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Water resource scheduling scheme based on multi-objective programming

Summary

How to utilize the limited water resources to achieve reasonable water resource dispatching is always a difficult problem to be solved. In this paper, the optimal scheme of water resource scheduling is formulated by establishing a water resource scheduling model and using computer simulation method.

First of all, in order to satisfy the demand of state regulations, based on the least total water supply planning target, whether each lake water as 0-1 decision variables, to the states of the water, electricity demand as constraint conditions, nonlinear 0-1 programming model is established, and the optimal allocation of water resources is obtained by Monte Carlo simulation, the specific results are shown in Table 5 . Water consumption is different in different seasons. This paper takes the minimum gap between supply and demand as the planning objective and takes the frequency of water supply in each state in each season as the integer decision variable to establish an integer programming model, so as to obtain the frequency of water supply in each state in different seasons, see Table 7 and Table 8 for the specific results .When the water supply from dams and reservoirs is reduced, the additional water supply is added to the above model to meet the specified demand, thus obtaining the additional water supply required by each state. The specific results are shown in the Table 10.

Secondly, in order to allocate water resources reasonably to each industry, this paper takes the profit maximization under a certain amount of water consumption in five states as the optimization objective, and establishes the optimal model of economic benefits of water consumption under the constraint of balance between supply and demand. For the convenience of calculation, a two-level hierarchical multi-objective optimization model is established based on the decomposition and coordination technique of large system optimization. With various industries to achieve benefits, the objective function is minimum deviation, considering that the proportion of investment states different industries caused by water resources allocation priority is different, here introduced priority of variables in the objective function, at the same time in various industries as far as possible to achieve benefits as constraint conditions, multi-objective hierarchical planning model is established. The dynamic programming algorithm is used to solve the formula (5-13), that is, the competing interests of different industries for water on different continents.

Then, in the case of insufficient water supply, with the optimization objective of maximizing the economic benefits brought by each industry, monte Carlo simulation is used to solve the problems of normal water supply and insufficient water supply respectively. The specific results are shown in Figure 8 and Figure 9 . Results by comparison, it is found that under the condition of insufficient water resources allocation, the total GDP decreases by about 13%, indicating that the model is effective, and puts forward the coping strategies of each industry.

Finally, the sensitivity of the model is analyzed. When industries in each region grow or shrink, variable α is introduced to change the water resource demand of each industry in the 6.2 model. After optimization, the growth of each industry is positively correlated with the water consumption of the reservoir. When the proportion of renewable energy increases, the introduced variable γ represents the increase value of the actual additional water supply in model 4.4. After optimization, the increase of the proportion of renewable energy is negatively correlated with the water consumption of the reservoir. When the proportion of water saving increases, the variable ε is introduced to reduce the supply of water resources in model 4.1 to achieve the effect of water resource saving. After optimization, the water resource saving is negatively correlated with the water consumption of the reservoir.

Keywords: water resource scheduling; Nonlinear programming; Second-order multi-objective optimization; Monte Carlo simulation

Contents

1 Introduction

1.1 Problem Background

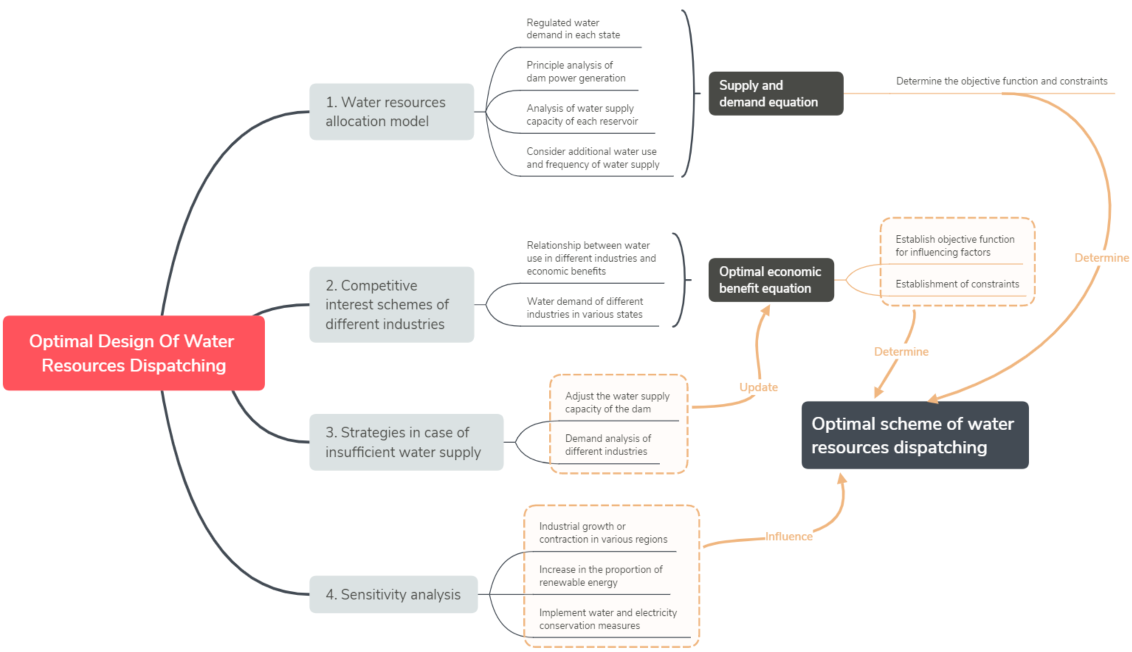
For centuries, reservoirs have been built on rivers and streams as a means of managing water supply. These reservoirs are used to store water for various purposes, provide an area for leisure and entertainment, help prevent downstream floods, and meet people's electricity needs by providing water to power generating turbines. With climate change, the amount of water from dams and reservoirs is gradually decreasing in many areas. If the drought continues, the amount of water will not be enough to meet the basic water and power generation needs of stakeholders. Therefore, it is very important to formulate a reasonable water resource allocation plan for the current and future water supply conditions.

1.2 Restatement of the Problem

Considering the background information and restricted conditions identified in the problem statement, we need to solve the following problems:

- Problem 1: The problem is divided into three parts. First, establish a water resource allocation plan to meet the water and power needs of five states by transferring the water of Lake Mead and Lake Powell; Second, when the demand is fixed, when no additional water is provided, how long will it take to meet the demand of each state; Finally, how much additional water must be supplied over time to ensure that these fixed needs are met.
- Problem 2: For the water resources supplied, each state is provided with an allocation scheme to solve the availability of water resources for general use and power production.
- Problem 3: When there is not enough water to meet all water and power needs due to external factors, provide a solution to solve the corresponding problems.
- Problem 4: Bring the model into the following three situations: when each industry grows or shrinks, when the proportion of renewable energy technology increases, and implement more water-saving measures
- Problem 5: The results of the study are presented to the journal drought in the form of papers

1.3 Our Work



• According to the water supply of the two lakes, on the one hand, power generation water, the demand equation of dam water demand is established. On the other hand, general water use, whether to choose each lake to supply water to each state is a 0-1 decision variable, with the minimum total water supply as the planning goal. Each state must meet the constraints of generating water, general water and the maximum water withdrawal from the lake. A nonlinear programming model is established here to determine the optimal water resource allocation scheme using Monte Carlo simulation. Aiming at the problem of system restart frequency, the power generation water can be converted into the required time through the physical relationship to obtain the restart frequency of power generation water system in different seasons. In the same way, the frequency of water supply in different seasons can be obtained according to the water supply and demand of DAMS. In view of the need for additional water supply, through rainfall probability, rainfall and groundwater as additional water sources, on the basis of the original introduction of additional water supply, that is, to ensure that under the minimum water supply, additional water supply can also achieve the minimum.

• Due to the conflict between power generation and water use, the objective function to be optimized in this paper is to maximize the profits of these five states under a certain amount of water use. Set up sub-regions, give priority ranking to each sub-region through data, then get local optimization solution for each sub-region, and feedback the results. If the optimal solution is not reached, the pre-score values of each sub-region are redistributed. In this way, the overall optimal solution of the economic zone is reached. Getting the optimal solution is a kind of relation and visualizing the relation. Right to Mexico and the Gulf of California quantifying the economics of water resources in conjunction with the agreement between the U.S. government and the Mexican government and the current state water use, compensation to Mexico.

