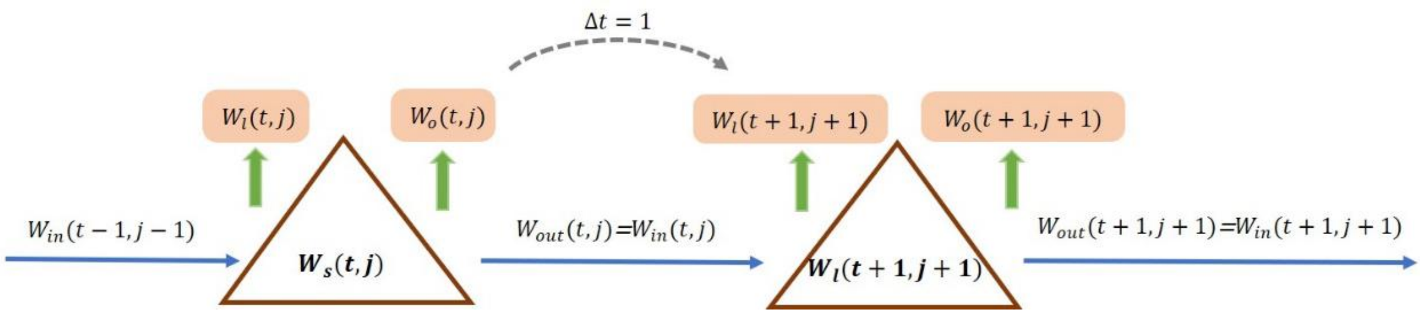

Fig. 5 The diagram of water balance of dam reservoir

Then the principles of water balance of each dam reservoir are:

$$W_{\mathrm{in}}=W_{\mathrm{r}}(\mathrm{t,j}) \quad (1)$$

$$W_{\mathrm{s}}(\mathrm{t+1,j+1})=W\mathrm{in}(\mathrm{t,j})+W_{\mathrm{s}}(\mathrm{t,j+1})\text{-}W_{\mathrm{l}}(\mathrm{t,j})\text{-}W_{\mathrm{o}}(\mathrm{t,j})\text{-}W \quad (2)$$

$$W_{\mathrm{s}}(\mathrm{t,j})=W_{\mathrm{in}}(\mathrm{t,j})\text{-}W_{\mathrm{l}}(\mathrm{t,j})\text{-}W_{\mathrm{o}}(\mathrm{t,j}) \geq V_{\mathrm{d}}(\mathrm{j}) \quad (3)$$

Where $W_{\mathrm{r}}(\mathrm{t,j})$ is the runoff of the area of the j-th dam at t time, which is the amount of rainfall minus the natural consumption (the sum of evaporation and infiltration); $W_{\mathrm{l}}(\mathrm{t,j})$ is the consumption of domestic water supply of the j-th dam reservoir at t time and $W_{\mathrm{o}}(\mathrm{t,j})$ is the consumption of other water supply in the area of the j-th dam reservoir at t time; $V_{\mathrm{d}}(\mathrm{j})$ is the dead capacity of the j-th dam reservoir.

4.1.2 The storage capacity and the flood

During the flood period, the reservoir should ensure that the water level is below the flood control limit level and above the dead water level (Fig. 6).

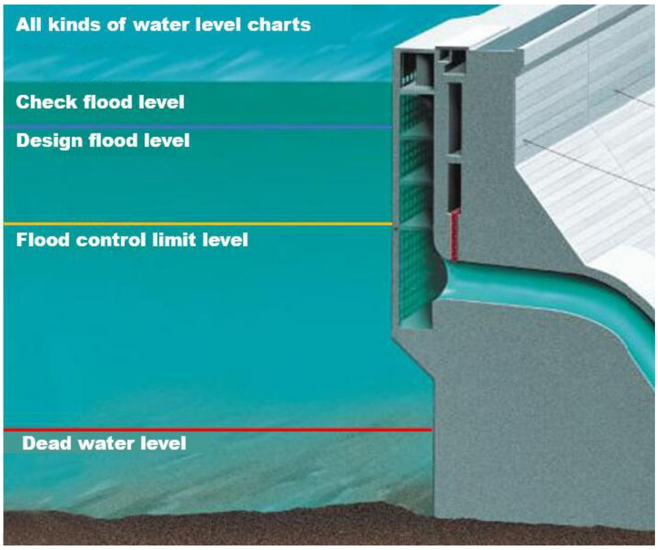

Fig. 6 The water level map of dam reservoir

The storage capacity of each dam reservoir should meet the sum of the original water storage capacity and flood control capacity, and the water storage capacity before flood should not be lower than the dead reservoir capacity, that is:

