Optimal water resource allocation based on stability – considering the correlation between water consumption and output value in different industries
Liming Yao, Lu Zhao, Li Pan and Xudong Chen

ABSTRACT
When multiple industries share a river, they compete for available water resources. In order to settle conflicts and ensure industrial stability, it is important for river basin managers to develop a water allocation plan. In addition, there is a correlation between water demand and output in different industries, which affects water allocation plans. From the perspective of river basin government, this paper constructs a flow distribution model among the three major industries of industry, agriculture, and service. River basin government allocates water resources to the stability of the three major industries. The water consumption of various industrial sectors is centered on their own vital interests. Different industries have different characteristics and restrictions on water consumption. The study also considers transactions in different industries on the water market, using dynamic programming methods to simulate this water allocation. This allocation model is different from the traditional industrial water allocation model, and considers the correlation between the water demand and output value of different industries. The results show that a reasonable understanding of the interrelationships between industries will be more helpful to decision makers and a fundamental guarantee for sustainable use of water resources.

Key words | correlation, dynamic programming, stability, supply rate

HIGHLIGHTS
- Considering correlation between water consumption and output value helps to stabilize the water distribution.
- Introduced power and weight coefficients to simulate the dynamic water distribution process.
- River basin governments and water markets are equally important for water distribution.
INTRODUCTION

The birth, growth, survival, evolution, and healthy reproduction of all living things on Earth is dependent on water. However, with today’s social and economic development, rapid population growth is clearly not conducive to sustainable water management (Gleick 1998; Raju et al. 2000). Studies by Vörösmarty et al. (2000) show that by 2025, a large proportion of the world’s population will face the pressure of water shortages. Arnell (2004) predicted that by 2020, there would be 374 million to 1.661 billion people in the world who would be worried about the lack of water resources.

Clark et al. (2004) proposed in 2005 that when a class of resources that are indispensable for human survival become scarce and such resources can be acquired or controlled, then competition for these resources is likely to cause conflicts. Water belongs in this class of resources. Hensel et al. (2006) believe that in the case of water shortages, competitors will be more likely to take militarized actions to ensure their own interests, but it is unlikely that problems will be solved by seeking third-party assistance (Hensel et al. 2006).

Although water resources are already scarce, the steady availability of water to meet our needs is still a basic human right. At the same time, there are statistics showing that there is a positive correlation between the inequality of water resource allocation and the risk of water conflict (Cullis & Van 2007). Countries with lower economic capacity and water availability are more likely to have water conflicts. Ashton (2007) observes that the location of African rivers or lakes with insufficient runoff is closely related to the distribution pattern of conflict zones. He believes that one of the causes of conflicts in Africa is the unequal distribution of water resources (Ashton 2007). Therefore, the allocation of water resources will be a major area of study in the future (Magnus Theisen 2008). After all, industries where improved water distribution would be productive, generally do not have an allocation plan to improve productivity (Hu & Eheart 2013).

As mentioned above, if water resources are not evenly distributed, it may lead to conflicts between industries (Oloomi Zad et al. 2015). Therefore, river basin managers need to find ways to develop stable water allocation plans.

If the stability of the decision-making scheme is not considered as part of a water resource allocation plan, then there may be conflicts between industrial competitors (Gunasekara et al. 2014). Regarding the goal of stability, current research is roughly divided into two groups, one is qualitative research and the other is quantitative research. However, quantitative research is relatively rare.

In the qualitative research field, Cahill-Ripley (2014) believes that it is essential to negotiate reasonably in water allocation. Mbengue (2014) proposes the need for shared water resources between regions to prevent conflicts and improve stability between regions, the issue being that among the industries that compete for water, this kind of negotiation is basically a zero-sum game. That is, for the
parties involved, one party's income necessarily means the other party's loss, and the sum of the gains and losses is always 'zero', and there is no possibility of cooperation between the two parties (Washburn 2014). However, this is not the preferred solution.