• Water shortage, how to coordinate to minimize the loss. Assume that water supplies are only 0.7 times normal. Moreover, each state can appropriately convert water consumption and economic output value of water consumption. When water resources are less than normal supply, the economic maximum equation of objective function should be established, and the relationship between water consumption in all aspects of each state and economic output value of water consumption, and the limitation of water consumption in each state should be taken as constraint conditions. MATLAB was used to solve nonlinear programming to get the proportion of water used in each direction of each state. The histogram was compared with the normal supply situation. In the direction with the least reduction of proportion, that is, in the case of less the same water, giving water resources can get higher economic capacity. Under the condition of water shortage, the optimal distribution situation is obtained, and targeted suggestions are put forward to each direction of the states.

• When industries in each region grow or shrink, variables are introduced to change the demand for water resources of each industry in the above model, so as to observe the change relationship between the growth of each industry and the water consumption of reservoirs. When the proportion of renewable energy increases, the increment value of the actual additional water supply in the model established in this paper is introduced to observe the relationship between the increase of the proportion of renewable energy and the water consumption of the reservoir. When the proportion of water saved increases, variable ε is introduced to reduce the supply of water resources in the model established in this paper to achieve the effect of water resources saved, and to observe the relationship between water resources saved and water consumption of reservoirs.

2 Assumptions and Justifications

Assumption 1：The conversion function between water resources and economic

capacity of water resources in various states is more appropriate to real life.

Justification: Since considering the best competitive interests requires economic production of energy, the problem is that the distribution of water resources in different directions maximizes the economy, There are different relations between water resources and economic productivity in different directions, but they can always be expressed by functions[7].If this function can be more appropriate to the water resources and economic capacity of water resources in real life, the target optimization can be better carried out, and the final result is the most consistent with real life.

Assumption 2：The five states get most of their water from two lakes.

Justification: The data obtained in water resource allocation is the basic amount of water used in all directions in the five states, while the water resources in the lake mainly flow into the five states through rivers and groundwater. If the water used in the five states also comes from other sources, the model used for these data will result in low results and the constraints will be reduced in the optimization process. If the hypothesis is true, it can highlight the allocation of water resources, competitive interests and water resources in the problem.

3 Notations

The key mathematical notations used in this paper are listed in Table 1.

Table 1: Notations used in this paper

Symbol	Description	Unit
N_{pe}	The amount of water used by glen Canyon Dam to generate electricity	Mm^3
N_{me}	The amount of water the Hoover Dam uses to generate electricity	Mm^3
N_{pw}	Glen Canyon Dam for domestic and other purposes	Mm^3
N_{mw}	Hoover Dam for domestic and other purposes	Mm^3
x_i， x_j	Glen Canyon Dam, hoover Dam supplies water to five states	
P_{Xi}	The amount of water each state needs for each week	Mm^3
Δ_p , Δ_m	The proportion of water supplied by the two lakes to each state	
α	Water supply attenuation coefficient	
θ	Shortage factor	
N_o	Additional water supply	Mm^3
C_k	Net output coefficient vector of n water industries in K State	
d_k^-， d_k^+	Negative, positive deviation variable	
X_{ki}	Gross industrial output	
w_j	Water efficiency by industry	

4 Water resource allocation model

4.1 Data Analysis

Due to the lack of data of each state, the water use of each state is collected through reference [1], as shown in Table 2:

Table 2: Water use by States

State name	*Residential consumption/ML*	*Industrial consumption/ ML*	*Agricultural consumption/ ML*	*Total consumption/ ML*	*Average monthly consumption/ ML*
AZ	2370.3	194.9	26555.5	29120.7	2426.7

CA	10532.3	21416.7	93153.8	125102.9	10425.2
CO	2781.6	569.9	64124.3	67475.8	5623.0
NM	296.3	272.9	13971.8	14541.0	1211.7
WY	177.3	433.6	27573.2	28184.2	2348.7

The table above shows the water consumption of each continent. The change of water consumption caused by climate is ignored, and the level analysis method mentioned in the time series index analysis in literature [2] is combined to process the annual water consumption and obtain the average monthly water consumption of each state, the key data supporting the establishment of the model. It is not difficult to find from the data that California has a large demand for water, while New Mexico has a small demand for water. In the absence of the specific amount of water that the reservoir sends to each state, the monthly water consumption is taken as the basic water demand of each state

In terms of electricity demand, hydropower accounts for a relatively small proportion in the power supply of each state, and the actual annual electricity demand of each state cannot reflect the electricity production situation of Glen Canyon and Hoover Dam. When the water quantity decreases, the electricity generated by the dam will decrease. In order to ensure the basic electricity demand of each state, Here, the average annual output of the dam under sufficient water is used as an indicator to measure the amount of water required for power generation.

4.2 Establishment and solution of water resource allocation model

- **4.2.1 Establishment of water supply model**

There are two main requirements for DAMS for states: basic water needs and basic electricity needs. Here it is divided into two parts：

1. Basic electricity demand：

Hydroelectric power generation is a way of making use of the water flow with potential energy at high places such as rivers and lakes to lower places, converting the potential energy contained therein into the kinetic energy of the turbine, and then using the turbine as the prime force to drive the generator to produce electric energy. Figure 2 is the schematic diagram of hydroelectric power generation：

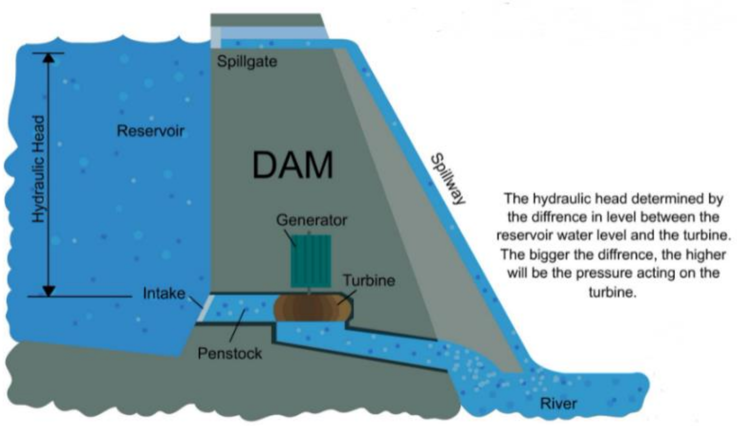


Figure 2: Geographical distribution of dam

First of all, only 70% of the water in the dam flows downstream [3] after it flows upstream。In order to ensure that the dam can reach the annual average power generation under the condition of water shortage, the dam flow is calculated to meet the needs of each state through the power generation of the dam, Combined with reference [3] and corresponding physical knowledge, the amount of water used for power generation of Glen Canyon Dam can be obtainedN_{pe}, And the amount of water the Hoover Dam uses to generate electricityN_{me}:

$$N_{pe} = \frac{n_p}{kH_p} t \qquad (4-1)$$

$$N_{me} = \frac{n_m}{kH_m} t \qquad (4-2)$$

Where, n_p is the power generation of Glen Canyon Dam, n_m is the power generation of Hoover Dam, k is the output coefficient, H_p is the drop of Glen Canyon Dam, H_m is the drop of Hoover Dam. By referring to references [4] and related materials, we can get:

Table 3: Value of *k*

	Large hydropower station N >25 MW	Medium sized hydropower station 25 MW > N >2.5 MW	Small hydropower station
Value of k	8.5	8.0	7.0~6.0

Therefore, the output coefficient k selected here is: 8.5, and the above data can be obtained by substituting:

$$N_{pe} = 736.28t \qquad (4-3)$$

$$N_{me} = 1526.46t \qquad (4-4)$$

2. Basic water needs:

The Colorado River is a river in the southwest United States and northwest Mexico. Most of the entire Colorado River system empties into the Gulf of California, while another part flows south to Mexico. Details are shown in Figure 2 and 3:

