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Optimal Deployment of Water Resources Based on Multi-Objective Genetic Algorithm

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Abstract

Freshwater is limited resource and it is shrinking rapidly due to the urbanization, contamination and climate change impacts. As a result, raising water demands and insufficient freshwater resources become the main reasons of water conflicts. Optimal water allocation model would be an effective method to achieve the optimal allocation of limited water resources, in terms of the conjunctive use planning and management. In this paper, a multi-objective optimal water resources allocation model is proposed and the social, economic and environmental benefits are regarded as the optimal objective functions. The presented model is applied to a case of planning water resources management in China. Furthermore, simulations and optimization modeling methods have been conducted to solve the allocation model. The Gray Model has been used to predict the fresh water demand and storage of different user parts in 2025 and the Genetic Algorithm technique has been employed to solve the multi-objective problem. The obtained results illustrate how to allocate the quantity of different water resource to different users while achieving maximum social, economic and environmental benefits, which is valuable and helpful to develop a water resources optimal allocation strategy.

Keywords: *sustainable water allocation strategy; multi-objective optimization model; gray model; genetic algorithm*

1. Introduction

Fresh water is an indispensable and valuable resource for human survival and society development. With the rapid development of economy, population and environmental pollution, fresh water becomes the limiting constraint for development in much of the world [1-2]. Hence, water resources optimization allocation management becomes the urgent sustainable development polices in many countries. As for China, though the total water resources of China ranks sixth in the world, the per capita of China accounts for only 25% of the world average [3], which indicates China is a water-scarce country. Moreover, the most significant character of water resource in China is uneven geographical distribution and also the amount of fresh water is dramatically affected by season [4]. Specifically, in the 21st century, the development of economy and population in China is faster than ever before, which mainly results in more serious water shortage and water pollution issues. Therefore, it is necessary to develop an effective, feasible and cost-effective water allocation strategy to dealing with the contradiction caused by increasing water demands and inadequate water supplies. Researchers proposed that an effective deployment strategy of water resources is helpful to achieve the coordinated development in terms of social economic resources and ecological environment [5]. Therefore, for the sake of relieving the water conflict and promoting sustainable development of water resources, it is of significance to develop a sustainable development police to allocate the limited water resources reasonably in China.

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Water allocation problems are mainly discussed and studied based on the theory of optimization techniques [6]. As far as we know, by reviewing previous literatures, past researches were mainly focused on using single objective optimization to resolve water allocation problem [7-11]. However, it is hard to make a feasible and reliable water allocation strategy based on only one water objective optimization. On the contrary, Multi-Objective Programming can be used resolve various water management issues effectively and reliably, water allocation management in especially, because multi-objective guarantees the sustainable utility of water allocation by considering different realistic aspects [12].

During recent years, a large numbers of Multi-Objective Programming model have been used for water allocation management. For instance, Babel *et. al.*, presented a water allocation model for a reservoir sustainable application in Thailand by using Multi-Objective Programming techniques [13]. They regarded the maximum of added water demand and the maximum economic benefit as the model objective, however the objective of social benefit or environmental benefit was ignored. Liu *et. al.*, proposed a Multi-Objective Programming model to optimize water allocation in Pearl River in China. The maximum economic and social benefit as well as the minimum amounts of polluted water were set as the objective functions[14]. However, the environmental benefit was not expressed in their model. Rezapour *et. al.*, developed a Multi-Objective Programming model which proposed three objective functions, but they failed to represent the economic and environmental factors [15]. In fact, there are various objectives (*e.g,* economic, social and environmental maximum benefit) should be considered in water allocation model to ensure the reliability and comprehensiveness of proposed model [16]. However, only few previous models included these multiple aims. Thus, in order to make water optimal allocation model more suitable and reasonable to the actual circumstances, we proposed a comprehensive multi-objective function in the model which includes the economic, environmental and social factors simultaneously.

In terms of approaches applied to solve the multi-objective programming problem, traditional methods like Main Objective Method and Ideal Point Method are easily affected by decision makers' personal preferences [17]. Furthermore, in order to obtain the optimal set of Pareto, traditional approaches are required to operate optimization process many times. But the optimization process of each time is independent, which results in inconsistent results and takes much time. Consequently, traditional methods could not solve multi-objective programming problem objectively and effectively. Instead, Genetic Algorithm can avoid these weak points as its solving process is not depend on gradient information and the target problem, meanwhile, it own robust and strong global search capability. Moreover, it can seek solutions in a larger space and generate multiple equilibrium solution in single optimization process, which dramatically enhance the efficiency of model solving. Therefore, Genetic Algorithms is an effective and suitable method to solve multi-objective programming problems.