In the quantitative research field, Read et al. (2014) quantified the negotiating indicators used in order to ensure stability in a water allocation plan, and proposed the power coefficient method to measure the stability of the decision-making process. However, they did not consider the constraints. Although Hu et al. (2016a, 2016b) considered stability indicators in water resource allocation, they ignored the existence of water markets (Wei & Hu 2015; Hu et al. 2016a, 2016b). After all, the redistribution of the water market is an even more powerful tool for river basin managers (Regnacq et al. 2016).

Correlation analysis is rarely considered in the literature on water allocation. As is known to all, there is a high correlation between industrial structure and water consumption (Chang et al. 2017). Since different industrial structures and lifestyles have different consumptions of water resources, when a river supplies water to multiple industries at the same time, if river basin government considers the relationship between water consumption of different industries and industrial structure in the decision-making process, will the allocation of water resources be more reasonable? This article will examine this question. If different industries are compared with distributors, then river basin government is equivalent to manufacturers with distribution rights. Just as in the research proposed by Professor Zhong et al. (Zhong et al. 2017), the supply ratio of different distributors is considered to make the distribution results more effective. Then, as for the distribution of water resources, this research can also introduce the concept of ‘supply ratio', which provides different supply rates for different industrial structures to better meet the water demand of different industries. After all, this would go a long way towards solving the problem of how water is properly distributed.

To strengthen the efficient allocation and rational utilization of water resources, it is not only necessary to start from the level of river basin governments. Secondly, the experience of countries around the world has proved that the existence of a water resources market is also effective in solving this problem (Raffensperger & Milke 2017). Market transactions of water resources mainly include water rights transactions between regions, water rights transactions between industries, and water rights transactions between enterprises (Zaeske & Krishnamurthy 2017). The existing literature often pays more attention to water rights transactions between different regions and water rights transactions between enterprises, but ignores water rights transactions between industries (Zaeske & Krishnamurthy 2017). The long-term development model of a water resource system is greatly influenced by the development of the macroeconomic system. Since the output efficiency of a water resource varies among different industries, water rights trading among different industries is more conducive to solving the problem of rational allocation of a water resource, and is of great benefit to the industries that are short of water.

In a global competition for scarce water, a stable water allocation plan is essential. This study finds that a reasonable understanding of the demand relationship among industries will be more helpful to decision makers when they develop stable water allocation plans. This relationship has two layers. First, different industrial sectors and lifestyles have different consumptions of water resources, and different economic development patterns will greatly change the demand for water. Therefore, dynamic analysis should be carried out on the macroeconomic system and water resource system at the same time, and the relationship between them should be used to better allocate water resources. Second, water rights can be traded in the market between various industries, and they can complete the transfer of water rights through the trade, so as to make the distribution of water resources more favorable to themselves.

However, in the study of water resource allocation, few researchers consider the four factors of stability, dynamic planning, water market, and the correlation between industrial water consumption and output value (Table 1).

The rest of this article is organized as follows. This article will clearly describe the research issues in the next section. In the third section, this paper uses a dynamic planning process to simulate the water resource allocation process in various industries. In the fourth section, this paper performs numerical analysis on the above models.
and solves the models. The fifth section is the concluding part. Comparing the distribution results of this article with the traditional distribution results, the results show that a reasonable understanding of the interrelationships between industries will be more helpful to decision makers. Finally, the paper also discusses the shortcomings of the research and proposes possible future research directions on water resource allocation.

**PROBLEM STATEMENT**

In order to make a stable decision scheme, this research established a water diversion process simulation diagram (Figure 1). Our goal is to develop a stable water distribution plan for river basin authorities (river basin managers). In this process, the government meets different supply rates for different industries. River basin managers make decisions based on dynamic programming models. Every month, the government needs to ensure that water supply rates are met for each industry. Then they will make the next month’s water transfer decision. After receiving water from the government, the industry can also transfer water rights in the water-rights trading market. Since the industry cannot obtain the actual water demand at present, it can only predict the water amount according to the previous water consumption data. So if the industry relies solely on river basin managers to allocate water, it may not be able to meet its own needs. Therefore, the industry needs to trade water rights in the water rights market.

