A study of multi-objective dynamic water resources allocation modeling of Huai River

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ABSTRACT

Water resources supply and demand has become a serious problem. Water resources allocation is usually a multi-objective problem, and has been of concern for many researchers. In the north of China, the lack of water resources in the Huai River Basin has handicapped the development of the economy, especially badly in the low-flow period. So it is necessary to study water resources allocation in this area. In this paper, a multi-objective dynamic water resources allocation model has been developed. The developed model took the overall satisfaction of water users in a time interval as the objective function, applied an improved simplex method to solve the calculation, considered the overall users’ satisfaction variation with time, and followed the principle that the variation of the system satisfaction within adjacent periods of time must be minimal. The established model was then applied to the Huai River, for the present situation (2010), short-term (2020) and long-term (2030) planning timeframes. From the calculation results, the overall satisfaction in late May and mid September in 2030 was 0.65 and 0.70. After using the model allocation optimization, the overall satisfaction was improved, increasing to 0.78 and 0.79, respectively, thus achieving the dynamic balance optimization of water resources allocation in time and space. This model can provide useful decision support in water resources allocation, when it is used to alleviate water shortages occurring in the low-flow period.

Key words | Huai River, modified simplex method, multi-objective dynamic optimization, water resources allocation

LIST OF ABBREVIATIONS

- $I$: certain time period
- $V_i$: water supply
- $B_{io}$: user’s minimum water demand
- $\beta_{io}$: priority factor of optimal level users
- $\Delta V_i$: the volume of emergency water
- $j$: region number, $j = 1, 2, \ldots, m$
- $k$: number of water users
- $W_{ijo}$: water supply of optimal level user at time period $i$ and district $j$
- $B_{ijo}$: the minimum water demand of optimal level user at time period $i$ and district $j$
- $\beta_{ijo}$: the supply loss coefficient of optimal level user at time period $i$ and district $j$
- $WVi$: the system water supply at the end of time period $i$
- $W_i$: the user’s total supply water of time period $i$
- $G_{ijk}$: the ideal water demand of users in $j$ region at $i$ time
- $B_{irie}$: the minimum water demand of other users
- $W_{ire}$: the actual amount of water
- $L_{ijke}$: the water shortage of other users after distribution
- $L_{ire}$: the water shortage of other users after distribution
- $a_{ij}$: at time $i$ the $j$ user weighting coefficients
- $S_i$: the system satisfaction at $i$ period
- $\Delta S_i$: the difference between two adjacent satisfactions with the system time
- $B_{ij}$: the minimum water demand in $j$ region at $i$ time
- $W_{ij}$: the actual amount of water in $j$ region at $i$ time
- $G_{ij}$: the ideal water demand of users in $j$ region at $i$ time
INTRODUCTION

Water, a limited resource, is vital for the existence of life on earth. With increasing demand for water, the problem of water shortages has become progressively worse and has attracted considerable attention. Water resources in China are scarce. The total amount of water resources in China was $2.41 \times 10^{13} \text{ m}^3$ in 2004, which is equal to 1.86 m$^3$ per capita (Zhang et al. 2007). Take three major river basins (Huang River Basin, Huai River Basin and Hai River Basin) as an example: these basins account for 35% of cultivated national land, 32% of gross domestic product, 35% of total population, but only 7% of water resources, and the water resources per capita is only 457 m$^3$. These basins are short of water resources (Lv et al. 2011; Han et al. 2013). The difference between the supply and demand for water resources in these basins is serious, so it is necessary to study the optimization of water resources allocation. One of the early studies on allocation of water resources was at Harvard University, where an ‘analysis of water resources systems’ was published in 1962. The researchers brought systems analysis into the planning of water resources allocation, and such water resources allocation models were also receiving more attention in Europe (Maas et al. 1995). In recent years, several methodologies have been proposed for water resources allocation. Bao et al. (2005) introduced a penalty function to single target processing, and gave the iterative algorithm to solve the multi-objective dynamic reservoir. Zhao et al. (2007) also proposed a new method of Euclidean Distance Judgment for interactive multi-objective decision-making based on the degree of satisfaction, to coordinate the balance objective comprehensive degree to control each single target, and provide a new effective way for the optimal allocation of regional water resources. Lu et al. (2009) proposed an inexact rough-interval two-stage stochastic programing method for conjunctive water allocation problems. Mahjouri & Ardestani (2010) introduced an optimization model, which can be utilized as an effective tool for optimal interbasin water allocation involving stakeholders with conflicting objectives subject to physical and environmental constraints. A decentralized optimization method is combined with a multiple-agent system framework for the Yellow River Basin developed by Yang et al. (2012), in which water users, reservoirs and downstream ecological zones are defined as agents. Zhao et al. (2013) compared water users’ behavior under administered systems (AS) and market-based systems (MS) through a consistent agent-based modeling framework for water allocation analysis that incorporates variables particular to both MS and AS (e.g., water trade and trading prices).