In summary, the purpose of this article is proposing a multi-objective programming model for water resources optimal allocation according to the situation of China. Proceeding from the realities, the proposed model improve the module of the previous water allocation model by adopting multi-objective functions which considers the economic, environmental and social benefit simultaneously, and methodologies like Genetic Algorithms and Gray Model are introduced in the multi-objective programming model. Later in this article, the multi-objective programming model is applied to a case study which aims to analyze the water resources optimal allocation strategy in 2025 in China. The presented model is able to be used to help governments to identify water resources allocation plans.

This article is organized as follows. In Section 2, we demonstrate the main approach of our model building. In Section 3, the basic data like the situation of water demand and supply in China is obtained and analyzed. In Section 4, the optimal water allocation model is presented including its definition of constraints and objective functions. In Section 5, some parameters are introduced and calculated. The output of model are presented and discussed in Section 6. Finally, conclusions of this article are given in Section 7.

2. The Proposed Method

In order to develop a reliable water resources optimal allocation strategy, we need to find out the classifications of water sources, use and the main issues as well as the actual amount of fresh water available in 2025. Gray Model (GM) is a fit method to make predictions when we take advantage of small and single time series data to make a long-term forecast. By conducting GM, we can get the fitting curve of water demanded between 2000 and 2025 and obtain the detail of fresh water demanded in 2025. On the other hand, we can obtain the actual amount of freshwater supply in 2025 by establishing an annual average reduction function based on the total reduce amount of water resources in the past eight years. At the same time, we consider the ways to make up for the shortage of fresh water to meet the water demand. We notice that desalination can relief the water shortage problem in the coastal city and wastewater treatment also is an exceptional approach to make up for the water applying.

Based on the output of GM, we analyze the optimal allocation between water resources and users. As described above, multi-objective optimization model can demonstrate the relationship between supply and demand in the various water resources and users. Moreover, taking advantage of genetic algorithm is able to get the optimal allocation among various users and water resources (including desalination) in 2025. After that, we conduct with water diversion project cost-benefit analysis. As we know, the construction and transportation cost of water diversion project is included in its water price. Therefore we could compare the water resources efficiency coefficient with unit price of water to analyze the cost-effectiveness.

In terms of water storage and transport analyzing, we suppose to solve the problem of water shortages cause from season and the problem of uneven in geographical distribution of water resources. According to the situation of China, we indicate that the effective control of lakes can alleviate droughts and floods problem and by increasing supply of fresh water. Moreover, water diversion project can alleviate the uneven geographic distribution of water resources. On the other hand, desalination can relieve water shortages in coastal cities. As to analyzing the effective and feasible of water strategy, we consider whether the above-mentioned measures can be implemented under the existing conditions. From Ref. [18], we can learn that these measures has been used in worldwide and attach water resources, economic and environmental benefits, which means it is feasible and effective.

3. Prediction Of Water Demand And Supply

In order to reflect the essence of the problem, and avoid the secondary factor to simplify the model, the proposed model is developed based on three hypotheses. They are listed as follows: (1) there is not devastating natural disasters and war between 2013 and 2025 in China. (2) the water average decreased rate (*i.e.,* loss of groundwater and river) of China remain unchanged till 2025. (3) the unit costs for desalination of sea water and fresh water transfer are the same in different areas.

3.1. Affiliations Prediction Of Water Demand

After seeking from the previous literatures, we notify that only few and single data is available for us to predict the trend of water demand from 2000 to 2025. Therefore, taking into account the characteristics of GM, we take advantage of GM (1, 1) to forecast the water demand of China in 2025.

According to the water situation of China and obtained data, we divide the application of water demand into four parts: industry, agriculture, domestic water and others. We obtained the original data of water demand between 2000 and 2010 from China Statistical Yearbook. The data of water demand in different parts between 2004 and 2010 are listed in Table 1.

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Table 1. Water Demand between 2004 and 2010 (10^8m^3).