At the decision-making level of river basin governments, their goal is to find a stable water allocation scheme. From the point of view of each industry, whether it is acquiring water from rivers or water trading markets, it has only one purpose: to obtain enough water to ensure its own development (Figure 2). The relationship between river basin and river basin government is not one of confrontation, but one of win–win cooperation. In the whole process of water rights allocation, the government plays a leading role. It takes into account the water needs of all industries and tries to find a distribution plan that all industries are satisfied with and that will not cause conflict.

What makes our model different is that this research considers the relationship between water consumption and output in each industry and uses these relationships to determine the supply ratio of different industries so that decision makers can make better decisions. Based on the classification of industry sectors in China’s input–output table, 42 industry sectors in the national economy were combined into primary industry, secondary industry and tertiary industry, which can also be called agriculture, industry, and service industry. The relationship between the water consumption of different industries and industrial structure is considered in water resource allocation, which has not been studied in this field.

**MODEL FORMULATION**

Our goal is to develop a stable plan for water distribution. The goal of stability is more of a river basin manager’s perspective. It analyzes the difference between the amount of water each industry expects to receive from the river and the amount it receives from the market and the actual water demand. It can also be interpreted as the satisfaction evaluation of the above schemes by various industries.

The dynamic water distribution model ensures the stable utilization of limited water resources. Every month, river basin managers need to develop a satisfactory water allocation plan to meet the needs of various industries and meet the ecological requirements of the river basins. Table 2 lists the meanings of the symbols used in the model.

<table>
<thead>
<tr>
<th>Relevant literature</th>
<th>Stability</th>
<th>Dynamic programming</th>
<th>Water market</th>
<th>Correlation analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bjornlund (2005)</td>
<td>___</td>
<td>___</td>
<td>X</td>
<td>___</td>
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<tr>
<td>Hughes et al. (2009)</td>
<td>___</td>
<td>X</td>
<td>X</td>
<td>___</td>
</tr>
<tr>
<td>Kronaveter &amp; Shamir (2009)</td>
<td>X</td>
<td>___</td>
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<tr>
<td>Zaman et al. (2009)</td>
<td>___</td>
<td>___</td>
<td>X</td>
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<tr>
<td>Read et al. (2014)</td>
<td>X</td>
<td>___</td>
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<tr>
<td>Eliasson (2015)</td>
<td>X</td>
<td>___</td>
<td>___</td>
<td>___</td>
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<tr>
<td>Hu et al. (2016a, 2016b)</td>
<td>X</td>
<td>___</td>
<td>___</td>
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<tr>
<td>This paper</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
**Objective function**

This research uses the power factor method to measure the stability of the distribution scheme (Teasley & McKinney 2014). The power coefficient is used to measure the ratio of personal satisfaction to group satisfaction. If the loss rate of the industry is greater than the loss rate of other industries in the same decision group, the decision makers in the industry may be dissatisfied with the decision plan and there may be behavior that undermines the plan. Therefore, the coefficient of variation of the power coefficient can be used to determine the stability of the water distribution scheme (Read et al. 2014).

Minimize maximization CV: Minimize the maximum coefficient of variation (CV) to maximize the stability of the water distribution scheme. This involves the economic power index, where the traditional power index can be rewritten as \( \theta_i(t) \) to measure the power index in the industries.

\[
\theta_i(t) = \frac{\rho_i [E(DQ_i(t)) - q_i(t)]}{\sum_{i=1}^{3} \rho_i [E(DQ_i(t)) - q_i(t)]}
\]

(1)

\[
\sum_{i=1}^{3} \theta_i(t) = 1
\]

(2)
where \( \rho_i(t) \) = the weight of industry \( i \) in the \( t \) phase; \( DQ_i(t) \) = water demand for stage \( t \) in industry \( i \); \( q_i(t) \) = final water volume in the \( i \) industry in \( t \) months (after water trading); \( \rho_i(t) \) = external parameters, representing the power of each industry based on economic, social, and demographic conditions in the industries. The higher the value of \( \rho_i(t) \), the

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**Figure 2** | River water distribution and water market.

