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Hydropower Sharing based on Multi-objective Programming

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Abstract

Aiming at the problem of resource allocation, this paper establishes a regional water resource allocation model based on a multi-objective programming algorithm. Specifically, we establish a linear programming model to identify two reservoirs with optimal water supply quantity and optimal power generation volume as objective functions. In addition, we establish a multi-objective programming model and determined the functional expressions of the two objectives of social benefit and economic benefit. The entropy weight method is used to determine the weights of the four major indicators of industry, agriculture, housing and electricity. Finally, we use MATLAB to solve the corresponding water demand, and use SPSS software to analyze the correlation between water, electricity supply and water demand, and obtain the influence of different variables in the model.

Keywords

Resource Allocation; Linear Programming; Multi-objective Programming; Entropy Weight Method; Correlation Analysis.

1. Introduction

In recent decades, due to climate deterioration, extreme weather, including extreme high temperature, extreme precipitation, and other phenomena have occurred frequently, resulting in the reduction of the water volume of the reservoirs of the two major lakes (Lake Powell and Lake Mead) in the Colorado Basin [1].

This directly affects water use in the area around the dam. In addition, the low water flow will also reduce the power generation of the dam's hydroelectric power station due to the reduction of water volume, which will affect the distribution of electricity in the corresponding area, and even stop generating electricity if the reservoir water volume is too low.

The Colorado River Basin in this paper is in the above-mentioned stage. Due to environmental changes and the recent long-term drought, the water flow in the Colorado River Basin has been decreasing year by year, and Lake Mead in the lower reaches of the Colorado River was even rumored to be drying up [5]. Therefore, to meet the water and electricity needs of the basin, we need to reallocate water resources at Glen Canyon Dam (Lake Powell) and Hoover Dam (Lake Mead) to address the five states of interest to agriculture, industry, and residential water and electricity distribution issues. At the same time, because Mexico is also in the Colorado River Basin and has the right to allocate the remaining water after consumption in the five states, the planning should also consider how to solve the problem of Mexico's power [6].

For centuries, people have built dams and reservoirs on rivers for various purposes. With climate change, the water in dams and reservoirs has gradually decreased, and at the same time, with the unreasonable allocation of water resources by various local governments, the contradiction between the ever-increasing water demand and the limited water supply has gradually intensified. Aiming at the problem of resource allocation, this paper establishes a regional water resource allocation model based on a multi-objective programming algorithm.

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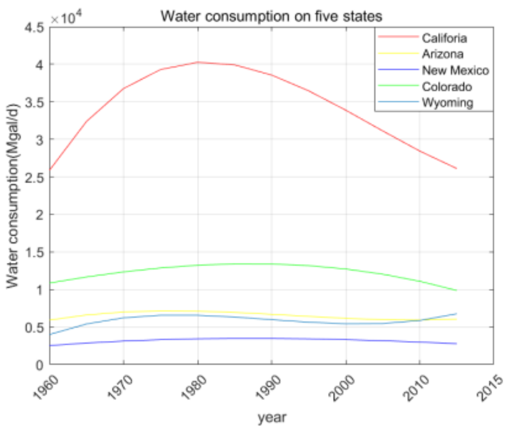
2. Linear Programming Model

To solve the problem of water resource scheduling, we must first have a certain understanding of the supply and demand of water resources, and at the same time, to solve practical problems, we need to analyze the local situation. Fig.1 displays the positional relationship between the two lakes. The data is fitted and forecasted to obtain the trend curve, and then the forecast for 2022 is obtained related data. Fig. 2 displays the fitting curve of water consumption in five states, and Fig. 3 displays the fitting curve of electricity consumption in five states [2].

Figure 1. Location of Lake Powell and Lake Mead



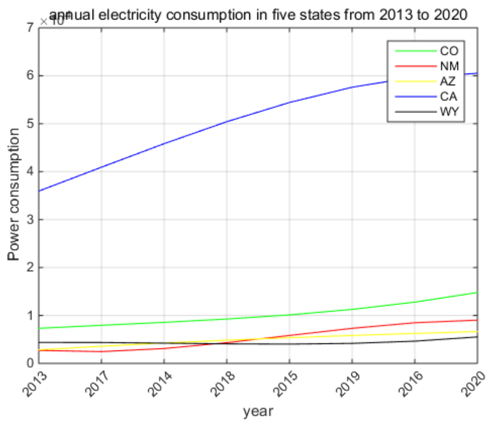


Figure 2. Water consumption on five states **Figure 3.** Power consumption in five states