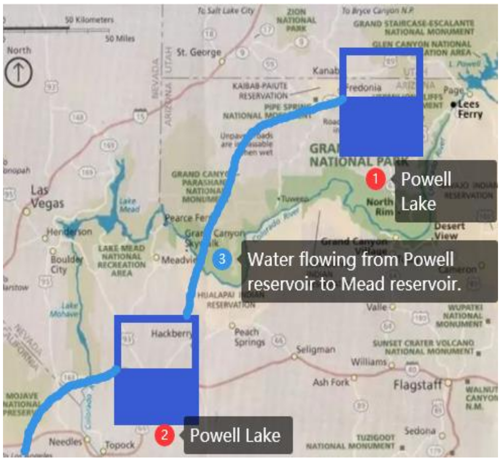


Figure 2: Geographical distribution of dam

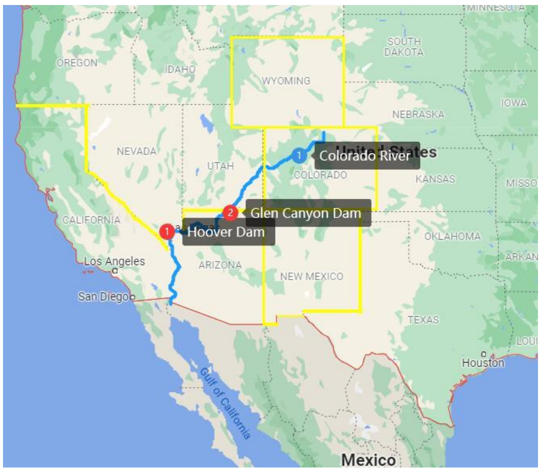


Figure 3: Distribution of states

Is not hard to find the river starts from the glen canyon dam and upstream area, partly by the hoover dam, into the gulf of California and Mexico, the whole river through the five states of water required, so for the five states, no matter from the lake Powell or lake mead transferred water, as long as meet the basic demand. The water consumption of glen Canyon Dam for domestic and other purposes is assumed to be N_{pw},Hoover Dam's water consumption for domestic and other purposes is N_{mw},so:

$$N_{mw} = \sum_{j=1}^{5} x_j * P_j \qquad (4-5)$$

$$N_{pw} = \sum_{i=1}^{5} x_i * P_i \qquad (4-6)$$

Where x_i and $x_j$respectively represent whether Glenn canyon dam and hoover dam supply water to five states （x_i，x_j={0，1}），while P_i and P_j respectively represent the water supply of Glenn canyon dam and hoover dam to five states.

The total water supply N can be obtained by combining the basic water demand and the basic electricity demand：

$$N = N_{mw} + N_{pw} + N_{pe} + N_{me} \qquad (4-7)$$

- **4.2.2 Establishment of optimization model**

Since the drought in the Colorado River will continue, the minimum water supply shall be ensured when all specified demands are met. Therefore, the optimization objective of the minimum total water supply is adopted here, namely:

$$min \;\; N = N_{mw} + N_{pw} + N_{pe} + N_{me}$$

It is important to note that Lake Powell does not supply the dam with water from any other basin. It is the equivalent of an artificial lake created by the Glen Canyon Dam, and the water supply means increasing the dam's capacity to meet the needs of five states, as does Lake Mead. So for the supply of water to Lake Powell he should be able to supply more water than five states need for the Glen Canyon dam，so：

$$0 \le N_{pe} + N_{pw} \le 0.3 * p * S_p \qquad (4-8)$$

Where, p is the original water level of Lake Powell, and S_p is the area of Lake Powell. Since it is impossible for the dam to transfer all the water to the downstream or use it for power generation, the water output should be 0.3 times the original capacity of Lake Powell by querying the lowest water level of the dam.

In the case of Hoover Dam, the water source is not only the supply from Lake Mead but also the water flowing from Glen Canyon Dam, which can be considered to be used for power generation, and only 70% of the water is transferred downstream and to Hoover Dam. So the hoover Dam's water supply should take into account the water that flows through glen Canyon Dam:

$$0.7 * N_{pe} \le N_{me} + N_{mw} \le m * S_m + 0.7 * N_{pe} \qquad (4-9)$$

Where p is the original water level of Lake Mead and S_p is the area of Lake Mead. Referring to the lowest water level of Hoover Dam, the water yield should be 0.3 times the original capacity of Lake Powell. And $0.7 * N_{mw}$ is the water flowing to Mexico and the Gulf of California.

For five states, water supply should exceed demand:

$$P_{Xi} \le \sum_{i=1}^{5} x_i * P_i + \sum_{j=1}^{5} x_j * m_j \le 1.1 P_{Xi} \;\; (i = 1\sim5, j = 1\sim5) \qquad (4-10)$$

P_{Xi} is the water quantity required by each state in each week.

To sum up, the sum model is

$$min \quad N = N_{mw} + N_{pw} + N_{pe} + N_{me}$$

$$
s.t.\begin{cases} 0 \le N_{pe} + N_{pw} \le 0.3 * p * S_p \\ 0.7 * N_{pe} \le N_{me} + N_{mw} \le m * S_m + 0.7 * N_{pe} \\ P_{Xi} \le \sum_{i=1}^{5} x_i * P_i + \sum_{j=1}^{5} x_j * m_j \le 1.1 P_{Xi} (i = 1\sim5, j = 1\sim5) \\ x_i,\ x_j = \{0,\ 1\} \end{cases} \qquad (4-11)
$$

➢ **4.2.3 Solution of optimization model**

This model belongs to nonlinear integer programming, so it is difficult to directly calculate the minimum value of the objective function. Here, MATLAB is used to solve the objective function using Monte Carlo simulation, as shown in the algorithm flow chart 4:

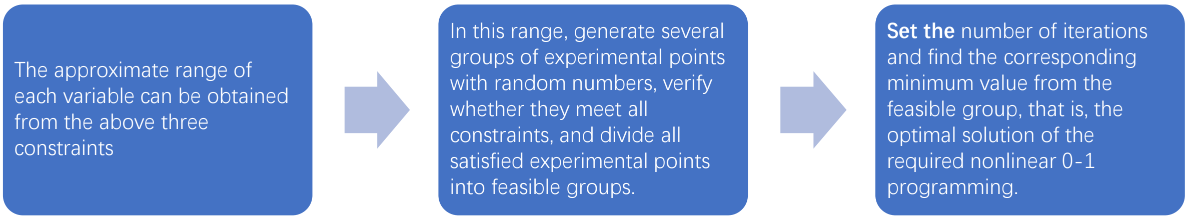


Figure 4: Calculation process

According to the above process, formula (4-11) can be solved and it can be obtained that when the minimum water supply is met, the total water supply of the two lakes is N= 3421.4Mm^3, and the water supply of each lake to each state is as follows:

Table 4: Results of water supply from lakes to States

	AZ	*CA*	*CO*	*NM*	*WY*
Powell Lake/ Mm^3	564.23	0.00	620.58	0.00	0.00
Mead Lake/ Mm^3	0.00	1058.58	0.00	516.43	661.62

Table 4 shows the water supply of each lake to each state. Considering that the required data is water level data, the data is processed here. According to Wikipedia, the water level of Lake Mead is 200 m and the area of lake mead is 65 Mm^2; the water level of Lake Powell is 68m and the area of the lake is 593 Mm^2. After calculation, the water level proportion of the two lakes supplied by each state can be obtained, as shown in Table 5 (p is the original water level of Lake Powell, m is the original water level of Lake Miller).

Table 5: Proportion of water level supply

	AZ	*CA*	*CO*	*NM*	*WY*
Powell Lake	0. 12*P*	0. 00	0. 13 *P*	0. 00	0. 00
Mead Lake	0. 00	0. 03 *M*	0. 00	0. 01 *M*	0. 02M

4.3 Establishment and solution of the "Time to meet demand" model

Consider that the prescribed needs fall into two categories: basic water needs and power generation needs. Electricity generation is mainly generated when turbines convert the potential energy of falling or fast-flowing water into mechanical energy, while basic water demand is more concerned with water resource scheduling. Therefore, this paper establishes models respectively for two different needs to solve the "time to meet the needs".

➢ **4.3.1 The establishment and solution of the "Generation demand time" model**

The demand for power for the five states is large, so the dam needs to be supplied multiple times and at different frequencies for different seasons. Table 6 shows the demand of five continents in four seasons, which is obtained through reference [1].

Table 6: Water used for power generation in different seasons in 5 states

	AZ	CA	CO	NM	WY
Spring/Mm^3 3	896	933.2	419.2	211.2	270.4
Summer/Mm^3	1671	1842.2	704.4	513.4	602.2
Autumn/Mm^3	1128.2	1212.2	330.4	228.4	305.2
Winter/Mm^3	386.4	444.2	237.4	51.2	224

Hydraulic power generation is a process in which potential energy is converted into kinetic energy by water flowing through turbine blades, which can be converted from the velocity of dam power generation water and the total electricity demand mentioned above, which can be obtained based on reference [3] and relevant physical knowledge：

$$E = \gamma * Q * H \quad (4-12)$$

In the formula, E represents the electric energy generated by the two DAMS, γ represents the energy conversion coefficient, Q represents the flow rate of water, and H represents the height of the dam. According to the total power generation of each state and the above process, formula (4-12) can be solved and Q=1920 m^3/s

Then, according to the relationship between the total amount and the flow rate, the power generation time required by each state in each season is obtained, and the power generation frequency of each state in each season is obtained by making the power generation time every 10 hours. The specific results are shown in Table 7.