$$V_{\mathrm{w}}(\mathrm{j})\text{-}W_{\mathrm{s}}(\mathrm{t,j}) \geq W_{\mathrm{a}}(\mathrm{t,j}) \quad (1)$$

$$W_{\mathrm{s}}(\mathrm{t,j}) \geq W_{\mathrm{d}}(\mathrm{j}) \quad (2)$$

Where $V_{\mathrm{w}}(\mathrm{j})$ is the maximum storage capacity of the j-th dam reservoir, and $W_{\mathrm{a}}(\mathrm{t,j})$ is the flood control operation capacity of the j-th dam reservoir at t time.

4.2 Hydroelectric capacity

Converting hydropower into electricity through dams is of great significance in promoting the development and utilization of water resources. Zambezi River is rich in hydropower resources, so the hydroelectric supply capacity of dams should meet the local electricity demand, that is:

$$Q_{\mathrm{e}}(\mathrm{t,j}) \geq N_{\mathrm{e}}(\mathrm{t,j}) \quad (1)$$

Where $Q_{\mathrm{e}}(\mathrm{t,j})$ is the actual power generation of the j-th dam reservoir at t time, and $N_{\mathrm{e}}(\mathrm{t,j})$ is the power demand in the area of the j-th dam at t time.

4.3 Domestic water supply capacity

Water is an indispensable resource for people to survive, and water supply is also one of the most important functions of dams. Therefore, the water supply of the dam must meet the domestic water needs of local residents, that is:

$$W_{\mathrm{l}}(\mathrm{t,j}) \geq N_{\mathrm{l}}(\mathrm{t,j}) \quad (1)$$

Where $N_{\mathrm{l}}(\mathrm{t,j})$ is the water demand of the residents around the j-th dam at the t time.

4.4 Other water supply capacity

For other water supplies in the Zambezi basin [10], we consider industrial water W_{ind}, agricultural water W_{agr}[11], and the other water supply W_{o} of the j-th dam reservoir at the t time, that is:

$$W_{\mathrm{o}}(\mathrm{t,j}) = W_{\mathrm{ind}}(\mathrm{t,j}) + W_{\mathrm{agr}}(\mathrm{t,j}) \quad (1)$$

$$W_{\mathrm{o}}(\mathrm{t,j}) \geq N_{\mathrm{o}}(\mathrm{t,j}) \quad (2)$$

Where $N_{\mathrm{o}}(\mathrm{t,j})$ is the other water demand around the j-th dam at t time.

4.5 Considering the actual situation of water shortage

Although the Zambezi River is rich in water resources, the population growth accompanied by the continuous increase in water demand has put great pressure on the supply of water resources. In addition, the climate in the basin is mainly savanna climate, which has the characteristics of distinct dry season and concentrated flood season, so that the water supply of the dam may not always meet the water needs of people around it.

Therefore, it is necessary to consider the situation that water supply falls short of demand in a short period T' . When domestic water supply and other water supply fall short of demand, we take the minimum value of demand and reservoir supply in this period (Fig. 7):

$$\int_0^{T'} W_l(t,j) = \min\left\{\int_0^{T'} N_l(t,j), \int_0^{T'} W_{la}(t,j)\right\} \quad (1)$$

$$\int_0^{T'} W_o(t,j) = \min\left\{\int_0^{T'} N_o(t,j), \int_0^{T'} W_{oa}(t,j)\right\} \quad (2)$$

Where $\sum_{t=1}^{T'} W_{la}(t,j)$ is the available capacity of domestic water supply in the T' period; $\sum_{t=1}^{T'} W_{oa}(t,j)$ is the available capacity of other water supply reservoirs in the T' period.