After fitting the data through MATLAB, the expression of the annual daily water of each state is obtained, as follows:

$$\begin{cases} w_{COpro} = 16.7w_c^3 - 111.4w_c^2 + 852.3w_c + 6556.7 \\ w_{NMpro} = -50.4w_c^3 + 745.5w_c^2 - 2132.4w_c + 4143.7 \\ w_{AZpro} = 2.3w_c^3 - 61.7w_c^2 + 933.9w_c + 1944.4 \\ w_{CApro} = -42w_c^3 + 211w_c^2 + 4640w_c + 31132 \\ w_{WYpro} = 18w_c^3 - 168.4w_c^2 + 365.5w_c + 4156.4 \end{cases} \quad (1)$$

After fitting the data through MATLAB, the expression of each state's annual and electricity is obtained, as follows:

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$$\begin{cases} l_{COpro} = 1600 l_c - 15965000 \\ l_{NMpro} = 4400 l_c - 4363400 \\ l_{AZpro} = 4400 l_c - 4363300 \\ l_{CApro} = 7000 l_c - 69581000 \\ l_{WYpro} = 4100 l_c - 4094800 \end{cases} \quad (2)$$

Reservoirs and dams store a large number of water resources. Taking Lake Powell and Glen Gap Dam as an example. Part of Lake Powell's water resources are directly supplied to the five states for industrial, agricultural, or housing use, and part is passed through Glen Gap. The dam converts electricity to five states, while a portion of Lake Powell's hydropower upstream is to be distributed downstream to Lake Mead. Fig. 4 displays a schematic diagram of the distribution of water resources in the two lakes.

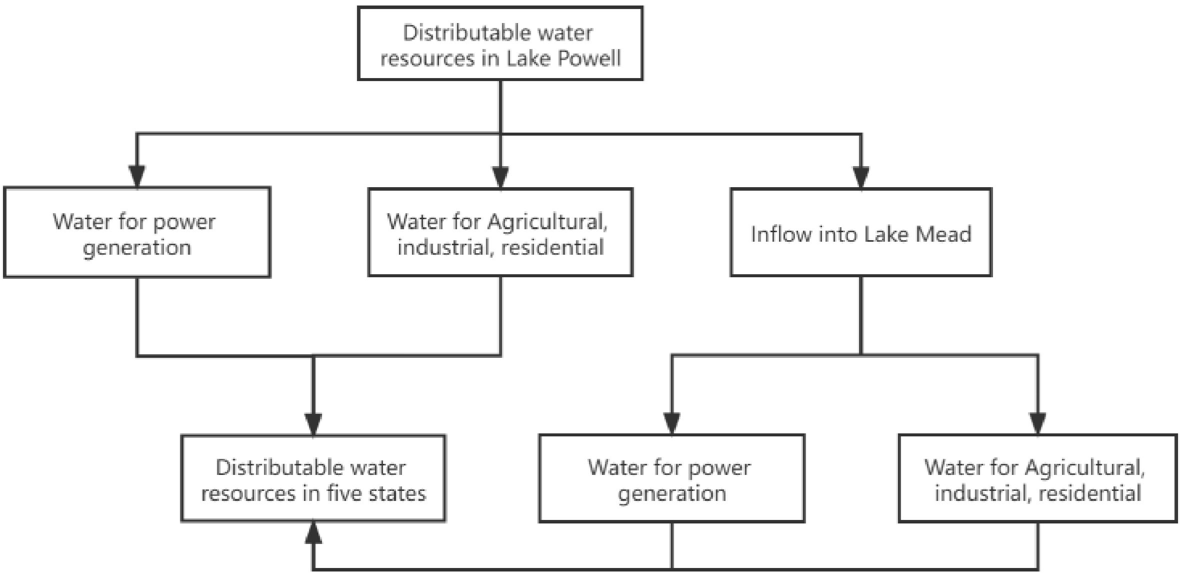

Figure 4. The distribution of water resources

If the water supply-demand can be fulfilled, the water supply from the two lakes to the five states is greater than or equal to the total water consumption of the five states, which is expressed as follows:

$$\sum_{i=1}^{n=5} l_i \le x_1 + y_1 \quad (3)$$

Power generation principle of hydropower station: Hydraulic utilization mainly uses potential energy. If you want to use potential energy, there must be a geographical drop in the water level. However, the natural drop of the river is generally gradually formed along the river, and the natural drop of the water flow is low in a short distance. It is necessary to manually increase the drop through appropriate engineering measures, that is, concentrate the scattered natural drop to form an available head.