Table 7: Frequency table for each season in each state

Season	AZ	CA	CO	NM	WY
Spring	13	14	6	3	4
Summer	24	26	10	8	9
Autumn	16	18	5	4	5
Winter	6	7	4	1	4

➢ 4.3.2 Establishment and solution of "basic water demand time" model

Modeling:

Taking into account that the demand for each continent is different in different seasons, only a certain amount of water can be supplied at a time according to the 4.2 model. Therefore, we need to consider how to run the model according to the frequency of different demands, so as to obtain the time to meet the demand.

$$\sum_{i=1}^{4}\sum_{j=1}^{5} \alpha * n_{ij} * \theta * f_{ij} = S \quad (4-13)$$

In Formula (4-15), the total water supply of S; n_{ij} represents the ith season and the jTH continent represents the water supply (which can be calculated using the model in 4.2); f_{ij} represents the frequency with which the ith season and jTH continent need to meet the requirements to run the model (f_{ij} will be solved as a decision variable in the planning equation). α represents the attenuation coefficient of water supply. The reason for setting this variable is that n_{ij} solves the water supply in each season. According to the reality, it is impossible to supply such a large amount of water at one time to meet the demand, so it is multiplied by an attenuation coefficient, according to literature [4], α is usually 0.1~0.4. So $\alpha \cdot n_{ij}$ represents the amount of water supply in the ith season and the jTH continent running the model once.

Considering the frequency of water supply and the amount of water supplied by running the model once, the difference between water supply and demand is expected to be as small as possible. Therefore, the model is established with the optimization goal of minimizing the difference between water supply and demand:

$$min \ \ X = R - S$$

$$s.t.\begin{cases} \sum_{i=1}^{4}\sum_{j=1}^{5} \alpha * n_{ij} * \theta * f_{ij} = S \\ 0.1 \le \alpha \le 0.4 \end{cases} \tag{4-14}$$

Where X represents the difference between supply and demand and R represents the demand.

Firstly, n_{ij} was solved by substituting the model in 4.2 for the different demand of each continent in each season. Then, this model was substituted into Matlab and monte Carlo simulation was used to solve α, as well as the water supply frequency of each continent in each season, namely, "the time to meet the basic water demand". The specific results are shown in Table 8

Table 8: Table of water supply frequency of each season in each state

	AZ	CA	CO	NM	WY
Spring	9	10	7	4	6
Summer	15	17	9	11	13
Autumn	11	10	4	5	6
Winter	7	6	3	2	7

4.4 Improvement and solution of water resource allocation model

In the ideal case without considering additional water supply, the water resource allocation model established above can well meet the water and electricity demand of each state. In practice, however, due to natural factors such as drought, it is likely that the amount of water and electricity generated by DAMS will not be able to meet the basic requirements of the states without additional supplies from outside, so additional supplies from outside will be necessary.

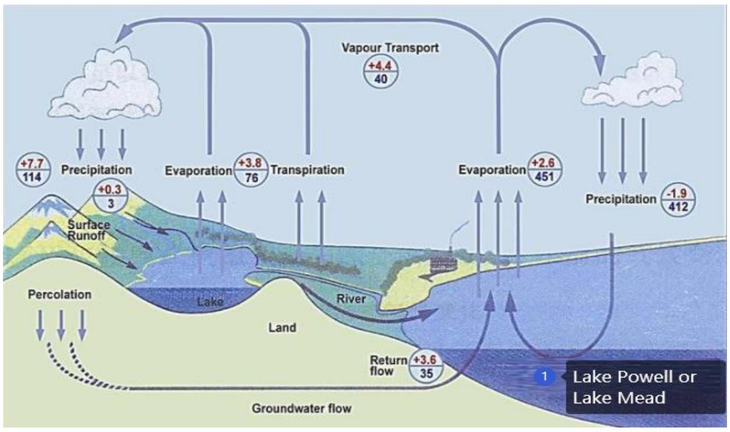


Figure 5: Water supply mode

Combined with Figure 5, water sources can be viewed in three ways: groundwater, precipitation, and inflow of upstream river water. These three types are collectively referred to as additional water supply N_o.

➢ **4.4.1 Improvement of water supply model**

In general, the improvement of the model in 4.2 is to consider the impact of additional water supply N_o.

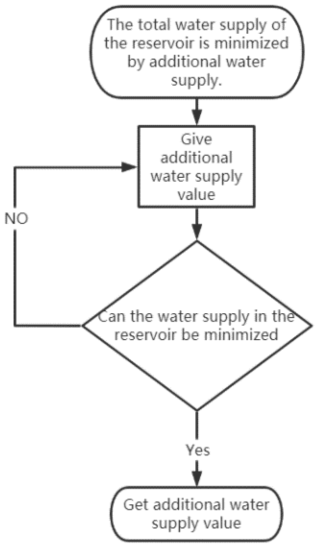


Figure 6: Summary of improvement ideas

For the improved model, the objective of this optimization is still the minimum water supply, and here, on the basis of the original, there is an additional water supply. That is, with the minimum water supply, additional water supply can be minimized:

$$\min\ N = N_{mw} + N_{pw} + N_{pe} + N_{me} + N_o \tag{4-15}$$

For glen Canyon Dam, the water comes not only from the supply of Lake Powell but also in part from the additional supply of Lake Powell and the surrounding area N_{op}

$$N_{pe} + \sum_{i=1}^{5} x_i * P_i \leq 0.3 * p * S_p + N_{op} \tag{4-16}$$

The hoover Dam is similarly supplied not only by Lake Miller and part of glen Canyon Dam, but also by Lake Miller and the surrounding areas along the way N_{om}

$$0.7 * N_{pe} \leq N_{me} + \sum_{j=1}^{5} x_j * P_j \leq 0.7 * N_{pe} + 0.3 * m * S_m + N_{om} \tag{4-17}$$

For the total water supply should also consider the states the situation of the additional water near here expressed in $N_{o1} \sim N_{o5}$ states of additional water supply, and the additional part of total water amount from the five continents as part of additional water from directly by the outside world means to five states water supply, so the water value should be greater than two the additional water of the lake, namely:

$$P_{Xi} \leq \sum_{i=1}^{5} x_i * P_i + \sum_{j=1}^{5} x_j * m_j + \sum_{i=1}^{5} N_{Oi} \leq 1.1 P_{Xi} (i = 1 \sim 5, j = 1 \sim 5) \tag{4-18}$$

$$\sum_{i=1}^{5} N_{Oi} \geq N_{om} + N_{op} \tag{4-19}$$

$$\sum_{i=1}^{5} N_{Oi} = N_o \tag{4-20}$$

To sum up, the total mathematical model is

$$min\ \ N = N_{mw} + N_{pw} + N_{pe} + N_{me} + N_o$$

$$s.t.\begin{cases} N_{pe} + \sum_{i=1}^{5} x_i * P_i \le 0.3 * p * S_p + N_{op} \\ 0.7 * N_{pe} \le N_{me} + \sum_{j=1}^{5} x_j * P_j \le 0.7 * N_{pe} + 0.3 * m * S_m + N_{om} \\ P_{Xi} \le \sum_{i=1}^{5} x_i * P_i + \sum_{j=1}^{5} x_j * m_j + \sum_{i=1}^{5} N_{Oi} \le 1.1 P_{Xi} (i = 1\sim5, j = 1\sim5) \\ \sum_{i=1}^{5} N_{Oi} \ge N_{om} + N_{op} \\ \sum_{i=1}^{5} N_{Oi} = N_o \\ x_i,\ \ x_j = \{0,\ \ 1\} \end{cases} \quad (4-21)$$

- **4.4.2 Solution of water supply model**

Through 4.2.3 solution and data processing, the following data are finally obtained, in which Table 9 is the water level proportion of the amount of water needed by Lake Powell and Miller Lake after the addition of additional water supply, and Table 10 is the necessary additional water supply:

Table 9: Proportion of water level

	AZ	CA	CO	NM	WY
Powell Lake	0.8p	0.00	0.09p	0.00	0.00
Mead Lake	0.00	0.02m	0.00	0.01m	0.015m

Table 10: Additional water supply

	AZ	CA	CO	NM	WY	Total
$N_o/\ Mm^3$	304.9	191.5	383.9	66.9	80.7	1027.9

5 Competitive interest schemes of different industries

5.1 Establishment of model

When water resources meet the basic water and electricity needs of each state, how to allocate these resources to various industries is another big problem that each state needs to solve. I'm going to ignore the water and electricity resources here except for the Glen Canyon Dam and the Hoover Dam, and only consider the supply from two DAMS. For the different resource needs of different industries, the limited resources can be rationally used on the premise of fixed resource quantity, with the goal of promoting the coordinated economic development of each state and obtaining as much comprehensive benefit as possible.