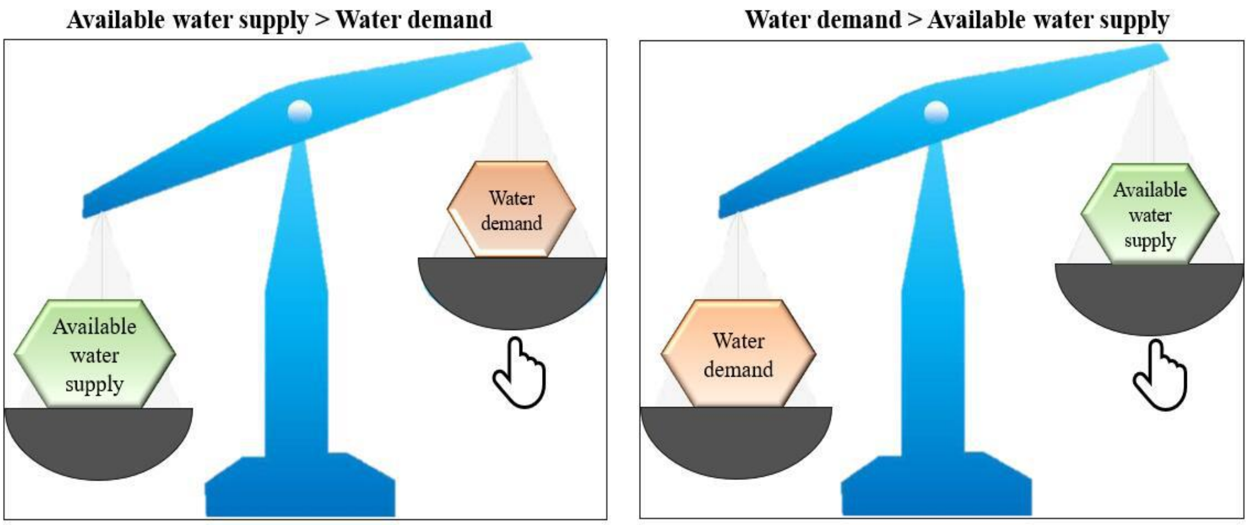

Fig. 7 The diagram of water supply and demand relationship

5. Set coverage model of multi-dam system

The set coverage model is a common model in the discrete location model. We can set up the corresponding objective function and constraints through the set coverage model, and solve the location and number of dam sites in the new dam group by neighborhood adaptive particle swarm optimization (NAPSO).

5.1 Determination of constraint conditions

5.1.1 Constraints on water management capacity

According to the question, the water management capacity of the new dam group should be equal or higher than that of the existing Kariba dam, that is:

$$\int_0^{T} [\sum_{j=1}^{n} X_j W_a(t,j) - W_a'(t)]dt \geq 0 \quad (1)$$

$$\int_0^{T} [\sum_{j=1}^{n} X_j Q_e(t,j) - Q_e'(t)]dt \geq 0 \quad (2)$$

$$\int_0^{T} [\sum_{j=1}^{n} X_j W_l(t,j) - W_l'(t)]dt \geq 0 \quad (3)$$

$$\int_{o}^{T}[\sum_{j=1}^{n}X_{j}W_{o}(t,j)\text{ -}W_{o}'(t)]\,dt\geq 0 \tag{4}$$

Where T is a period of time; $W_{a}'(t)$、$Q_{e}'(t)$、$W_{l}'(t)$、$W_{o}'(t)$ represent the flood storage and control capacity, hydraulic power generation, domestic water supply and other water supply of the existing Kariba dam, respectively.

5.1.2 Constraints on reservoir capacity and water balance of the dam

The constraints on reservoir capacity and water balance of the dam are as follows:

$$V_{d}(j)\leq W_{S}(t,j)\leq V_{w}(j) \tag{1}$$

$$W_{s}(t+1,j+1)=Win(t,j)+W_{s}(t,j+1)\text{-}W_{l}(t,j)\text{-}W_{o}(t,j)\text{-}W_{in}(t+1,j+1) \tag{2}$$

5.1.3 Constraints on the number of dams

According to the question, the constraints on the number of dams are as follows:

$$j=1,2,3,\cdots,m;\ a\in[10,20],\ a\in Z \tag{1}$$

5.2 Determination of objective function and the definition of 0-1 variable

Set the 0-1 variable X_{j} to judge whether to build the dam at the j-th dam site, that is:

$$X_{j}=\begin{cases}1, \text{construction}\\ 0, \text{no construction}\end{cases} \tag{1}$$

For economic considerations, the construction of the dam needs to comply with the principle of cost-benefit, which means to achieve certain benefits at the lowest possible cost. Here, we determine that the objective function is to minimize the benefit cost C_{j}, that is:

$$C_{j}=\epsilon_{j}A \tag{2}$$

Where ϵ_{j} is the relative feasibility index of the j-th dam construction, and A is the expected average construction cost of the dam, which is a constant.