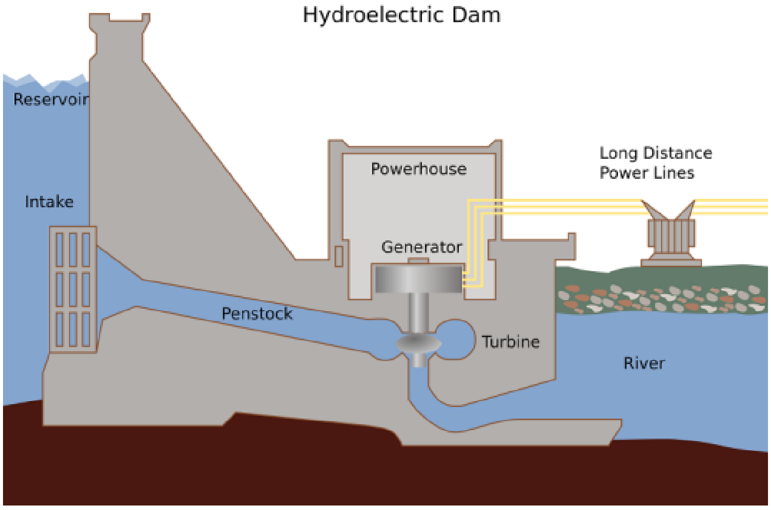

Figure 5. dam-type power generation

Build dams in river sections with large drops, build reservoirs to store water to raise the water level, and install turbines outside the dams. The water flow from the reservoir passes through the aqueduct (aqueduct) to the turbine at a low place outside the dam. The water flow drives the turbine to rotate and drives the generator to generate electricity. Then through the tailrace to the downstream river, this is the way to build a dam and build a library to generate electricity. The principle of dam-type power generation is shown in Fig. 5 [3].

When the power generation water volume should meet the current lake water volume and the area between the two lakes, that is, the calculation formula of the storage capacity curve of the two dams is about the relationship between the water area surrounded by the adjacent two contour lines and the water level difference between the water levels.

Storage capacity curve of total water volume and water level P in Lake Powell can be expressed as:

$$M_{powell} = \frac{1}{3}(S_1 + \sqrt{S_1 S_2} + S_2)P, (M_{powell} = \sum_{i=1}^{n=3} x_i) \tag{4}$$

Storage capacity curve of total water volume and water level P in Lake Mead can be expressed as:

$$M_{mead} = \frac{1}{3}(S_2 + \sqrt{S_2 S_3} + S_3)M + x_3, (M_{mead} = \sum_{i=1}^{n=3} y_i) \tag{5}$$

The multivariate dynamic programming model is established, which can be expressed as:

$$\min z = \frac{x_2 \rho g(P - x_3) + y_2 \rho g(M - y_3) - \sum_{i=1}^{n=5} w_i}{\sum_{i=1}^{n=5} w_i} + \frac{x_1 + y_1 - \sum_{i=1}^{n=5} l_i}{\sum_{i=1}^{n=5} l_i} \tag{6}$$

Taking one day as the standard period, when t is less than or equal to one day, means that the two dams have completed the daily discharge and met the needs of five states. When t is greater than 1 day, it means that the daily discharge of the dam cannot meet the needs of the five states, and

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additional water needs to be provided to meet the needs. When the displacement is insufficient, the actual displacement as follows formula:

$$Q_p = \begin{cases} y_1^{'} + 24V_1, t_1 > 24, t_2 < 24 \\ x_1^{'} + 24V_2, t_1 < 24, t_2 > 24 \end{cases} \tag{7}$$

The way of calculating the amount of additional water that needs to be replenished is the amount of discharge required minus the amount that has been discharged, as follows the formula:

$$Q_b = \begin{cases} x_1^{'} - 24V_1, t_1 > 24, t_2 < 24 \\ y_1^{'} - 24V_2, t_1 < 24, t_2 > 24 \end{cases} \tag{8}$$

3. Multi-Objective Programming Model

The purpose of water allocation is to address the competing interests of water availability for general (agricultural, industrial, residential) use and electricity production. To better describe the model, we investigated the data of the ministry of reclamation to obtain the details of water consumption and used MATLAB to make the fitting curves of industrial, agricultural, and residential water demand in five states as a reference for social benefits. Fig. 6 shows the fitted curve for the trends in water demand by state.