**Table 2** | The meanings of the symbols used in the model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>coefficient of variation of ( \theta_i(t) )</td>
</tr>
<tr>
<td>( \sigma(t) )</td>
<td>standard deviation of the power coefficient ( \theta_i(t) )</td>
</tr>
<tr>
<td>( \overline{\theta}(t) )</td>
<td>mean of the power coefficient ( \theta_i(t) )</td>
</tr>
<tr>
<td>( \theta_i(t) )</td>
<td>weight coefficient of the ( t ) month of the ( i ) industry</td>
</tr>
<tr>
<td>( \rho_i(t) )</td>
<td>external parameter indicating each industrial power based on its economic, social, and demographic status</td>
</tr>
<tr>
<td>( q_i(t) )</td>
<td>the amount of water allocated to the ( i ) industry by the government in the ( t ) month</td>
</tr>
<tr>
<td>( q_0^i(t) )</td>
<td>final water volume in the ( i ) industry in ( t ) months (after water trading)</td>
</tr>
<tr>
<td>( AW(t) )</td>
<td>available water for rivers in the ( t ) month</td>
</tr>
<tr>
<td>( AW(t+1) )</td>
<td>available water for rivers in the ( t+1 ) month</td>
</tr>
<tr>
<td>( OSW(t) )</td>
<td>available water from other sources of the river at ( t ) months</td>
</tr>
<tr>
<td>( OSW_i(t) )</td>
<td>available water from other sources in the ( i ) industry at ( t ) months</td>
</tr>
<tr>
<td>( DQ_i(t) )</td>
<td>water demand in the ( i ) industry in the ( t ) month (random variable)</td>
</tr>
<tr>
<td>( \beta_i(t) )</td>
<td>the ( t ) month, the ( i ) industrial supply rate requirements for the government</td>
</tr>
<tr>
<td>( \beta_0^i(t) )</td>
<td>supply rate requirement for water trading in the ( i ) industry in the ( t ) month</td>
</tr>
<tr>
<td>( E_{\text{min}} )</td>
<td>minimum ecological water demand of rivers</td>
</tr>
<tr>
<td>( \alpha_i^{\text{loss}}(t) )</td>
<td>loss rate during water transport in the ( i ) industry in the ( t ) month</td>
</tr>
<tr>
<td>( BW_i^+(t) )</td>
<td>the amount of water bought in the water market in the ( i ) industry in the ( t ) month</td>
</tr>
<tr>
<td>( SW_i^-(t) )</td>
<td>the amount of water sold in the water market in the ( i ) industry in the ( t ) month</td>
</tr>
<tr>
<td>( RC_i )</td>
<td>maximum water storage capacity of reservoir capacity in the ( i ) industry</td>
</tr>
<tr>
<td>( Q_a )</td>
<td>the water consumption of registered users</td>
</tr>
</tbody>
</table>
greater the influence of industry \(i\) in \(t\)-stage decision making, that is, the industry with a larger traditional entitlement coefficient has a higher proportion of revenue than other industries. The coefficient of variation is used to measure the stability of water distribution schemes.

\[
\text{minmax CV} = \frac{\sigma(t)}{\overline{\theta(t)}}, \quad t = 1, 2, \ldots 12
\]  

(3)

where \(\sigma(t)\) represents the change in the standard deviation of the power index \(\theta_i(t)\); and \(\overline{\theta(t)}\) is the average of the \(\theta_i(t)\) calculated across the three industries. It can be seen that the lower the \(CV\) value of the river basin water distribution scheme, the more likely the scheme is to be stable (or the more feasible the scheme).