5.3 Set coverage model of multi-dam system

In summary, on the basis of the balance between safety and cost, we can combine the formula (16)-(31) to establish the following set coverage model to meet the water management capacity of the new dam group:

$$X_{j}=\begin{cases}1, \text{construction}\\ 0, \text{no construction}\end{cases} \tag{1}$$

$$\text{Min}\sum_{j=1}^{n}C_{j}=\sum_{j=1}^{n}X_{j}\epsilon_{j}A \tag{2}$$

$$\text{s.t.}\begin{cases}\int_{0}^{T}[\sum_{j=1}^{n}X_{j}W_{a}(t,j)\text{ -}W_{a}'(t)]dt\geq 0\\ \int_{0}^{T}[\sum_{j=1}^{n}X_{j}Q_{e}(t,j)\text{ -}Q_{e}'(t)]\,dt\geq 0\\ \int_{0}^{T}[\sum_{j=1}^{n}X_{j}W_{l}(t,j)\text{ -}W_{l}'(t)]dt\geq 0\\ \int_{o}^{T}\left[\sum_{j=1}^{n}X_{j}W_{o}(t,j)\text{ -}W_{o}'(t)\right]dt\geq 0\\ W_{s}(t+1,j+1)=Win(t,j)+W_{s}(t,j+1)\text{-}W_{l}(t,j)\text{-}W_{o}(t,j)\text{-}W_{in}(t+1,j+1)\\ V_{d}(j)\leq W_{S}(t,j)\leq V_{w}(j)\end{cases} \tag{3}$$

Where it is known that $W_{a}'(t)$、$Q_{e}'(t)$、$W_{l}'(t)$、 $W_{o}'(t)$ are unary functions with respect to t, and T is a constant representing the point in time; j=1, 2, 3,⋯, m; a∈[10,20], a∈Z.

6. Neighborhood adaptive particle swarm optimization algorithm

Then the neighborhood adaptive particle swarm optimization algorithm (NAPSO) with fast search speed and high efficiency is used to realize the optimal programming. Particle swarm optimization (PSO) is a population-based stochastic optimization technique proposed by Eberhart and Kennedy in 1995. It expresses each possible solution as every particle in the group, each particle has its own position vector and velocity vector, and a fitness determined by the objective function. All parti- cles fly at a certain speed in the search space and iteratively search for the optimal solution after initializing a set of random solutions. The solving process is shown in Fig. 8.

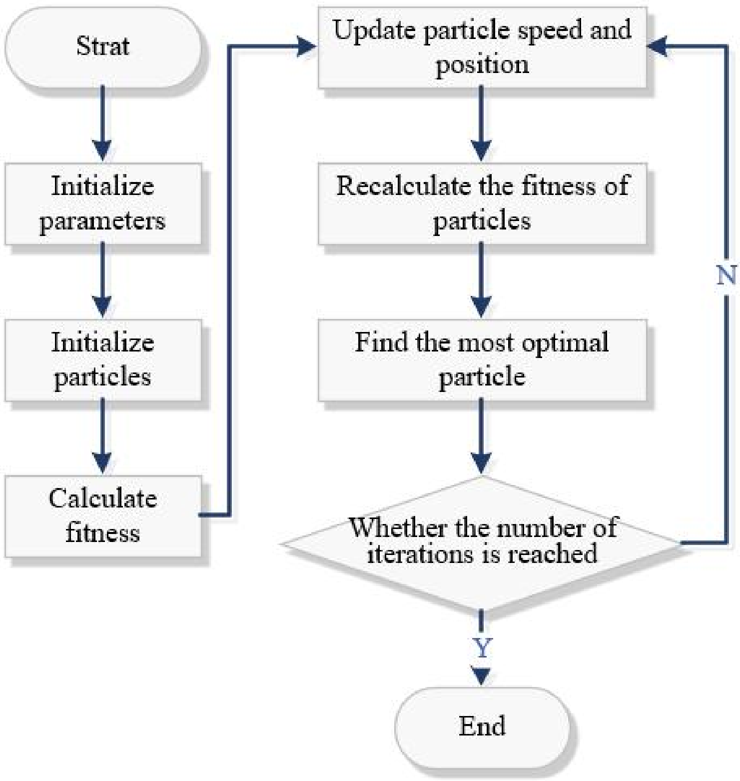

Fig. 8 The flow chart of particle swarm optimization algorithm

It is assumed that PSO has s b-dimensional individuals $X_{\mathrm{k}}=\{x_{\mathrm{k},1},x_{\mathrm{k},2},\cdots,x_{\mathrm{k,b}}\}$, $(k=1, 2,\cdots, s)$ to find the optimal solution through iteration in the feasible region, where s is the population size and $s=100$; b is the matrix dimension, and $b=22$. In the iterative process, each individual learns and updates the current position and speed by learning and updating the current position and speed from its own historical optimal location and population optimal location, and the update formulas are as follows:

$$v_{\mathrm{k}}^{\mathrm{d}}=wv_{\mathrm{k}}^{\mathrm{d-1}}+c_1r_1\left(pbest_{\mathrm{k}}^{\mathrm{d}}-x_{\mathrm{k}}^{\mathrm{d}}\right)+c_2r_2\left(gbest^{\mathrm{d}}-x_{\mathrm{k}}^{\mathrm{d}}\right) \tag{1}$$

$$x_{\mathrm{k}}^{\mathrm{d+1}}=x_{\mathrm{k}}^{\mathrm{d}}+v_{\mathrm{k}}^{\mathrm{d}} \tag{2}$$

Where w is the inertia weight of particles, c_1 is individual learning factor and c_1=1.49, c_2 is social learning factor and c_2=1.49; r_1 and r_2 are independent pseudo-random numbers which obey uniform distribution on [0,1], $pbest_{\mathrm{k}}^{\mathrm{d}}$ is the best position for the k-th particle to the d-th iteration, $gbest^{\mathrm{d}}$ is the best position for all particles to the d-th iteration.

In view of the precocious phenomenon of PSO, this paper introduced neighborhood adaptive particle swarm optimization algorithm (NAPSO). The NAPSO firstly assigned several individuals with the closest distance to each individual according to the distance between each individual, and then a neighborhood is formed. Then, the optimal individual $lbest$ in the neighborhood is used to update the speed and position. The particle ratio in the neighborhood adopted in this paper is 0.25, and the calculation formulas are as follows:

$$v_k^d = w v_k^{d-1} + c_1 r_1 \left(pbest_k^d - x_k^d\right) + c_2 r_2 \left(lbest_k^d - x_k^d\right) \quad (3)$$

$$x_k^{d+1} = c_3 x_k^d \quad (4)$$

Where the inertia weight interval of w is [0.1, 1.1], and the inertia weight will take adaptive measures in the iterative process, and it will be adjusted continuously with the iterative process. $lbest_k^d$ is the optimal individual in the k-th particle neighborhood in the d-th iteration. c_3 is a learning factor, its value will significantly affect the convergence performance of the population, too large will easily make the population into the local optimal solution, too small will affect the convergence rate of the population. After many experiments of our study, c_3 is set as 1.8 [12] in this paper.

For the 0-1 variable in the set coverage model, we assumed that the X_i greater than 0 will be regarded as 1 (construction) and the X_i less than 0 will be regarded as 0 (no construction) in the solving process of NAPSO algorithm. The number of dam sites of the new multi-dam system is 12, and the distribution of each dam site is shown in Fig. 9.

