Optimal allocation model of the water resources in Harbin under representative concentration pathway scenarios
Fanxiang Meng, Linqi Li, Tianxiao Li and Qiang Fu

ABSTRACT

Water conservation is a strategic choice for sustainable societal development. Rational planning and allocation of water resources is an effective way to improve the efficiency of water resource utilization. Taking Harbin as an example, this paper constructs a linear fractional programming model based on chance-constrained programming. The model can reflect the randomness of water inflow under different climatic conditions while taking into account the interests of different decision makers at the upper and lower levels and the two contradictory objectives of maximizing economic benefits and minimizing water demands to improve water distribution efficiency and reduce the complexity of water resource distribution systems. The results showed that under the three climatic scenarios of RCP4.5, RCP6.0, and RCP8.5, the agricultural water supply accounted for 90.04%, 87.66%, and 84.15% of the total regional water supply, respectively. In the process of building the model, considering the importance of sewage treatment in water safety evaluations, the cost of sewage treatment is included in the upper-level benefits of the model. The sustainable development of water resources should be guaranteed while rationally allocating water resources and pursuing economic benefits.

Key words | chance-constrained programming, linear fractional programming, water resource allocation

HIGHLIGHTS

- A multi-objective programming model is developed for sustainable water resources allocation.
- The randomness of water inflow under different climatic conditions can be handled.
- The complexity of water resource distribution systems can be reduced by taking into account the interests of different decision makers at the upper and lower levels and the two contradictory objectives of maximizing economic benefits and minimizing water demands.

INTRODUCTION

With the increase in population and the rapid development of the economy, the water resources shortage has made conserving water resources a focus of attention (Han et al. 2018). Water resource utilization provides the basis for regional social and economic development. Optimal allocation of regional water resources is an important method for the rational development and utilization of water resources (Fang et al. 2018). Regional water resource allocation has the advantages of unified management and a complete water supply system. Meanwhile, climate change has a greater impact on water resources, balancing surface water resources and groundwater resources, and there are contradictions between supply and demand among water departments. For example, due to the impact of climate change, the interannual change in surface water resources is uneven and irregular. In areas where groundwater...
overexploitation is intense, the use ratio of surface water and groundwater becomes important. In areas with water shortage, by measuring the benefits of the water supply, we can ensure that the water demand of the water sector is met. Moreover, it is also necessary to consider the sustainable development of water resources when solving the problem of regional water resource allocation. At present, the optimal allocation of regional water resources considering the needs of decision makers is worth studying.

The uncertainty of climate change has a serious impact on surface water resources (Faiz et al. 2019; Zhang et al. 2019). Correct prediction of future surface water resources can ensure the reliability of optimal regional water resource allocation. The fifth assessment report (AR5) released by the Intergovernmental Panel on Climate Change (IPCC) provides a comprehensive assessment of almost all global climate models (GCMs) under representative concentration pathways developed by global centers for climate modelling and research currently participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5). GCMs use mathematical equations, and climate models can simulate the exchange of air, water, and energy among components given user-specified input parameters (Matthews & Lamontagne 2017). Pierce et al. (2008) found that the average value of multimodal sets is superior to any individual model in global and regional studies. Researchers often examine water resource changes using global circulation models (GCMs) (Gaetani & Mohino 2013; Zamani & Berndtsson 2019). Yan et al. (2015) found that river flows within the Pearl River basin will become more variable in the future based on using GCMs to study future climate change. Zhang et al. (2016) estimated streamflows in the Xin River Basin, China, based on climate change scenarios downscaled from different GCMs. Four GCMs were selected in this study to estimated regional climate change, especially the temperature and precipitation changes in the future.

Making decisions is part of our daily lives. In the last two decades, multiple objective decision making (MODM) techniques have been applied to solve practical problems such as systems reliability, transportation planning, traffic management, water resource management, forest management, and so on. Many scholars have proposed a series of models to solve these problems (Han et al. 2018; Liu et al. 2019). Li et al. (2019) has adopted an integrated model, called AWEFSM, for the sustainable management of limited water-energy-food resource in an agricultural system. Lv et al. (2022) developed interval fuzzy bilevel programming (IFBP), which can weigh the optimality and reliability of different water use sectors to reasonably supply water under uncertain conditions. Linear fractional programming (LFP) with chance-constrained programming (CCP) has proven to be an effective approach. Zhu & Huang (2011) combined linear fractional programming (LFP) with the chance-constrained programming (CCP) model to solve the problem of waste flow distribution in municipal solid waste management systems. Ren et al. (2013) applied this method to optimize the industrial structure of Jinchang and analysed whether its carrying capacity can meet the requirements of economic development in Jinchang. In this study, the LFP model can better balance the contradiction between benefits and water resources allocation by using the upper and lower targets. Meanwhile, the different climate change scenarios are considered, and the probability of occurrence of each scenario can be appropriately weighed by the CCP model. Considering the contradiction between economic benefits and water supply, this paper couples LFP and CCP to establish an optimal allocation model of regional water resources to adjust the water allocation quota of each water user.

Considering climate change, LFP and CCP were coupled. Taking Harbin city as an example, the optimal allocation model of regional water resources was established. Under the target year water shortage scenario, the joint water allocation scheme of surface water and groundwater was established. Under the target year maximum water scenario, after guaranteeing the water storage requirements of each user, the water supply scheme with a high economic benefit ratio was considered.