Years	2004	2005	2006	2007	2008	2009	2010
Total water	5547.8	5633	5795	5818.7	5909.95	5965.15	6021.99
Industrial water	1218.9	1285.2	1333.8	1351.3	1343.7	1352.5	1366.5
Agriculture water	3643.7	3633.8	3694.3	3699.9	3775.7	3795.8	3841.6
Domestic water	633.6	651.2	695.1	693.8	710.2	726.4	713.8
Others	51.6	62.8	71.8	73.7	80.35	90.45	102.37

According to these original data, we make use of GM (1, 1) to predict the corresponding water demand in 2025. The results are shown in Table 2.

Table 2. The Output of GM (1, 1).

Category	C Value	P Value	Precision	Water demand (10^8m^3)
Industrial water demand	23.2%	100%	grade 1	1926.0
Agriculture water demand	57.7%	81.8%	grade 2	3987.9
Domestic water demand	15.9%	100%	grade 1	1063.4
Others	11.7%	100%	grade 1	584.6

From Table 2, we can obtain that the precision of GM (1, 1) is high and acceptable, which means the predicted water demand in 2025 can be used in further research.

3.2. Prediction Of Water Supply

We divided the source of water supply into four aspects: surface water, groundwater, desalination and wastewater reuse. By looking over the database of China Statistical Yearbook, we obtained the fact that the storage of surface water and groundwater decreased by 13% from 2000 to 2008. The storage of surface water and groundwater were $8000*10^8m^3$ and $1457*10^8m^3$ respectively in 2013. According to the second hypothesis, we get equation (1)

$$(1+x)^8 = 1-13\% \tag{1}$$

where X refers to the percentage of reduction of surface water and groundwater in each year. By solving equation (1), the value of X is -1.7%.

After that, we can calculate the amount of surface water and groundwater in 2025 through equation (2)

$$Y_{2025} = Y_{2013}(1-0.17)^{12} \quad (2)$$

where Y_{2013} refers to the storage of surface water or groundwater in 2013. Through equation (2), we get the amount of surface water and groundwater in 2025 are $6512.3*10^8 m^3$ and $1186*10^8 m^3$ respectively.

Moreover, according to the development of Chinese current sewage recycling processing technology and desalination technology, we estimate the supply of wastewater recycling could reach 45 $*10^8 m^3$ and the the demand of wastewater recycling could reach $10*10^8 m^3$ each year from 2014 to 2025.

4. Optimal Water Allocation Model

4.1. Introduction Of Genetic Algorithm

Genetic Algorithm is adapted to use in complex and nonlinear systems optimization by adaptive probability optimization techniques and its mechanism operation is based on the biological genetic and evolutionary mechanisms. The solving process of Genetic Algorithm is not depended on gradient information and the target problem and it has strong ability of solution seeking in a lager solution space. Thus it is quite suitable to be a tool to solve multi-objective programming problem. The algorithmic process of Genetic Algorithm is shown in Figure (1).

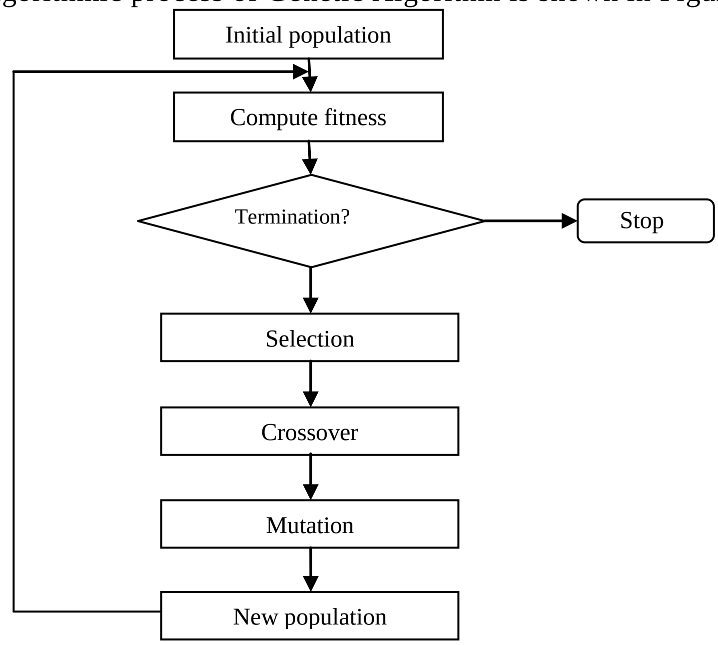

Figure 1. The Algorithmic Process of GA

4.1. Model Building

4.2.1. Water Supply And Demand Relationship: We take advantage of matrix R to demonstrate the supply and demand relationship between water resources and users.