**Constraints**

State transfer equation for water distribution: this study divides the water distribution phase into 12 cycles, which can be understood as 12 months. At the beginning of each month, the water volume of the river basin, based on government statistics, is recorded as \(AW(t)\), and other sources of water (including groundwater and precipitation, etc.), are recorded as \(OSW(t)\). The basin government divides the total available water (the amount of water available at the beginning of this month plus the amount of water from other sources) by industry, and then at the end of each month, the available water is again counted. The water consumption is the amount of water available at the beginning of the month plus the amount of water from other sources, minus the amount of water distributed to each industry (assuming a total of three industries) that month, and the available water volume is the amount of water available at the beginning of the next month. Water is then dispensed in this order for 12 months. This is a dynamic planning problem. This research knows that the state of this stage in dynamic planning is often the result of the previous stage (Schrage & Baker 1978). Our state transition equation is as follows:

\[
AW(t + 1) = AW(t) - \sum_{t=1}^{3} q_i(t) + OSW(t)
\]  

(4)

The boundary conditions for the above dynamic transfer equation are as follows:

\[
AW(1) = AW_0, \quad AW_0 = AW(13)
\]  

(5)

\[
AW(t) \geq E^{\text{min}}
\]  

(6)

At the beginning of January, the amount of water available according to statistics is \(AW_0\). Here setting the \(t\) value from 1 to 12, in the first year, we give \(AW(1) = AW_0\) at the time of the second year, because of our dynamic programming being a closed loop process, at the end of first year, we can get the value in \(AW(15)\), \(AW(13)\) value given in the second year of \(AW_0\), \(AW_0\) in the second year and \(AW(1)\) in the second year, and the solution can be recycled many times, to get more accurate results. At the same time, in the process of distributing water, the government cannot arbitrarily divide water in order to meet industries' demand for water. The local ecological needs should be considered as well (Cheng & Zhao 2006). \(E^{\text{min}}\) represents the amount of basic ecological water needed locally each month (Xu et al. 2019).

Water availability limits for water resources: the amount of water required in each industry is allocated by the basin authorities. Naturally, each month the government decides that the total amount of water allocated to each industry must not exceed the amount of water available in the river (Hu et al. 2016a, 2016b).

\[
\sum_{t=1}^{3} q_i(t) \leq AW(t)
\]  

(7)

Supply rate requirements: each industry has a requirement for the amount of water it can get from the river. When the government formulates a water diversion plan, it must consider the supply rate requirements of each industry. If the government cannot meet its own needs, conflicts may arise (Ohlsson 2000). In addition, in the process of water allocation, a portion of the water is lost. The water demand data here have taken out the impact of water from other sources.

The amount of leaked water refers to the difference between the total water supply and the water consumption...
of registered users. It is composed of water loss, metered water loss and other water loss. The leak rate is the ratio of the amount of leaked water in the pipe network to the total amount of water supplied, usually expressed as a percentage. The calculation formula of leakage rate is shown below ($Q_s$ refers to the water consumption of registered users). The water consumption data of registered users comes from the ‘Water Resources Bulletin of Sichuan Province’.

\[
\frac{(1 - a_i^{\text{loss}}(t))q_i(t)}{E[DQ_i(t)]} \geq \beta_i
\]

(8)

\[
a_i^{\text{loss}}(t) = \frac{(q_i(t) - Q_s)}{q_i(t)} \times 100\%
\]

(9)

The final amount of water in the industry: the industry receives government-derived water (considering the loss of water during transport) and water from other sources. The industry will trade again on the water market to get more water or sell excess water. After the transaction, the amount of water available in the industry is the final amount of water. Why is there still a water trade in the industry? Because the supply rate requirements provided by the industry to the government are based on data from the same month of the previous year, and the actual situation may change from year to year. The industry needs to use the water market platform to obtain the required water volume in real time (Bjornlund 2003).

\[
(1 - a_i^{\text{loss}}(t))q_i(t) + OSW_i(t) + BW^+_i(t) - SW^-_i(t) = q_i(t)
\]

(10)

Industrial water limit: there are two restrictions on the final water volume in the industry. One limitation is that the water volume in the industry must not exceed the reservoir capacity. Another limitation is that the amount of water in the industry must meet a certain proportion of its own needs (Chong & Sunding 2006).

\[
\beta_i(t) \times E[DQ_i(t)] \leq q_i(t) \leq RC_i
\]

(11)