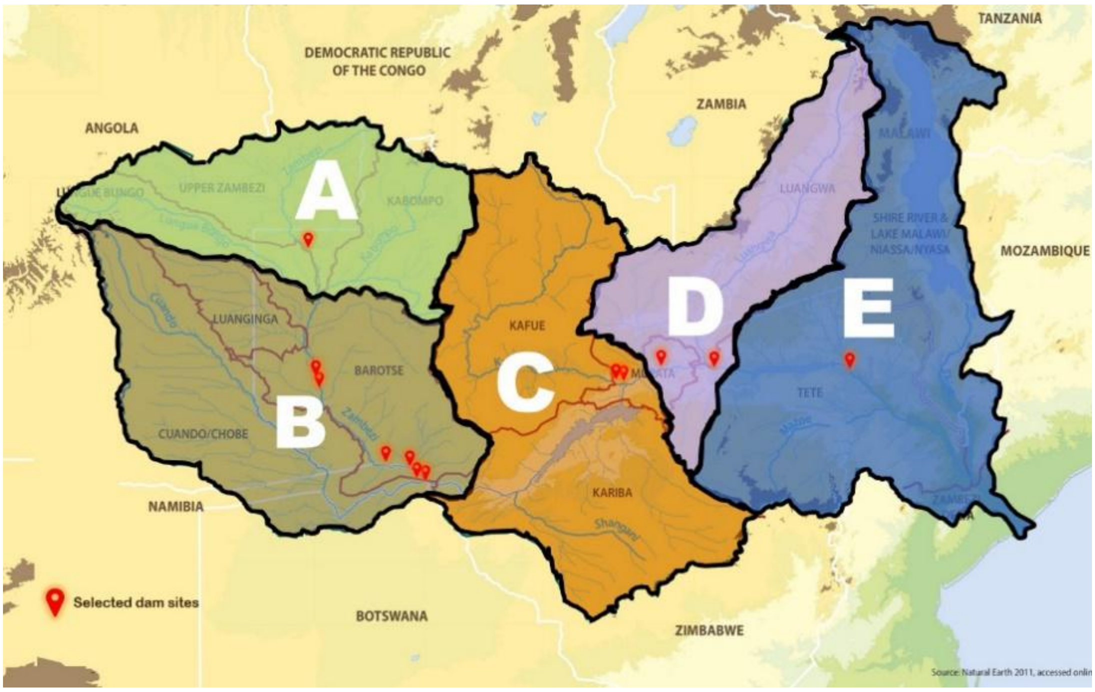

Fig. 9 Distribution of dam sites of new dam groups.

In order to better deal with the cooperative operation and dispatching in the case of emergency flow, we divide the above five sub-basins A, B, C, D and E in the Zambezi River Basin according to their characteristics of water system distribution, annual average rainfall and dam distribution (Fig. 9). In addition, the ratios of the four water management capacities of the new dam group and the original Kariba dam are: water storage and flood control capacity 346/103, hydropower capacity 5894/1681, domestic water supply capacity 84/29, other water supply capacity 466/144 (Fig. 10), which means the water management capacity of the new dam group is 235.92%, 250.62%, 189.66% and 223.61% higher than that of the original Kariba dam, respectively, and shows the superiority of this dam selection method.

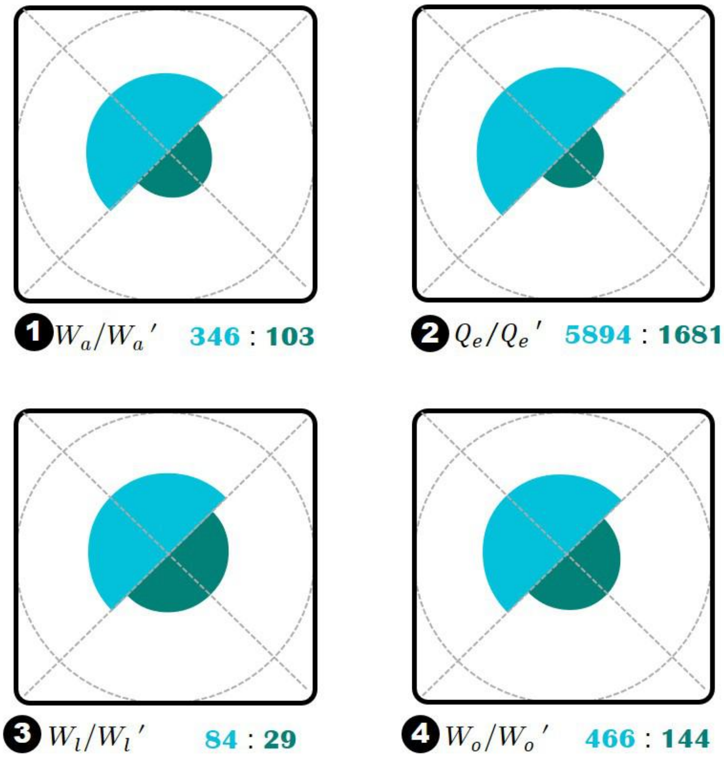

Fig. 10 Comparison of water management capacity between new dam group and original Kariba dam

7. Conclusion

This paper studied the dam location problem in the Zambezi river basin. Based on the candidate dam sites scored by experts, the entropy weight-grey correlation model was in- troduced to analyze the feasibility index of dam construction. Then an integral set coverage model is established and the neighborhood adaptive particle swarm optimization (NAPSO) algorithm is used to solve the number and location of dam sites. Finally, the 12 dam sites for construction have been determined by this new method. Compared with the original Kariba dam, its water storage and flood control capacity, hydropower capacity, domestic water supply capacity and other water supply capacity are increased by 235.92%, 250.62%, 189.66% and 223.61% respectively, which fully shows the superiority of the dam selection method.

In order to better deal with the cooperative operation of dam group, we also divided the Zambezi river basin into five sub-basins according to the characteristics of water system distribution, annual average rainfall and dam distribution. Our study has not only engineering guiding significance, but also shows the good engineering benefits and social effects of proposed dam group.

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