In this work, a multi-objective dynamic water resources allocation model was built, in which the overall satisfaction of each user was taken as the objective function, following multi-objective optimization and dynamic planning theory, and using a modified simplex method with the addition of a time variable to achieve the dynamic balance optimization of water resources allocation. The developed model was applied to allocation of water resources over different timeframes for the main stream of the Huai River from Zhengyangguan to Bengbu Sluice, where scarcity of freshwater resources is experienced in the low-flow period. After using the model allocation optimization, the overall satisfaction was improved, thus achieving the dynamic balance optimization of water resources allocation in time and space in the low-flow period. The model can provide useful decision support to water resources allocation.

METHODOLOGY

Comparing the volumes of water supply and water demand, according to the principles of water resources allocation, the model was divided into three types as follows.

1. In a certain time period $i$, if the actual total amount of water supply $V_i$ is less than the optimal level (life and thermal power water) users’ minimum water demand $B_{io}$, then:

$$V_i \leq \frac{B_{io}}{1 - \beta_{io}}$$

(1)

where, $\beta_{io}$ is the priority factor of optimal level users. Emergency water diversion should be carried out, the total volume of emergency water ($\Delta V_i$) is given to optimal level users to satisfy their minimum water demand.
The available water for other users is zero, and the remaining available water is zero until the end of this time period.

$$W_{jio} = \frac{(1 - \beta_{ijo})V_i B_{ijo}}{B_{io}}$$  \hspace{1cm} (2)

$$W_{ije} = 0$$  \hspace{1cm} (3)

$$\sum_{j=1}^{m} \frac{W_{jio}}{1 - \beta_{ijo}} = V_i + \Delta V_i$$  \hspace{1cm} (4)

$$WVi = V_i + \Delta V_i - W_i = 0$$  \hspace{1cm} (5)

where, $j$ represents the region number, assuming that the study area contains $m$ regions, then $j = 1, 2, \ldots, m$; $k$ represents the number of water users, representing the volume of water available in $i$ period of the study area; $W_{jio}$ represents the water supply of optimal level users at time period $i$ and district $j$; $B_{ijo}$ represents the minimum water demand of optimal level users at time period $i$ and district $j$; $WVi$ represents the system water supply at the end of the time period $i$; $W_i$ represents the total supply for water users of the time period $i$.

(2) In a certain time period $i$, if the actual total amount of water supply $V_i$ is less than the ideal water demand of all users, but greater than the optimal level users’ minimum water demand, namely,

$$\frac{B_{io}}{1 - \beta_{io}} \leq V_i \leq \sum_{j=1}^{m} \sum_{k=1}^{n} \frac{G_{ijk}}{1 - \beta_{ijk}}$$  \hspace{1cm} (6)

$$\frac{B_{io}}{1 - \beta_{io}} = \sum_{j=1}^{m} \frac{B_{ijo}}{1 - \beta_{ijo}}$$  \hspace{1cm} (7)

where, $k$ represents the number of water users, then $k = 1, 2, \ldots, n$. Then in accordance with the minimum requirements for domestic water of the study area, because domestic use and electricity generation have priority for water, if the water supply is greater than the minimum water requirements of domestic use and electricity generation etc. If the water supply is sufficient, all the water demand can be satisfied. The remaining water is distributed proportionally according to the priority and minimum water demand of each user. If water is still available, then the process is repeated, the loop ends when there is no water left. That is,

$$W_{jio} = B_{jio}$$  \hspace{1cm} (8)

$$W_{ije} = \frac{V_i - B_{io} - B_{ije}}{1 - \beta_{ijo}} (B_i - B_{io})$$  \hspace{1cm} (9)

$$WVi = G_{ijo} - B_{ijo}$$  \hspace{1cm} (10)

$$Wije = (V_i - W_i - G_{ijo}) \frac{L_{ijk}}{L_{it}}$$  \hspace{1cm} (11)

$$WVi = V_i - W_i = 0$$  \hspace{1cm} (12)

(3) In a certain time period $i$, if the actual total amount of water supply $V_i$ is more than the ideal water demand of all users:

$$V_i \geq \sum_{j=1}^{m} \sum_{k=1}^{n} \frac{B_{ijk}}{1 - \beta_{ijk}}$$  \hspace{1cm} (13)

Then all users are satisfied, and the remaining available water is greater than zero. That is:

$$W_{ijk} = G_{ijk}$$  \hspace{1cm} (14)

$$WVi = V_i - W_i > 0$$  \hspace{1cm} (15)