Water market trading requirements: every month, the industry trades with any industry in the water market (except for itself), regardless of the transaction. For itself, the result is either a reduction in water or an increase in water. The reduction in water volume is because the amount of water sold in the industry is greater than the amount of water purchased, and thus, it can be approximated as sold water. Similarly, the increase in water volume is due to the fact that the amount of water purchased in the industry is greater than the amount of water sold, which can be approximated as buying water.

\[
BW^+_i(t) \times SW^-_i(t) = 0
\]

(12)

Total water volume trading requirements in the market: the amount of water sold in all industries of the market is equal to the amount of water purchased each month. In the water market, the flow of water rights only has two options: buying and selling.

\[
\sum_{i=1}^{3} BW^+_i(t) = \sum_{j=1}^{3} SW^-_j(t), \quad i \neq j
\]

(13)

The amount of water sold on the market: the amount of water sold in the industry each month should not be greater than the amount of water allocated to the government that month (considering the loss during transportation). If more water is sold each month than the government gets that month, it will cause chaos and uncontrollable market transactions. The above situation is not a good thing for the river basin authorities.

\[
SW^-_i(t) \leq (1 - a_i^{\text{loss}}(t))q_i(t)
\]

(14)

Correlation analysis: this research studies how to allocate water reasonably according to relevant requirements to achieve stability and balance in all aspects. Therefore, correlation analysis is essential. Correlation refers to a concept according to which people describe the interrelation between things by analyzing the phenomenon that things change with each other. Its measurement index is called a correlation coefficient.

In this paper, this research takes two variables $x$ and $y$, where $x$ represents the water consumption of each industry, and $y$ represents the proportion of each industry in GDP, and calculates the correlation coefficient $r$ of the three
Among them, there is a correlation between water consumption and output value in different industries. The correlation is shown in Equation (15).

**CASE STUDY**

This research illustrates our water allocation plan by a hypothesis testing existing water resources decision-making issues in the Min River. The Min River is located on the western edge of the Sichuan Basin (Figure 3). It is the largest tributary of the Yangtze River, with a water supply capacity of 10.14 billion m³.

The Min River involves Qinghai, Sichuan Province, 11 administrative districts above the prefecture level, and 73 county-level administrative districts. The Min River basin has an area of approximately 135,411 km²; within Sichuan Province it has an area of 125,763 km², accounting for 93% of the total area of the basin, and within the territory of Qinghai Province it has an area of 9,648 km², accounting for 7% of the total area of the basin. The basin provides water for 19.1572 million people in the 11 administrative districts. Since the ‘Twelfth Five-Year Plan’ for national economic and social development, the economic development of these administrative regions has expanded, and thus, the water consumption for industrial and agricultural production and urban living has been increasing. The water shortage in the middle reaches of the mainstream of the Min River in April and May is becoming more serious. The contradiction between resource supply and demand is more prominent. Therefore, traditional water resource solutions cannot solve the stability problem. In the Min River basin, river authority managers and industry managers usually plan for the allocation of water resources for the next year at the end of December. After considering the water demand data from previous years and the supply rate requirements, the river basin management department combines these with the historical transaction data from the water market to determine the amount of water allocated to industry.

Water resource information of three industries (primary industry, secondary industry and tertiary industry) was selected to simulate the distribution process.

\[ r = \frac{n \left( \sum_{i=1}^{n} x_i y_i \right) - \left( \sum_{i=1}^{n} x_i \right) \left( \sum_{i=1}^{n} y_i \right)}{\sqrt{n \sum_{i=1}^{n} x_i^2 - \left( \sum_{i=1}^{n} x_i \right)^2} \cdot \sqrt{n \sum_{i=1}^{n} y_i^2 - \left( \sum_{i=1}^{n} y_i \right)^2}} \]  

(15)

where \( q_i(t) \) is the decision variable, \( DQ_i(t) \) is the random variable.
The relevant data of three industries for ten years was selected. Figure 4 shows the GDP of Sichuan Province’s industry, agriculture, and services from 2002 to 2011. Judging from the situation reflected in Figure 4, Sichuan’s gross national product has been increasing year by year, both as a whole and in various industries. In addition, the GDP growth rate of the secondary and tertiary industries is much higher than that of the primary industry. The data come from the Statistical Yearbook of Sichuan Province.