$$R=\left(r_{ij}\right)=\begin{pmatrix}1&1&1&1\\1&1&1&1\\0&1&1&0\\0&1&0&0\end{pmatrix} \tag{3}$$

where r_{ij} represents the relationship between supply and demand of water source i and user j. Specifically, r_{i1} , r_{i2} , r_{i3} , r_{i4} represent agricultural water, industry water, domestic water and others respectively and r_{1j} , r_{2j} , r_{3j} , r_{4j} refer to surface water, groundwater, desalination and wastewater reuse separately. While r_{ij} =1 means water source i provides water to user j and r_{ij} =0 indicates water source i does not provide water to user j.

4.2.2. Objective Functions:

(1) The function of economic benefit $f_1(x)$: maximize the benefit of water supply

$$\max\ f_1\left(x\right)=\sum_{j=1}^{4}\sum_{i=1}^{4}\left(b_{ij}-c_{ij}\right)x_{ij}\alpha_i\beta_j w_k \tag{4}$$

where x_{ij} represents the amount of water source i provides to user j (hundred million m^3); b_{ij} refers to the water supply effective coefficient of water resources i with user j (RMB/ m^3); c_{ij} represents the water supply cost coefficients of water resources i with user j (RMB/ m^3); α_i refers to the priority coefficient of water supply; β_j refers to the fair coefficient of the user using water; wk refers to the supply of water resources k.

(2) The function of social benefit $f_2(x)$: minimum water deficit

$$\min f_2\left(x\right)=\sum_{j=1}^{4}(\mathrm{D}_j-\sum_{i=1}^{4}x_{ij}) \tag{5}$$

where D_j represents the water demand of user j (hundred million m^3).

(3) The function of environmental benefit $f_3(x)$: minimum discharge of COD

$$\min f_3\left(x\right)=0.01\sum_{j=1}^{4}d_j p_j\sum_{i=1}^{4}x_{ij} \tag{6}$$

where d_j refers to the content of pollution factor (Chemical Oxygen COD) in sewage per unit volume owned by user j (mg/L); p_j represents the sewage discharge coefficient of user j.

4.2.3. Model Constraints:

(1) constraints of water resources available

$$\sum_{j=1}^{4}x_{ij}\le W_i \tag{7}$$

where W_i represents the storage of water source i.

(2) constraints of water supply upper limits

$$x_{ij}\le Q_{ij},\quad Q_{ij}=\min\left\{W_i,D_j\right\} \tag{8}$$

Compared against constraint (1), constraint (2) constrains the supply upper limits of single user. Constraint (1) and (2) illustrate that the supply of water source i provides to user j cannot exceed its storage and the water demand of user j.

(3) constraints of water demand

$$L_j \leq \sum_{j=1}^{4} x_{ij} \leq H_j \tag{9}$$

where L_j refers to the water demand lower limits of user j and H_j refers to the water demand upper limits of user j.

(4) constraints of coordinated regional development

$$\mu = \sqrt{\mu_{B1}(\sigma_1)\mu_{B2}(\sigma_2)} \geq 0.8 \tag{10}$$

where μ_{B1} refers to the ratio of water supply and demand; μ_{B1} refers to the ratio of per capita GDP growth and COD emissions growth. We take advantage of these two coefficients to reflect the coordinated regional development which includes the utilization of water resources, economic development and environmental improvement. Moreover, by referring Ref.[18], we assume the lowest value of coordinated regional development index is 0.8.

(5)Water supply non-negative

$$x_{ij} \geq 0 \tag{11}$$

5. Calculation Of Parameters

5.1. α_i And β_j

According to the principle of fairness, we define β_j to descirbe the priority of user j getting water supply. As domestic water is more important than the production of water, the water allocation strategy should give higher priority to domestic water. Therefore, we can get the priority water demand rank which is listed as follow (from high to low): domestic water, industrial water, agricultural water and others. According to equation (12),

$$\beta_j = \frac{1 + n_{\max} - n_j}{\sum_{j=1}^{4}\left(1 + n_{\max} - n_j\right)} \tag{12}$$

we obtain the values of fair coefficients are 0.4, 0.3, 0.2 and 0.1 respectively.

Similarly, according to low cost priority principle, we can get the priority water supply rank which is listed as follow (from high to low): surface water, groundwater, wastewater reuse and desalination. According to equation (12), we get the values of the fair coefficients are 0.4, 0.3, 0.2 and 0.1 respectively.