Here, the five states are represented as k ($k \in (1,5)$), and there is no definition of specific state between 1 and 5). It is assumed that the indicators of various industries in each state are known.

$$max\ Z = \sum_{k=1}^{5} C_k * X_k \qquad (5-1)$$

Where, C_k is the coefficient vector of net output value of n water use industries in k state, X_k is the amount of water resources consumed per unit product of each water-using industry in k state, so the objective function to be optimized is to maximize profit Z of these 5 states under a certain amount of water use

$$A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + A_5X_5 = a \qquad (5-2)$$

$$\begin{cases} B_1X_1 & & = Q_1 \\ & \ddots & \vdots \\ & B_5X_5 & = Q_5 \end{cases} \qquad (5-3)$$

Where, A_k and B_k are respectively the water resource consumption per unit product of each water consumption industry in 5 states and the row vector of water resource quantity coefficient in this region, namely the water consumption quota of each water consumption industry.

$$\sum_{k=1}^{5} P_k * X_k \le G_j + b_j \qquad (5-4)$$

Where G_j is the i (i =1,2... M) the ownership of various public resources (energy, capital, materials, etc.), b_j is the possible total supply of resource i in five states.P_k is the coefficient matrix of resource i required by the j-th industry to produce unit product in k state. Then the capital constraint is that the consumption of producing a certain resource is equal to the supply of corresponding public resource.

Water demand constraint:

$$D_k^U \ge X_k \ge D_k^L \qquad (5-5)$$

D_k^U and D_k^L are the maximum and minimum water consumption stipulated by each industry, that is, the upper and lower limits of the planned water consumption index of each industry

$$X_k \in R_k \qquad (5-6)$$

$$X_k \ge 0 \qquad (5-7)$$

The economic optimization model is:

$$max\ Z = \sum_{k=1}^{5} C_k * X_k$$

$$s.t.\begin{cases} A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + A_5X_5 = a \\ \begin{cases} B_1X_1 & & = Q_1 \\ & \ddots & \vdots \\ & B_5X_5 & = Q_5 \end{cases} \\ \sum_{k=1}^{5} P_k * X_k \le G_j + b_j \\ D_k^U \ge X_k \ge D_k^L \\ X_k \in R_k \\ X_k \ge 0 \end{cases} \qquad (5-8)$$

It is worth noting here that the above optimization model optimizes the allocation of water resources in the case of economic maximization. However, the above planning model is not only relatively large in scale, but also complicated due to the coupling constraints of each sub-region (Equations (5-2) and (5-4)). In order to simplify the operation, according to the decomposition and coordination technology of large-scale system optimization [5], a two-level hierarchical multi-objective optimization model is established as shown in Figure 7.

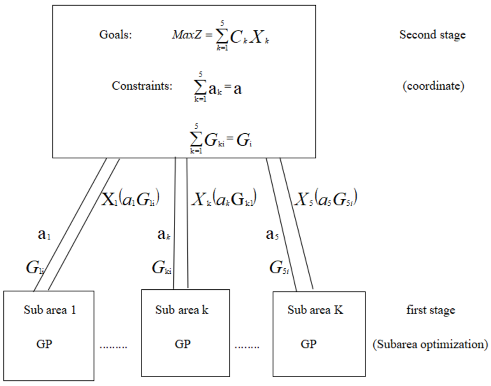


Figure 7: Two-level hierarchical multi-objective optimization model

The first level is divided into k sub-areas according to the state, which is based on the premise of the pre-score value of the shared resources given at the second level: $\sum_{k=1}^{5} a_k = a$, $\sum_{k=1}^{5} G_{ik} = G_j$, the optimization of each sub-area is carried out, and the target programming method in the multi-objective optimization technology is adopted.

The goal planning model for state K is as follows：

$$min\ F_k = p_1(d_{k1}^- + d_{k1}^+) + p_2(d_{k2}^- + d_{k2}^+) + p_3(d_{k3}^- + d_{k3}^+) + p_4(d_{k4}^- + d_{k4}^+) \qquad (5-9)$$

$p_N(N = 1,2,3,4)$ is the priority of each object, divided by its relative importance, and $p_N \gg p_{N+1}$. Note here is for states to each state for the proportion of investment of agriculture, industry and other industries is different, so different states of water resources allocation for each state priority is not the same, it needs to be combined with the actual situation to differentiate different state industry priority, the priority will be divided into concrete is given in the process of solving the model. In goal programming, d_k^-， d_k^+ are called negative and positive deviation variables respectively (both are non-negative variables). Since the decision value cannot be both above and below the target value, at least one of d_k^-， d_k^+ is 0. For this state, how to minimize the deviation under reasonable resource allocation is a problem that needs to be solved in the two-level optimization model.

$$s.t.\begin{cases} \text{Power production value} & X_{k1} + d_{ka}^- - d_{ka}^+ = E_k \\ \text{Total agricultural output value} & X_{k2} + d_{kb}^- - d_{kb}^+ = A_k \\ \text{Gross industrial output value} & X_{k3} + d_{kc}^- - d_{kc}^+ = I_k \\ \text{Residential water consumption} & \frac{1}{\rho_k} X_{k4} + d_{kd}^- - d_{kd}^+ = W_k \end{cases} \qquad (5-10)$$

Where X_{kj} is the output value or output of the j-th industry in the k-th state. Then for the power, agriculture and industrial production values, the output value of the power production part of the state plus or minus the deviation is the planned target value; As for the income X_{k4} obtained by the government for residential water, in order to unify the units of constraint conditions, ρ_k is introduced here, and ρ_k is the price of domestic water in k state. Then, the amount of domestic water consumption can be obtained by dividing the income by the price, and the deviation added or subtracted is the planned target value W_k

The second-order optimization equation is：

$$\min\ F_k = p_1(d_{k1}^- + d_{k1}^+) + p_2(d_{k2}^- + d_{k2}^+) + p_3(d_{k3}^- + d_{k3}^+) + p_4(d_{k4}^- + d_{k4}^+)$$

$$s.t.\begin{cases} \text{Power production value} \quad X_{k1} + d_{ka}^- - d_{ka}^+ = E_k \\ \text{Total agricultural output value } X_{k2} + d_{kb}^- - d_{kb}^+ = A_k \\ \text{Gross industrial output value } X_{k3} + d_{kc}^- - d_{kc}^+ = I_k \\ \text{Residential water consumption } \dfrac{1}{\rho_k} X_{k4} + d_{kd}^- - d_{kd}^+ = W_k \end{cases} \quad (5-11)$$

$$s.t.\begin{cases} \sum_{j=1}^{4} g_{ij}^k * X_{kj} \le b_{ki} + b_{kj} \\ X_k \in R_k \\ X_k \ge 0 \end{cases}$$

5.2 Solution of model

• Step1：Prioritize the continents for different types of water use：

Since the demand for water in agriculture, industry, housing and electricity is different in five continents, the model is solved based on the different demand for water in different continents. That is, according to the demand status of different continents, different fields are divided into priority. According to the model in 5.1, $p_N(N = 1,2,3,4)$ represents priority, and $p_N \gg p_{N+1}$. The specific results are shown in Table 11

Table 11: Priorities for different water use types for different state

State name	*Residential*	*Industrial*	*Agricultural*	*Electricity*
AZ	p_3	p_4	p_2	p_1
CA	p_4	p_3	p_1	p_2
CO	p_4	p_3	p_2	p_1
NM	p_3	p_4	p_2	p_1
WY	p_3	p_4	p_2	p_1

• Step2：Solution of model

As the solving process of multi-level objective programming is complex, dynamic programming algorithm is used to substitute the model into MATLAB for solving. The specific process is as follows:

The local optimization solution X_k obtained by each sub-region at the first level is the a_k, G_k functions of the pre-partitioning value of common resources, but it is not necessarily the optimal solution, which needs to be feedback to the second-level coordination.

The second level of coordination is to obtain the optimal allocation of public resources in each sub-area, that is, to satisfy:

$$\max Z = \sum_{k=1}^{5} C_k X_k$$

$$s.t.\begin{cases} \sum_{k=1}^{5} a_k = a \\ \sum_{k=1}^{5} G_{ki} = G_i \end{cases} \quad (5-12)$$

If the optimal solution is not reached, the pre-score values of public resources in their respective regions are adjusted to continue the optimization of each sub-region at the first level, and then feedback to the second level. This repeatedly iteration, coordination, optimization, until the economic zone to achieve the overall optimal.