Figure 5 shows the total water consumption for production in Sichuan province from 2002 to 2011, and the proportion of water consumption for industry, agriculture and service industry. From the perspective of the total amount, water consumption is increasing year by year. From the change range of water consumption in the three major industries, the proportion of water consumption in the primary industry gradually decreased, while the proportion of water consumption in the secondary industry and the tertiary industry gradually increased. Except in 2008, due to the impact of the Wenchuan earthquake, there were some changes in the water consumption data of the three major industries. The data come from the Sichuan water resources bulletin.

According to the data in Figures 4 and 5 and Equation (15) in the previous section, we can calculate the correlation coefficients between the three major industries and the output value, and the specific values are shown below (note: in 2008, an earthquake occurred in Wenchuan, Sichuan, and the data are not consistent with the normal situation, so the data of that year were excluded), where $r_1$ represents the correlation coefficient between water consumption in the primary industry and output value, $r_2$ represents the correlation coefficient between water consumption in the secondary industry and output value, and $r_3$ represents the correlation coefficient between water consumption in the tertiary industry and output value. It can be seen that the water consumption of the primary industry is positively correlated with the output value. In other words,
if more water is given to the primary industry, more output value will be created. The relationship between the proportion of secondary industry in GDP structure and its water consumption structure is relatively weak, that is to say, the relationship between industrial water use and the proportion of industrial output in GDP is relatively weak. The water consumption of the tertiary industry is negatively correlated with the output value, and its water demand is relatively weak. That is to say, to vigorously develop the tertiary industry is a relatively small pressure on increasingly strained water resources, but its output value is very high.

\[
\begin{align*}
r_1 &= 0.7527 \\
r_2 &= -0.3901 \\
r_3 &= -0.7426
\end{align*}
\]

The weights of each industry are shown in Table 3. The weights indicate the relative control of each industry in relation to the entire agreement.
Because we are simulating the water allocation plan for each of the three industries each month, we completed some processing of the above data. It was assumed that each month’s water demand is subject to a normal distribution. The mean and standard deviation of the normal distribution of the three industries are shown in Table 4.

This research mainly uses MATLAB tools to solve the model. As mentioned above, assuming that the demand of each industry follows a normal distribution with known variance and mean, there is a correlation between the water demand of different industries (that is, the water consumption in Figure 4) and the output value (Figure 5). Based on the method of Zhong Yuanguang and other researchers (Zhong et al. 2017), i.e. the principle of maximum debt priority, the water resources of various industries are allocated.

First of all, this research simulates 1,000 experiments, each experiment taking a random number between 0.7 and 0.9 to represent the supply rate, so we get a matrix of 1,000 rows and three columns. Then the matrix is reordered according to the principle of maximum debt priority. For example, the first random number is (0.7, 0.8, 0.9), the second random number is (0.75, 0.85, 0.9), and the third random number is (0.76, 0.88, 0.9). After sorting, the first random number is the same, the second random number is (0.9, 0.85, 0.75), and the third random number is (0.76, 0.8, 0.9). The principle of maximum debt priority is to compensate for the small supply rate in the last time and give priority to the high supply rate in the next time. The distribution results after reordering were observed and 81.2% of the times were less than 0.1861 (Table 5), so the confidence interval of the distribution results with 90% reliability was (0.7823, 0.8233).

Then a controlled trial is conducted according to the correlation. The largest random number of the three random numbers in the above experiment was assigned to the primary industry, the smallest value was assigned to the tertiary industry, and the middle value of the three random numbers was assigned to the secondary industry. Other things being equal, 1,000 experiments were simulated. When the results of the 1,000 trials were observed, 83.5% of the results were less than 0.1515 (Table 5), so the confidence interval of the distribution results with 90% reliability was (0.8157, 0.8543). The distribution results are shown in Figure 6.