**Objective function**

In case (2), we allocated the water resources optimally. The purpose of water resources optimal allocation is to obtain
the highest system satisfaction. Also, taking into account the dynamic nature of water allocation, the system requires two adjacent periods of satisfaction with the smallest difference:

\[
\max S_i = \sum_{j=1}^{n} \left( \frac{W_{iq}}{G_{iq}} \right) \alpha_{ij} \\
\min \Delta S_i = |S_i - S_{i+1}| (16)
\]

where, \(i\) is the period number; \(j\) represents the number of users, \(n\) represents the total number of users; \(\alpha_{ij}\) represents at \(i\) time the \(j\) user weighting coefficients, \(S_i\) represents the system satisfaction at \(i\) period. As the objective function indicator system, a larger value of \(S_i\) is better. \(\Delta S_i\) represents the difference between two adjacent satisfactions with the system time, which is another indicator system of the objective function; a smaller value of \(\Delta S_i\) is also better.

\section*{Constrained conditions}

\subsection*{Water volume constrained}

\[
W_i \leq V_i + \Delta V_i (18)
\]

where, \(W_i\) represents the total water supply at \(i\) time period, \(V_i\) represents the system water volume available and \(\Delta V\) represents the sum interval of water entering and leaving the system, including upstream of the river and surrounding tributaries of the river.

\subsection*{Water volume constrained by maximum and minimum water demand}

\[
B_{iq} \leq W_{iq} \leq G_{iq} (19)
\]

where, \(B_{iq}\), \(W_{iq}\) and \(G_{iq}\) represent the minimum water demand, the actual amount of water and the ideal water demand of users in \(j\) region at \(i\) time.

\subsection*{Water volume balance constrained by time}

\[
V_{i+1} \leq V_i + \sum_{k=1}^{m} LV_{ki} - SV_i - QV_i (20)
\]

where, \(V_{i+1}\), \(V_i\) represent the system water volume available at \(i + 1\) and \(i\) time, \(\sum_{k=1}^{m} LV_{ki}\) represents the sum of \(k\) channel water volume at \(i\) time, \(SV_i\) represents the system water loss at \(i\) time and \(QV_i\) represents the abandoned water at \(i\) time.

\section*{Model solution}

The first step is to set the initial conditions and input the model parameters. This includes setting the water usage and water quality, and information about the river water intake conditions. There are urban water users, industrial, agricultural and other users. The water demand contains the ideal water requirement and the minimum water requirement. Water intake information can be broadly divided into two categories: agricultural and non-agricultural water intake. River conditions include the upper and lower water level settings. Other settings include selecting each weight coefficient of water users, the water loss coefficient, etc.

The second step is to compare the volume of available water with the water demand. If the volume of available water is less than the minimum water demand of priority water users, the emergency water diversion is carried out to increase the amount of water available, and to best meet the basic needs of priority water users. If the available water is greater than the volume of water required for each user, then the satisfaction of each water user is 100%. If the volume of available water lies between the above two conditions, priority is given to meet the minimum water requirement of urban life and the key industries (priority water users), and then water is allocated to other users by weighting coefficients until the available water is zero. Finally, the results are produced, and the satisfaction of each water user’s supply is obtained. The scheme is shown in Figure 1.

\section*{APPLICATION}

\subsection*{Area description}

In Huai River, from Zhengyangguan to Bengbu Sluice, the difference between water supply and demand is serious in the low-flow period, and a study on the regional water resources optimal allocation is needed. Zhengyangguan and Bengbu Sluice are located in the middle reaches of Huai River (Figure 2), most of the area is flat terrain,
a slope from the northwest to the southeast, and the ground elevation is generally about 30 m. The study area geology is mostly alluvial plain with some lacustrine plain. The aquifer is poor on water storage and drainage.

The study area is also located in China’s north-south climate transition zone. The average annual rainfall is 600–1,400 mm, the average annual runoff depth is 270–300 mm, the average annual runoff coefficient is about 0.2–0.3, the average annual evaporation is 1,000–1,100 mm, and the drought index is about 1–1.5. The maximum rainfall is 3–4 times greater than the minimum rainfall, and the ratio between maximum and minimum runoff is 5–30. The annual distribution of rainfall and runoff is extremely uneven; there are often several significant rainfall events in 1–2 months and a serious flood in the flood season (Peng 2013).
The status of water resources

Precipitation

Based on the Huai River Basin water resources survey, according to the 2001–2010 Huai River water resources bulletin, the regional average precipitation is 994.3 mm. The precipitation distribution is not uniform; the southern area of the Huai River Basin experiences more precipitation than that of the northern area, and there is more precipitation upstream compared to downstream. The interannual precipitation upstream of the Bengbu sluice varies greatly; the precipitation quantity difference coefficient changes between 0.2 and 0.25, increasing from the south to the north. According to the average rainfall statistics from 1956–2010, there were 18 years of abundant water, accounting for 40%, and 17 years of water scarcity, accounting for 38%; wet and dry years alternate frequently, and often occur continuously.