To sum up, it can be seen from the solution of the model that, under the condition of meeting the assumptions of the model, when the competing interest conflicts of electricity consumption, agriculture, industry and residential water use occur, the water use standards of each state can be obtained by referring to the economic development status of different states and the priorities of different water demands:

$$\begin{cases} Y_1 = 0.62(x_1 - 102)^2 + 0.19x_2 + 0.08\ln(x_3 - 194) - 0.18(x_4 - 237)^2 \\ Y_2 = 0.62(x_1 - 80)^2 + 0.24x_2 + 0.30\ln(x_3 - 214) - 0.29(x_4 - 1053)^2 \\ Y_3 = 0.62(x_1 - 42)^2 + 0.48x_2 + 0.02\ln(x_3 - 641) - 0.23(x_4 - 278)^2 \\ Y_4 = 0.53(x_1 - 25)^2 + 0.35x_2 + 0.04\ln(x_3 - 214) - 0.08(x_4 - 1053)^2 \\ Y_5 = 0.48(x_1 - 35)^2 + 0.45x_2 + 0.04\ln(x_3 - 433) - 0.03(x_4 - 1053)^2 \end{cases} \quad (5-13)$$

Where $Y_i(\mathrm{i} = 1 \sim 5)$ represents the total water supply of AZ, CA, CO, NM and WY respectively, $x_1 \dots x_4$ represents the water used for power generation, agriculture, industry and housing in each state (unit: ML).

5.3 Impact of allocated water resources on the Colorado River and Mexico

The water flowing into Mexico from the Colorado River mainly comes from the power source of Hoover Dam, and then evaporates and loses water through the river. Moreover, the arid and semi-arid areas are wide, with sparse vegetation, loose soil and serious soil erosion. So the amount of water that can reach the Gulf of California is only alpha times as much as the Hoover Dam generates electricity. Combined with reference [6] and different rainfall rates in Colorado waters in different periods, α is about 0.47-0.51 in winter and 0.62-0.68 in summer.

In 1922, seven states in the basin signed the first water distribution agreement. The agreement divides the Colorado River basin into upper and lower sections with The River As the boundary, and distributes water according to the annual runoff at the River's control station, The River's river. First, the lower Colorado River region's water allocation was met, and then, if water volume allowed, an additional 1.23 billion cubic meters were allocated to the Lower Colorado River Region to ensure that Mexico's 10-year moving average water allocation was no less than 9.25 billion cubic meters (the annual average runoff calculated at that time was 21.58 billion cubic meters). In recent years, due to low water in rivers and reservoirs can't normal water supply to the states, but will not be able to meet the water to Mexico is converted into economic indicators, according to the Mexican agricultural water, industrial water, water and other water assessment, as well as the pollution brought by the Colorado river upstream compensation, can claim compensation from the Mexican government $35 billion a year. In addition, the U.S. government will build a large water purification plant to reduce environmental pollution in Mexico.

6 Strategies in case of insufficient water supply

6.1 Background

With the development of economy and the increase of population, the demand for water resources is increasing, and there is unreasonable exploitation and utilization of water resources, many countries and regions have different degrees of water shortage. Many factors will affect the water storage, the Colorado river basin due to the climate is facing serious water shortage, is also faced with water shortages but before by artificial rainfall, water diversion from other lakes, etc, were improved, but may face increasingly serious environmental problems, the extra rainfall is difficult to maintain five states under the premise of normal water supply demand, How to allocate the existing water resources reasonably to maximize the benefit

6.2 Establishment of model

It can be considered that the water resources supplied by Lake Powell and Lake Mead to the five states are certain, and the total water supply optimized by the objective function in 4.2 model is selected here. In the case of water supply, it is considered to maximize the economic benefit of existing resources to achieve the effect of redistribution. Then the objective function is:

$$\max\ lnc = w_1 + w_2 + w_3 + w_4 \qquad (6-1)$$

Where, w_1， w_2， w_3， w_4 are respectively the economic benefits of water consumed by electricity, industrial, agricultural and residential water respectively. I'm going to use w_j for the sake of the rest of the statement.

$$w_j = \sum_{j=1}^{4}\sum_{i=1}^{5} \beta_j lne_{ji} \qquad (6-2)$$

The objective function of these benefits is the total benefit of the five states in these segments. So for w_j, these benefits come from the total water consumption in j in these 5 states, namely: $\sum_{i=1}^{5} lne_{ji}$, where e_{ji} represents the water consumption of the ith state in part J, and for each state, it should be less than the maximum water consumption stipulated by each industry H_{ji}, which is taken logarithm here for convenience in subsequent calculation [7]. The total amount of water will be related to the economic benefit of water consumption through a regression coefficient β_j. According to reference [7], β_1=0.028, β_2=12.62, β_3=29.13, β_4=-5.5.

$$\begin{cases} w_i = \sum_{j=1}^{4} \beta_{\mathrm{j}} * lne_{1i} \\ e_{ji} \le H_{ji} \end{cases} \qquad (6-3)$$

Note here is due to the lack of water resources, the actual water supply should be less than the total water supply when the water N, here introduce a theta to represent the problem in short supply coefficient, when the water is sufficient theta tend to 1, and water the lack of the theta to converge to zero, only consider here when the water is 70% of the original water, For other cases, you can vary the value of θ to get results. Then the total water consumption of each continent should be equal to the actual water supply, i.e. :

$$\sum_{j=1}^{4}\sum_{i=1}^{5} \beta_j lne_{ji} = \theta * N \qquad (6-4)$$

Then the final water resource allocation model under special circumstances can be obtained：

$$\max\ lnc = w_1 + w_2 + w_3 + w_4$$

$$s.t.\begin{cases} \sum_{j=1}^{4}\sum_{i=1}^{5} \beta_j lne_{ji} = \theta * N \\ w_i = \sum_{j=1}^{4} \beta_{\mathrm{j}} * lne_{1i} \\ e_{ji} \le H_{ji} \end{cases} \qquad (6-5)$$

6.3 Solution of model

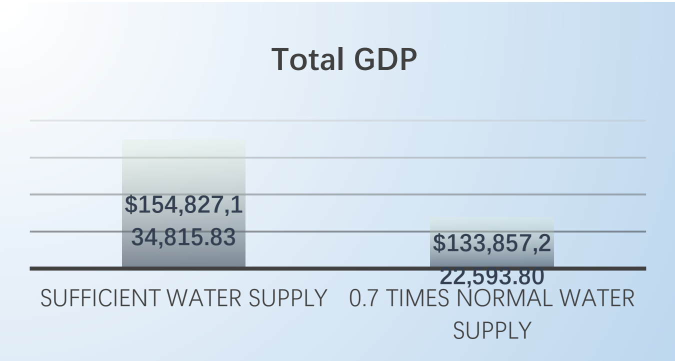
According to the reference [6], table 12 shows the maximum water consumption limit for each aspect in each state.

Table 12: Maximum limit of industrial water use in each state

State	Residential	Industrial	Agricultural	Electricity
AZ	11866.05	19.48	2423.12	264.46
CA	8356.42	2140.59	8500.06	1175.11
CO	3450.89	56.97	5851.18	310.35
NM	2522.48	27.28	1274.89	33.06
WY	3966.59	43.34	2515.99	19.78

The maximum limit as a constraint condition makes the allocation of water resources more in line with the development of each state so as to obtain the maximum benefits.

This model belongs to nonlinear integer programming, so it is difficult to directly calculate the minimum value of the objective function, here using MATLAB monte Carlo simulation to solve the objective function. Figure 8 is the histogram of water distribution in various aspects in each state when water resources are sufficient and insufficient. Figure 8 and 9 are the histogram of economic value created by water resources.



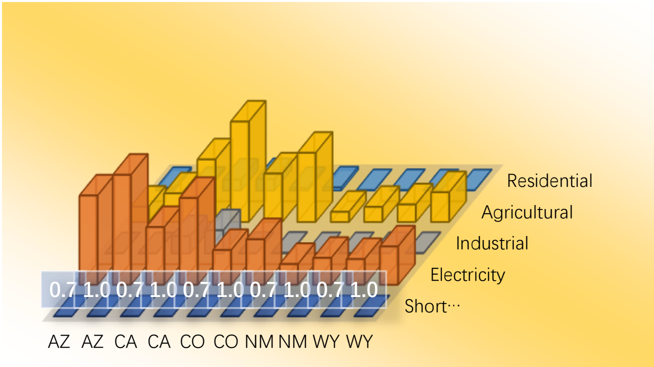


Figure 8、9: Two types of water supply produce total GDP

When the demand exceeds supply coefficient $\theta=0.7$, the water consumption of different states decreases, but the decrease proportion of residential and industrial water consumption is less, and the decrease proportion of power generation water consumption is larger.