From the results in Table 5, it can be seen that the result of allocating water resources based on correlation is better than the other case. The coefficient of variation is the ratio of the standard deviation to the mean. Compare the coefficients of variation of the two cases. If the average of the two cases is equal, it is not difficult to see, then the smaller is the coefficient of variation (that is, the standard deviation is smaller), and the better and more stable. In our case, the average of the two cases must be equal, because:

\[ \sum_{i=1}^{3} \theta_i(t) = 1 \]

So it is better to have a small coefficient of variation. From Table 5, it can be seen that, whether it is the minimum-maximized CV or the average CV, the result based on correlation is always smaller than the result of priority allocation of maximum debt. Therefore, when river basin governments are formulating water resource allocation plans, prioritizing the relevance of various industries will help better distribution. The comparison of the CV under the mean is to prevent the minimum-maximized CV from hiding the worst-case CV.

In this paper, this research introduces the concept of supply ratio when making decision plans. This is both a

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Weights of each industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary industry</td>
<td>Secondary industry</td>
</tr>
<tr>
<td>Weights (%)</td>
<td>18.59</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Water demand per month in the three industries follows a normal distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary industry</td>
<td>Mean (10^5 m^3)</td>
</tr>
<tr>
<td>Secondary industry</td>
<td>15.89144</td>
</tr>
<tr>
<td>Tertiary industry</td>
<td>0.367426</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5</th>
<th>CV at different supply rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimax</td>
<td>Maximum debt priority distribution</td>
</tr>
<tr>
<td>Mean</td>
<td>0.1861</td>
</tr>
<tr>
<td>Mean</td>
<td>0.1584</td>
</tr>
</tbody>
</table>

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challenge and an opportunity for river basin managers. Although this challenge is inevitable, river basin authorities need to keep an eye on water demand, rainfall information, water market transactions and other information of various industries in real time. By making full use of this information, a stable water distribution plan can be established to avoid conflicts caused by uneven distribution of water resources or social and economic development.

In the past, the relationships among the three industries in water allocation programs were ignored. First of all, since there is a correlation between output value and water consumption, it is essential to use different water supply rates to ensure the development of this industry according to different industries. Secondly, different industries are connected by water resources. There is an explicit flow of water between different industries, and they trade with each other to redistribute water in the market. From the results in Table 5, it can be seen that more accurate supply ratio results for different industries will be better than random allocation. From this perspective, it may be easier for river basin managers to find a stable decision-making scheme.

CONCLUSION

With the increasing scarcity of water resources in the world, river basin managers should try their best to meet the needs of all parties when making decisions and plans. But this goal is a complex task for river basin managers. In this paper, a dynamic programming model is proposed to solve the water distribution problem in a single river basin, and data from the Minjiang River basin (southwest China) are used to verify the efficiency of the model.

From the perspective of river basin government, this paper constructs a flow distribution model among the three industries of industry, agriculture and service. The river basin government takes the overall interests as the center, manages each water-use industry, and evaluates the stability of the distribution result. Each industry sector has its own vital interests as the center, with different water-use characteristics and constraints, and at the same time, each industry can also conduct market transactions. This model is different from the traditional industrial water resource distribution model, considering the water

Figure 6 | Maximum debt priority distribution and correlation-based distribution results (10^3 m³).
demand relationship between different industries, and introducing the coefficient of variation to measure the stability of the distribution results. The results of the case study can provide some insights for Minjiang River basin administration and other policy makers on the issue of water allocation in a single river basin:

1. A reasonable understanding of the correlation between the output and water consumption of each industry will be more helpful to policy makers and is the fundamental guarantee of sustainable use of water resources.
2. In the allocation of water resources, the authority should start from the overall situation and consider the stability of all parties.
3. Priority can be given to water-based industries, such as primary industries.

In this paper, a dynamic programming model is established to simulate the water supply problem in multiple industries. This model can provide a stable distribution scheme for water resource managers in a single river basin. The power index and coefficient of variation are incorporated into the water distribution problem, thus contributing to the water distribution research.

When managers make a distribution plan that meets all the demands, it may be easier to find a breakthrough in terms of the correlation between demands. Although this study has only one objective function (stability), some other objectives in future can be considered, such as equity or profit maximization.

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**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

**REFERENCES**