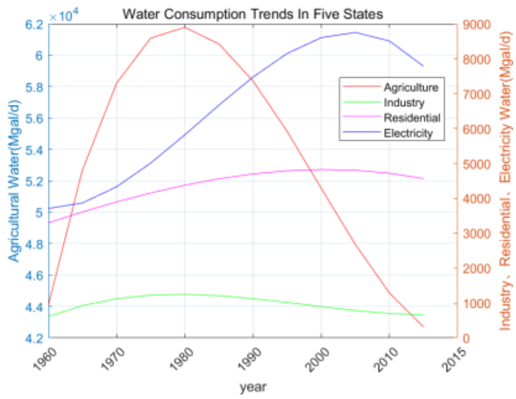

Figure 6. Five state water demand trends

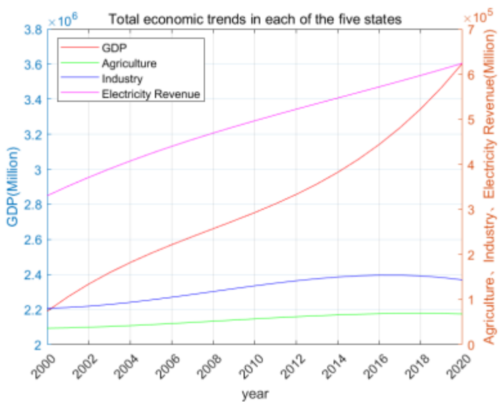

Figure 7. Economic trends in each of the five states

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According to the data of the electric power bureau, the income of agriculture, industry, housing, and electric power industry in five states are obtained [4], and MATLAB is used to make a fitting curve as a reference for economic benefits. Fig. 7 is the fitted curve of the output value of the corresponding industries in each state in recent years.

From Fig. 7, it can be seen that in the past few decades, agricultural water use and power generation water have dominated. The lake's water supply to the five states has shown a hump-like trend over time and has declined in recent years, possibly due to increased demand, reduced river flow, high temperatures, and drought. To solve the basic water demand-supply in each state, we need to allocate resources reasonably.

To determine the specific allocation scheme, it is necessary to use the entropy weight method to determine the target weight of each indicator. The entropy weight method is used to analyze the economic benefit information of the five states' water resources.

To get weights using the entropy weight method, we first need to organize the data. By retrieving data from the Economic Bureau, we obtained the sum of the economic benefits for the four indicators (agriculture, industry, residential, power generation) for five states, as shown in table 1.

Table 1. The sum of the economic benefits of all indicators for five states in five years

Year	Industry	Agriculture	Residential	Electricity production
2020	105455.532	71465.475	3459181.1	629200.213
2019	185992.271	68788.868	3553511.6	598320.461
2018	169467.265	66938.680	3428717.9	600881.144
2017	154891.432	66187.372	3300646.1	586472.898
2016	150432.555	62632.553	3165463.7	560406.719

The standardization formula is as follows:

$$Y_{ij} = \frac{X_{ij} - \min(X_i)}{\max(X_i) - \min(X_i)} \tag{9}$$

According to the definition of information entropy in information theory, the information entropy H_i of a set of data:

$$H_i = -\frac{1}{\ln(n)} \sum_{j=1}^{n} p_{ij} \ln(p_{ij}) \tag{10}$$

where $p_{ij} = Y_{ij} / \sum_{i=1}^{n} Y_i$.

According to the information entropy calculation formula, the information entropy of each index is obtained as shown in table 2.

Table 2. Information entropy of each indicator

	Industry	Agricultural	Residential	Electricity production
Information entropy	0.989853	0.999412	0.999502	0.999564

The formula for calculating the weight of each indicator through information entropy is as follows:

$$W_i = \frac{1-H_i}{\sum_{i=1}^{n}(1-H_i)} \tag{11}$$

The calculation results of the weights of each indicator are as follows in table 3.

Table 3. Final weight of each indicator

	Industry	Agricultural	Residential	Electricity production
Final weight	0.869569	0.050390	0.042677	0.037364

Because water shortage is closely related to social benefits, total water demand is used as an indicator to measure social benefits, which can be expressed as:

$$\max f_1(x) = -\min \sum_{k=1}^{n=5} \sum_{j=1}^{J(k)} \left[D_j - \sum_{i=1}^{I(k)} x_{ij} \right] \tag{12}$$

where D_j is the water supply of the four indicators, and x_{ij} is the water demand of the four indicators.