5.2. Upper And Lower Limits Of Water Demand

Based on the water consumption characteristics of each user, we define the upper and lower limits of water demand as follow:

(1) upper and lower limits of domestic water

$$H_1 = L_1 = D_1 \tag{13}$$

(2) upper and lower limits of industrial water

$$\begin{cases} H_2 = D_2 \\ L_2 = 0.8D_2 \end{cases} \tag{14}$$

(3) upper and lower limits of agricultural water

$$\begin{cases} H_3 = D_3 \\ L_3 = 0.7D_3 \end{cases} \tag{15}$$

(4) upper and lower limits of other water

$$\begin{cases} H_4 = D_4 \\ L_4 = 0.6D_4 \end{cases} \tag{16}$$

5.3. Weight Coefficients And Other Parameters

According to equation (12), the weight values of the economic, social and environmental goals are 0.40, 0.33 and 0.27 separately. On the other hand, we refer to Sun's research [18] and obtain the values of the water supply cost coefficients c_{ij} and effective coefficient b_{ij} which are listed as follow:

$$c_{ij} = \begin{pmatrix} 1 & 4 & 2 & 1 \\ 1 & 4 & 2 & 1 \\ & 5 & 4 & \\ & 5 & & \end{pmatrix} \tag{17}$$

$$b_{ij} = \begin{pmatrix} 20.88 & 78.74 & 0 & 11.53 \\ 20.88 & 78.74 & 0 & 11.53 \\ & 78.74 & 0 & \\ & 78.74 & & \end{pmatrix} \tag{18}$$

6. Results And Discussions

We transform multi-objective functions into a single objective function and construct a penalty function p(x)

$$p(x) = \begin{cases} 0, \text{ when x is feasible} \\ \sum g_k(x), \text{ when x is not feasible} \end{cases} \tag{19}$$

where $g_i(x)$ represents constraint condition (1) and (3).

$$\sum g_k(x) = \left|(\sum_{j=1}^{4} x_{ij} - W_i) + (\sum_{j=1}^{4} x_{ij} - H_j) + (L_j - \sum_{j=1}^{4} x_{ij})\right| \tag{20}$$

Then we can obtain the equation of new single objective function $h_i(x)$ listed below:

$$\min h_i(x) = f_i(x) + \theta p(x) \quad (i = 1,2,3) \tag{21}$$

where Θ represents the penalty factor. The value of penalty factor indicates the significance of outliers to model. Larger penalty factor means less simples would be abandoned. As samples are important for model solvin, we decided to set Θ equal to 60, which had a better performance for model solution after simulating penalty factor with 20, 40, 60, 80, 100.

Then, by using the GA toolbox in Matlab to solve the single objective optimization model, we get the optimal values f^*_1, f^*_2 and f^*_3. The distance function R(x) is defined as follow.

$$\min R(x) = \sqrt{(f_1(x) - f_1^*)^2 + (f_2(x) - f_2^*)^2 + (f_3(x) - f_3^*)^2} \tag{21}$$

Similarly, we use Genetic Algorithm toolbox in Matlab to solve the single objective optimization model with $Population\ size = 100$, $Chromosome\ length = 160$, $Crossover\ probability = 0.6$, $Mutation\ probability = 0.01$ and $Hereditary\ algebra = 100$. We obtained the final results shown in Figure 2.

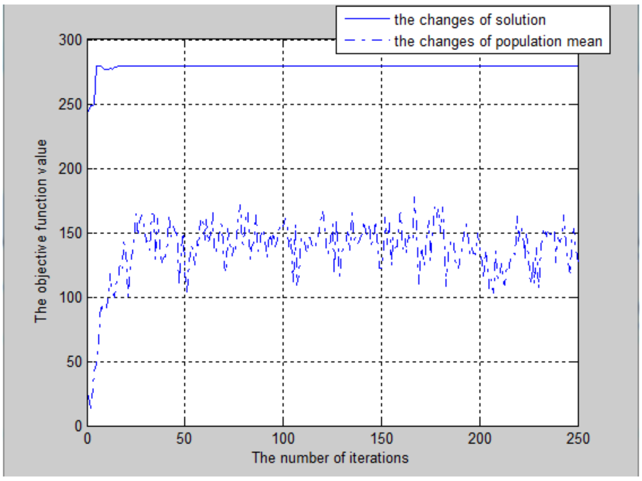

Figure 2. The SolutionTtrend in the Iterations

From Figure 2, we can know that at about 20th generation the solution reaches maximum value and stabilizes around 280. The corresponding values of x are shown below.