The volume of surface water resources

According to the 1956–2010 natural runoff series analysis, the maximum annual natural precipitation is $1.81 \times 10^{10}$ m³, and the minimum annual natural runoff is $1.85 \times 10^{8}$ m³. From Lutaizi to Bengbu Sluice, the multi-year average runoff depth is 220 mm.

The volume of groundwater resources

Based on the Huai River water resources survey, according to the 2001–2010 Huai River resources bulletin, the average groundwater resource in the middle reaches of Huai River is $1.70 \times 10^{10}$ m³. This ranges from $1.32 \times 10^{10}$ m³ in the plains, and $3.74 \times 10^{9}$ m³ in the hills.

In this paper, three factors were considered when computer models of water resources allocation of the study area were proposed: (1) the inflow conditions at the Bengbu Sluice; (2) the normal water level at the Bengbu Sluice; (3) the diversion water level at the Bengbu Sluice. According to the present situation of water resources allocation, and the relevant planning combined with different timeframes, different schemes of water resources allocation were obtained.

For both the present situation and planning timeframes, the normal water level at the Bengbu Sluice is 18.0 m, and the starting regulation level is 17.25 m, which is in accordance with the multi-year (1956–2010) average water level at the end of the flood season. The water supply level is according to the rates of 90% typical years.

The allocation scheme is as follows. (1) In the present situation (2010), the water volume is determined by the actual water discharge, the lower water level limit at the Bengbu Sluice is set at 16.0 m. (2) In the short-term planning timeframe (2020), the water volume is reduced by 10% of the present situation. The lower water level limit at the Bengbu Sluice is set at 15.5 m. (3) In the long-term planning timeframe (2030), the water volume is reduced by 20% of the present situation. The lower water level limit at the Bengbu Sluice is set at 15.5 m. For each year, the low-flow period is determined according to the water discharge and consumption, and the lower water level is also adjusted by the actual condition.

**DISCUSSION**

In both the present situation and short-term planning timeframes (2010, 2020), the equilibrium of supply and demand was calculated using the model, and the water allocation results were obtained. In each period, the satisfaction of each water user (urban living, industry, agricultural irrigation and other users), was close to 1, and the non-agricultural water intake can be carried out according to the design flow of the water intake.

In the long-term planning timeframe (2030), the equilibrium of supply and demand in different typical years was calculated using the model, and the water allocation results were obtained. In late May and September, the system satisfaction was very much lower, hence, considering the principle of sustainable water utilization, the water supply scheme was adjusted, and the result is shown in Figures 3 and 4.

In Figure 3, the columns show the satisfaction in mid and late May before adjustment, the overall satisfaction in mid May is close to 1, while in late May, the satisfaction of the system is lower, because there is insufficient water for tertiary industry, general industry and other water users can't get enough water. The triangles show the satisfaction after using the model to adjust the water allocation, the overall satisfaction increases and the objective function $\Delta S_i$ decreases.
Figure 4 shows the overall satisfaction from late August to mid September, the satisfaction of mid September before adjustment is low. By using the model to adjust the water allocation of late August and early September, the overall satisfaction increases.

Compared to other water allocation models, this model not only considered the space factor, but also included time as a variable.

On the whole, this model applied this condition: the water supply is more than the minimum water demand of priority water users and less than the total amount of water users’ needs. This model gave priority to meet the minimum water requirement of urban life and the key industries (priority water users), and then allocated water to other users by weighting coefficients. In addition, the satisfaction level is solely based on the water supply available in this basin, and this is one of the limitations of this study.

CONCLUSIONS

Water shortage has already become a common global crisis, and water resources play an important role in people’s production and life. There is quite a large difference in water distribution between the north and south of China. The precipitation belt tends to be in south China and much reduced north of the Yangzi River. With the rapid development of economy and society, the difference between the supply and demand for water resources is becoming increasingly acute in the main stream of the Huai River from
Zhengyangguan to the Bengbu Sluice. This was the area of research. This study built a multi-objective dynamic water resources allocation model, which took the overall satisfaction of users in a time interval as the objective function, using an improved simplex method calculation, considered the overall satisfaction variation with time, and followed the principle that the system satisfaction within adjacent periods of time must be minimal. This achieved the dynamic balance optimization of allocation of water resources in time and space. After application, the users’ satisfaction of users in the study area in low-flow periods was increased, and conflict between water supply and demand was appeased. These results provide direction for future research.

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