Different suggestions can be made to increase economic capacity according to the decline of water consumption in different areas of the state. In WY and CO, more wind and solar power generation can be adopted to keep the economic capacity of electric power from declining without occupying the economic capacity of water resources; The decline of agriculture in NM state is relatively small, so artificial precipitation and water-saving irrigation technology can be adopted in order to keep the economic disparity of water resources from decreasing. CA state mainly relies on industrial development, so its economic capacity of water resources is in industry. Therefore, it can adjust the industrial structure, restrict the development of industries with high energy consumption, high water consumption and high pollution, eliminate and transform backward and high water consumption technology and equipment. None of the five states can reduce its residential water deficit, so they can diversify their water resources by developing technologies such as sewage treatment and desalination. As shown in Figure 8, when water supply is insufficient, the total GDP decreases by only about 13% by changing the different water use ratios of different aspects in five states, indicating that the model is effective.

7 Sensitivity analysis

7.1 Impact of industrial growth or contraction on the model

Due to the influence of various factors in the actual case, under the influence of different industries in different will have different degrees of growth or contraction, in this case, different industry water use would also be affected, when the industry is in a state of continuous on due to increased water consumption will increase, such as production when the industry is under the negative influence of the outside world, The corresponding demand for water will also be reduced to some extent. The water resource allocation model in special case discusses the water resource allocation of various industries when water resource supply is insufficient. Under the condition that the proportion of economic benefits of each industry remains unchanged, the model background is changed to the population of each state, and the water demand of agriculture and industry has changed. This process is equivalent to the sensitivity analysis of the water resource allocation model under special circumstances in 6.2.

$$\sum_{j=1}^{4}\sum_{i=1}^{5}\beta_j lne_{ji} = \alpha * \theta * N \quad (7-1)$$

In the case of drought, a coefficient θ is introduced to reflect the water shortage. In this part, another variable α is introduced, at which time (6-4) is transformed into (7-1) as shown in the equation. The water supply of each industry in each state under the change of total demand can be expressed by multiplying α by the supply-demand coefficient θ, and the distribution relationship of water consumption in each industry under the change can be obtained by maximizing the economy under the current demand. Among them, the variable α*θ can be changed according to the actual growth trend. Here, $\alpha * \theta$=0.7 when the demand is normal (because $\theta = 0.7$ in 6.2, $\alpha = 1$ means the demand is normal), $\alpha * \theta$=0.5 when the demand is decreasing, and $\alpha * \theta$=1. when the demand is increasing are selected respectively to be substituted into the model for detailed explanation. For other situations, specific changes can be made according to actual conditions. In combination with 6.3, the following conclusions can be drawn:

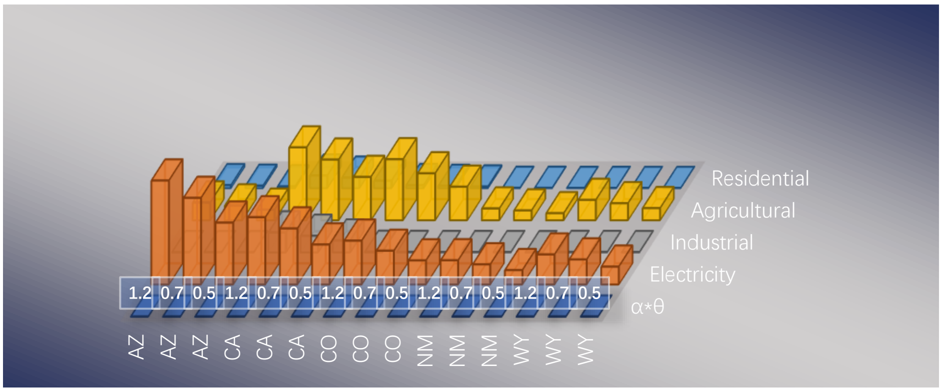


Figure 10: Impact of industrial change

Can be seen from the figure 10, for each state for the local population, agriculture, industry is in growth, the water requirement and the corresponding rise along with the rising proportion of exponential type, when the local population, agriculture, industry, contraction, the demand for water will decrease, and when the atrophy degree is higher and higher, The reduction in water demand will not change much.

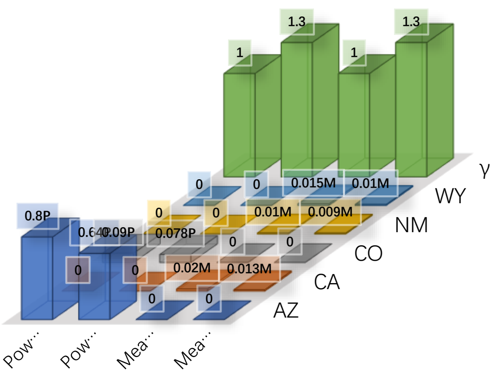
7.2 Influence on the model when the proportion of renewable energy increases

When renewable energy or other sources of supply increase, it is equivalent to an increase of additional water supply for each state except for two DAMS. In 4.4, the model of optimal allocation of water resources in each state only takes into account artificial precipitation, groundwater and water supply from other rivers, and considers the provision of other renewable energy sources. The introduced process is equivalent to the sensitivity analysis of the water resource allocation model in 4.4. The variable γ is introduced here, where γN_o represents the total water supply with the renewable energy, and γ represents the water supply is γ times of the original water supply. Then, the relationship in the model (4-15) becomes the following:

$$min \;\; N = N_{mw} + N_{pw} + N_{pe} + N_{me} + \gamma N_o \qquad (7-2)$$

Among them, γ is a variable which can be modified according to the actual situation to achieve the corresponding strategy in different situations. Here, γ=1.3 is used for specific analysis. The following conclusions can be drawn by referring to the solution of the model in 4.4:

FIG. 11,12 is a visual comparison of the operation situation and additional water supply situation of the two reservoirs solved by the model in 4.4 by substituting γ=1.3 and γ=1 respectively. The results are as follows：



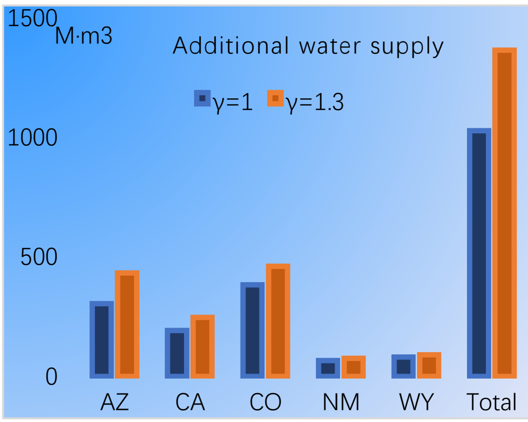


Figure 11、12: Operation of two reservoirs、Additional water supply

As the share of renewable energy increased, and additional water was added, the total amount of water supplied by the dam to the five states decreased. The amount of water supplied to glen Canyon Dam and Hoover Dam varies from state to state. As additional water is added, the amount of water supplied to the dam decreases and tends to stabilize.

7.3 Influence of the model under more water-saving measures

When more water-saving measures after states in each industry of the total water consumption should be compared to before the amount of the fixed demand of water to the corresponding decrease, the duty, considering two dam water supply under the condition of no account of additional water supply, water supply reduction is equivalent to about 4.2 a sensitivity analysis of water resources allocation model, under the condition of invariable when the other variables, As long as the corresponding degree of change in water supply can be obtained in different cases of different results. The variable ε is introduced here, so (4-18) becomes the following formula:

$$\varepsilon * P_{Xi} \leq \sum_{i=1}^{5} x_i * P_i + \sum_{j=1}^{5} x_j * m_j \leq 1.1\varepsilon P_{Xi} (i = 1\sim5, j = 1\sim5) \qquad (7-3)$$

$\varepsilon * P_{Xi}$ is the least amount of water consumption, and $1.1\varepsilon P_{Xi}$ is the most amount of water supply, in which ε can be changed according to different periods and policies of different states. The modified model is as follows: select ε=0.8 for discussion, refer to the problem solving in 4.2, we can draw the following conclusions:

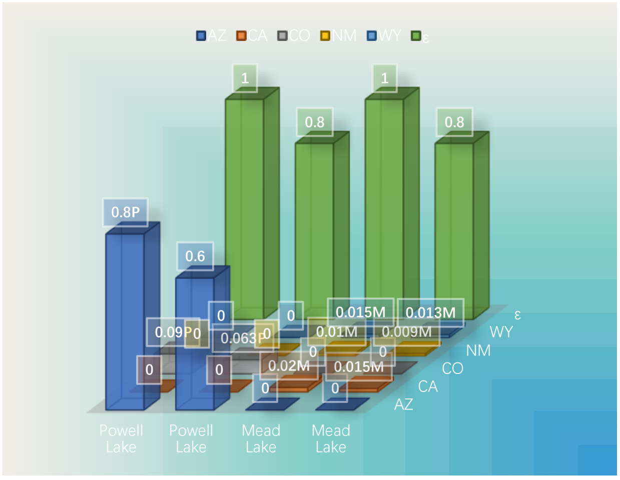


Figure 13: Water supply

As figure 13 shows, when more water saving measures are taken, the amount of water provided by each dam will decrease and the amount of water used by each state will decrease to varying degrees.