Calculation method of water equity coefficient:

$$\beta_j = \frac{1+n_{\max}-n_j}{\sum_{i=1}^{I(k)}(1+n_{\max}-n_j)} \tag{13}$$

where n_j represents the serial number of the jth index water in the five states.

Assuming that x_{ij} represents the water supply volume of I water source to j index, according to the water supply volume should be greater than the water demand, the following constraint equation can be obtained.

$$\sum_{i=1}^{n=5} w_i \le \sum_{i=1}^{n=5} \sum_{j=1}^{J(i)} x_{ij} \tag{14}$$

where w_i represents the water demand of the five state.

The water demand of each indicator in the area should have upper and lower limits, from which the following formula can be obtained:

$$N_{\min} \le \sum_{i=1}^{n=5} \sum_{j=1}^{J(i)} x_{ij} \le N_{\max} \tag{15}$$

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where $N_{\min}$ and $N_{\max}$ are the minima and maximum water demand of the I water source and j index.

Summarizing the above objective functions and constraint equations together, the following multi-objective optimal allocation model of water resources is:

$$obj.F(x)=opt\{f_1(x),f_2(x)\}$$
$$=\begin{cases}\max f_1(x)=-\min\sum_{k=1}^{n=5}\sum_{j=1}^{J(k)}\left[D_j-\sum_{i=1}^{I(k)}x_{ij}\right]\\ \max f_2(x)=\max\sum_{k=1}^{n=5}\sum_{j=1}^{J(k)}\sum_{i=1}^{I(k)}(b_{ij}-c_{ij})x_{ij}\beta_j\end{cases} \tag{16}$$

Given a set of water demand and the upper and lower limits of water demand for each indicator, as shown in Table 4.

Table 4. Water demand for each indicator

	Industry	Agricultural	Residential	Electricity production
Demand(water)	724	42673	4567	7498
Maximum demand	1086	64009.5	6850.5	11247
Minimum demand	724	42673	4567	7498

4. Model Compressive Ability Test

To test the model in the state of water scarcity, the simulation here reduces the water supply of the optimal solution by 90%, 75%, and 55% in turn. The calculation formula is as follows:

$$\sum_{i=1}^{n=2}\sum_{j=1}^{n=4}x_{i1}*0.9,\sum_{i=1}^{n=2}\sum_{j=1}^{n=4}x_{i1}*0.75,\sum_{i=1}^{n=2}\sum_{j=1}^{n=4}x_{i1}*0.55 \tag{17}$$

The obtained water supply is compared with the water demand, and then the water shortage $rate$ is calculated. The calculation formula is as follows:

$$rate=\frac{\delta_n-\delta_g}{\delta_n}\times 100\% \tag{18}$$

where δ_n is the demand of each indicator water, δ_g is the supply amount of each indicator water.

Through the analysis of water shortage in table 5, the water demand of each indicator is fixed, and the actual water demand is 641.19 million m3. When the minimum water supply is provided, that is, 55% of the original water is about 637.15 million m3. , the water shortage amounted to 4.04 million m3, thus the water shortage rate was calculated to be 5.85%.

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Table 5. Summary of water resources allocation results for each indicator

Guaranteed rate	Sub Option	Industry	Agriculture	Electricity	Residential	Total
90%	water distribution	871	50511	4816	8428	64626
	water demand	889	49753	4938	8539	64119
	water shortage	18	0	122	111	251
	Water scarcity rate(%)	2.02	0	2.47	1.30	5.80
75%	water distribution	869	49560	4813	8431	63672
	water demand	889	49753	4938	8539	64119
	water shortage	21	194	125	108	447
	water scarcity rate(%)	2.31	0.39	2.53	1.26	6.49
55%	water distribution	874	49601	4811	8429	63715
	water demand	889	49753	4938	8539	64119
	water shortage	15	152	127	110	404
	water scarcity rate(%)	1.69	0.31	2.57	1.29	5.85

5. Conclusion

This paper according to the relationship between the Glen Canyon Dam and the Hoover Dam proposes a solution for the rational distribution of water and electricity for agriculture, industry, and more in the five states around the basin. When the demand to be met by the five states is fixed, only the relationship between the Glen Canyon Dam and the Hoover Dam needs to be adjusted to meet the prescribed demand. When the fixed resources do not belong to the supply of the factors between the two dams, the time to satisfy the fixed demand after the fixed demand is eliminated is related to the discharge volume of the two dams. The distribution of water used in agriculture, industry, housing, and power production can be reasonably distributed by comprehensively weighing the amount of use and the benefits it brings.

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