$$x = \left(x_{ij}\right) = \begin{pmatrix} 3363.63 & 1527.8 & 953.921 & 554.357 \\ 593.58 & 220.887 & 127.61 & 29.23 \\ 0 & 36.81 & 10.634 & 0 \\ 0 & 55.22 & 0 & 0 \end{pmatrix} \tag{22}$$

From the value of x, we are able to get data between the supply and demand relationship in the water optimal allocation, which is obtained under the premise of achieving the maximum economic, social and environmental benefit. Specifically, in order to satisfy the water demand of difference users and achieve the objective functions, the resource of surface water should supply quantity of about $3363.63*10^8 m^3$ to agriculture user, $1527.8*10^8 m^3$ to industry user, $953.921*10^8 m^3$ to domestic user and $554.357*10^8 m^3$ to others. The allocation details are listed in Table 3.

Table 3. The Supply of Different Water Resources to Different Users (108m3)

	Agricultural water	Industry water	Domestic water	Others
Surface water	3363.63	1527.8	953.92	554.36
Groundwater	593.58	220.89	127.61	29.23
Desalination	0	36.81	10.63	0
Wastewater Reuse	0	55.22	0	0

When the social, economic and environmental benefits achieve the maximum value, the optimal allocation of water sources in different users is shown in Figure 3.

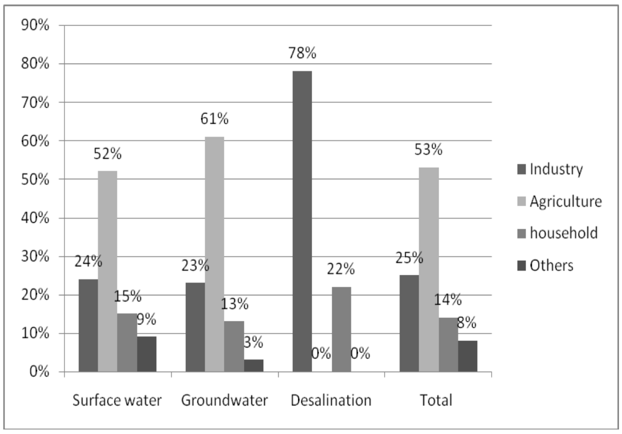

Figure 3. The Allocation of Water Sources in Different Users

By solving this multi-objective water allocation model, we are able to understand how to allocate the quantity of different water resource to different users when achieving maximum social, economic and environmental benefits. Thus, we could further develop the water resources optimal allocation strategy based on this model.

7. Conclusions

In this study, a multi-objective water allocation model with three objective functions has been presented. The objective functions aimed to address the social, economic and environmental factors which are necessary to be considered for the sake of achieving a sustainable water allocation. Later in this article, the proposed model was applied in a case study in China which purposes to develop an optimal water allocation strategy. Considering the multiple objective and uncertainties in water resources allocation system, the basic water optimal allocation plans and the precise quantity of water supply to different users were obtained. Besides, the results of the presented model provided scientific basis water allocation data for further developing water resource optimal allocation strategy. Moreover, the proposed model could be further applied for water optimal allocation in a specific city, which could further expand its practical significance.

Though reasonable solutions have been obtained through the multi-objective water allocation model, there are still some extensive research works to be done. In this paper, real word problems are simplified into several situations and hypotheses. For example, the rate of the water reduce is hard to predict as it is affected by many factors (*i.e.*, climate change, water policy and the development of industrialization *etc.*,). However, in this study, the presented model is built under the premise of assuming the rate remain unchanged in the future. Besides, more objective functions should be paid attention to. For instance, the maximum profit of shared basin derived from allocated water to different users could be considered, which also is an importance perspective of effective water resource allocations. Consequently, the integration of these limitations as well as searching for more efficient solution methods to solve optimal multi-objectives problem would be interesting topics that deserve future research efforts.

9. Conflict Of Interest Statement

This article content has no financial, commercial and associative relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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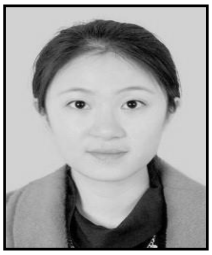

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