8 Model Evaluation and Further Discussion

8.1 Strengths

1. Optimize the economic productivity of water resources for different uses based on nonlinear programming model, explain the way of water resources allocation, and the results are reasonable and intuitive.

2. Sensitivity analysis is adopted to test the model and find the optimal scheme according to the changes of different parameters, and improve the scheme.

3. The calculation of the model adopts dynamic programming algorithm, and the results obtained are highly reliable through a large number of data iteration.

8.2 Weaknesses

1.The model is established under the ideal environment of water supply and economic productivity of water resources. If you want to implement the model, you need to combine concrete practices. The higher the complexity of the model, the lower the accuracy.

2.Many variables are introduced in the process of model building, which is easy to cause "dimension disaster" and is not conducive to processing.

8.3 Further Discussion

1. This model has the function of transforming data into characteristic quantity indicators, and can carry out preference selection and prediction on this basis. It can be used for selection and so on.

2. In the overall optimization model, some constraints are only given a rough range, so that more accurate relationships can be found in the operation data to make the optimization

model more accurate.

3. In some places, phase orbit analysis of ordinary differential model can be carried out to make up for the lack of model accuracy.

9 Conclusion

In view of the first problem, it is mainly a supply and demand problem.The nonlinear programming model shows that the two lakes distribute a total of 2759M m3 of water to the five states. And according to the water resources demanded by different states in different seasons, the system restart frequency is 130 per year. The minimum additional water supply is $1027.9Mm^3$ through the expanded constraints of additional water resources.

In view of question 2, through the relationship between water resources and economic capacity of water resources, and through the maximum economic objective function, The local optimal solution is obtained from each sub-region, and iterated, coordinated and optimized repeatedly until the overall optimal solution of the economic zone is reached. The optimal solution of water resources allocation in each direction of each state is obtained with water resources demand of each state as constraint condition. The optimal allocation model is constructed by using relevant constraints and economic objectives, and the dynamic programming algorithm is used to solve the model. The scientific and reasonable allocation scheme can meet the future water demand and provide some guidance for the sustainable utilization and scientific management of Colorado River water resources. The dynamic programming optimization algorithm has good effectiveness and adaptability in solving the optimal allocation of water resources. It can effectively solve the problems existing in traditional algorithms and has certain application value in the field of optimal allocation of water resources.

In view of the third problem, redistributing water resources can minimize the difference in gross economic value on the premise of water shortage. Obtain the proportion of water used in each direction in each state under the maximum economic capacity, and make a bar chart comparison with the normal supply situation. Under the condition that the water shortage coefficient is 0.7, only 13% of GDP is reduced, indicating that the model is effective.

For question 4, the sensitivity analysis of the above model is carried out. When industries in each region grow or shrink, the water resource demand of each industry in model 6.2 is changed by introducing variable α .After optimization, the growth of each industry is positively correlated with the water consumption of the reservoir. When the proportion of renewable energy increases, the increase value of the actual additional water supply in model 4.4 is represented by introducing variable γ .The proportion of renewable energy is negatively correlated with the water consumption of the reservoir. When the proportion of water saving increases, the effect of water resource saving is achieved by introducing variable ε to reduce the supply of water resource in model 4.1. After optimization, the water resource saving is negatively correlated with the water consumption of the reservoir.

10 Article

Analysis of water resources allocation plan in Colorado River Region

The Colorado River is a river in the southwestern United States and northwestern Mexico. It is about 2,333 kilometers long and covers seven STATES in the United States and two in Mexico. The entire Colorado River system is largely within the United States, Originating mainly in the western Rocky Mountains, the continental divide, The main stream originates in Colorado's Rocky Mountain National Park, with tributaries in Wyoming, Nevada, and New

Mexico, and a small amount in Sonora, Mexico. The main stream flows from Colorado through Utah, Arizona, and then forms the Arizona-Nevada and Arizona-California borders.

In order to make better use of water resources for economic development, since the 1930s, the United States has built nearly 10 DAMS on the Colorado River, including the famous Hoover Dam and the Grand Canyon Dam, it has formed lake Powell and other famous scenic spots, which plays a very important role in promoting local economic development and adjusting climate environment. However, the reservoir has been criticized for its influence on downstream water consumption and irreversible changes to the ecology of the basin. In recent years, with the change of climate and environment, the Colorado River is faced with the test of water shortage, flow interruption and reduced function. Due to the drought in the region and the increasing use of water for industrial and agricultural production and living, the Colorado River is facing great water pressure. In recent 10 years, the continuous drought and lack of rain in the basin area aggravated the threat of water shortage. The imbalance between supply and demand has caused the river to frequently stop flowing before it empties into the Pacific Ocean, with significant impacts on wildlife, ecosystems and human life in the basin. To address potential future basic water problems in Arizona (AZ), California (CA), Wyoming (WY), New Mexico (NM), and Colorado (CO),This paper deals with the possible water problems in these five states through the allocation of water resources from glen Canyon Dam and Hoover Dam in Colorado Basin.

Given the abundance of water available, glen Canyon Dam and Hoover Dam could be alleviated by diverting additional water from Lake Powell and Lake Mead at a time when the current water supply cannot meet the additional water and power needs of the five states。 By building optimization model： min $N = N_{mw} + N_{pw} + N_{pe} + N_{me}$ let the water supply resources be minimized, and the total water supply and the water supply of each lake can be obtained through the constraints of conditions.

$$s.t.\begin{cases} 736.28t + \sum_{i=1}^{5} x_i * P_i \le 0.3 * p * S_p \\ 0.7 * 736.28t \le 1526.46t + \sum_{j=1}^{5} x_j * P_j \le 0.7 * 736.28t + 0.3 * m * S_m \\ P_{Xi} \le \sum_{i=1}^{5} x_i * P_i + \sum_{j=1}^{5} x_j * m_j \le 1.1P_{Xi} (i = 1\sim5, j = 1\sim5) \end{cases}$$

Where: The water consumption of Glen Canyon Dam for domestic use is N_{pw}, the water consumption of Hoover Dam for domestic use is N_{mw}, x_i, x_j represent glen Canyon Dam and whether Hoover Dam supplies water to five states respectively, while P_i, $P_j$represent the water supply of Glen Canyon Dam and Hoover Dam to five states respectively.

When the current water supply is difficult to maintain the basic water consumption of each state, additional water supply is needed at this time. By adding an additional water consumption N_o, the optimization model continues to be constructed: $min\ \ N = N_{mw} + N_{pw} + N_{pe} + N_{me} + N_o$, and the additional amount of water consumption can be obtained by limiting constraints

$$\begin{cases} 736.28t + \sum_{i=1}^{5} x_i * P_i \le 0.3 * p * S_p + N_{op} \\ 0.7 * 736.28t \le 1526.46t + \sum_{j=1}^{5} x_j * P_j \le 0.7 * 736.28t + 0.3 * m * S_m + N_{om} \\ P_{Xi} \le \sum_{i=1}^{5} x_i * P_i + \sum_{j=1}^{5} x_j * m_j + \sum_{i=1}^{5} N_{Oi} \le 1.1 P_{Xi} (i = 1 \sim 5, j = 1 \sim 5) \end{cases}$$

In general, the models established above give some reasonable supplementary opinions on allocation when water resources are available. At present, with the development of economy and the increase of population, the demand for water resources is increasing. In addition, irrational exploitation and utilization of water resources has caused water shortage in many countries and regions to varying degrees. The most promising solution to the problem of water scarcity is the exploitation of water that is not available. Such as desalination, the exploitation and harvesting of groundwater, and the use of polar glaciers. In fact, the amount of water on earth is sufficient, and when we talk about water shortage, we only mean fresh water, or the scarcity of disposable water. So, changing from not being able to use water to being able to use water is one way. In addition, calling on people to solve water use and reuse is another way. In addition, there is to prevent water pollution, water pollution is also an important cause of water shortage.

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