Accordingly, the study entailed the following elements:

1. By coupling LFP and CCP, the model can solve the contradiction of water demand departments and adjust the mode and quantity of water supply in water-deficient areas.
2. Four GCMs estimated regional climate change, reducing the uncertain influence on the optimal allocation of regional water resources.
(3) Considering the importance of sewage treatment, the cost of sewage treatment was included in the upper-level benefits of the model.

**LINEAR FRACTIONAL PROGRAMMING MODEL BASED ON CHANCE-CONSTRAINED PROGRAMMING**

**Linear fractional programming (LFP)**

LFP can address the situation in which the ratio between two functions, such as cost and time, cost and volume, and cost and profit, are considered simultaneously. Sometimes, an LFP model can better balance the contradiction between the two goals and obtain a better optimization solution than optimizing each function separately.

LFP is used to solve the ratio of programming problems that have two goals in the upper and lower levels of the model. Common fractional programming models can be expressed as follows (Lotfi et al. 2010):

\[
\begin{align*}
\text{max} f(x) &= \frac{cx + a}{dx + \beta} \\
Ax &\leq b \\
x &\geq 0
\end{align*}
\]  

(1)

where \( A \) is an \( m \times n \) matrix, \( x \in \mathbb{R}^n \), and \( b \in \mathbb{R}^m \); \( c \) and \( d \) are row vectors of the \( n \) dimension vector, \( a \) and \( \beta \) are parameters, and \( dx + \beta > 0 \) because the denominator is constant in sign in the feasible region (Charnes & Cooper 1962).

The duality theory is used to solve the LFP model. The duality of LFP has been studied by many scholars (Chadha 1977; Chadha & Chadha 2007). Bector (1973) describes the duality of LFP, which is constrained by variables of the original programming. Swarup (1968) proposed the duality of LFP and claimed that the objective function is a linear fraction but the constraints are essentially nonlinear. Charnes & Cooper (1962) showed that if the denominator is constant in sign in the feasible region, the LFP can be optimized by solving a linear programming problem. The dual model is denoted as DP (dual programming) and is represented as follows:

\[
\begin{align*}
\min g(y, z) &= z \\
A^T y + d^T z &\geq c^T \\
-b^T y + \beta z &= \alpha \\
y &\geq 0
\end{align*}
\]  

(2)

where \( T \) represents the transposition of a matrix, \( L \) denotes the set of constraints for dual problems, \( y \) is a column vector with \( m \) components, and \( z \) is a scalar. That is, \( L = \{ y, z; A^T y + d^T z \geq c^T; -b^T y + \beta z \geq \alpha; y \geq 0 \} \).

Model (2) is a linear model that can easily obtain its optimal solution \((\hat{y}, \hat{z})\). The relaxation column vector \( \hat{v} \) is introduced, where \( \hat{v} = a^T \hat{y} + d^T \hat{x} - c^T \) and \( \hat{v} \geq 0 \). When \( \hat{x} \) is the optimal solution of model (1), \( \hat{v} \) is the relaxation column vector, \( a\hat{x} + \hat{u} = b \), and \( \hat{u} \geq 0 \). According to the relaxation theorem, if \( \hat{x} \hat{u}_i = 0 \) and \( \hat{y} \hat{u}_i = 0 \), then models (1) and (2) have the same optimal solution. Thus, the LFP model can be solved by the above optimal transformation.

**Chance-constrained programming (CCP)**

CCP can quantitatively address practical problems with randomness. It is necessary to calculate the probability of constraints. According to Pagnoncelli et al. (2009), the CCP model can be expressed as follows:

\[
\min f(x), \text{s.t.} \text{prob}(G(x, \xi) \leq 0) \geq 1 - \alpha
\]  

(3)

where \( x \in \mathbb{R}^n \), \( \xi \) is a random vector, \( P \) is a probability distribution with \( \alpha \in (0, 1) \), and \( f: \mathbb{R}^n \to \mathbb{R} \) is a real-valued function. In the CCP model, even for simple equations \( G(x, \xi) \), the numerical solution of Equation (3) is difficult. One reason for this difficulty is that for a given value \( x \in X \), it is difficult to calculate prob\((G(x, \xi) \leq 0) \) because multi-dimensional integration of the equation is needed. To address stochastic constraints, the Monte Carlo simulation is employed to check the feasibility of a solution in the proposed genetic algorithm (Iwamura & Baoding 1996). Therefore, the Monte Carlo simulation can test the feasibility of a given \( x \in X \). Another reason is that even if set \( X \) is convex and function \( G(x, \xi) \) is convex in \( x \), the feasible set of Equation (3) can be nonconvex. Therefore, there
are two different ways to solve this phenomenon to a certain extent. One method is to discretize the probability distribution $P$ by giving the probability level $p_i$ of the number of $i$ constraints by the Monte Carlo simulation; in this case, $p_i \in [0, 1]$. Another method is convex approximation using chance constraints. Because of the large amount of calculation in the Monte Carlo simulation, we chose to solve the CCP model by discretizing the probability distribution.

**Linear fractional programming model based on chance-constrained programming**

CCP is integrated into LFP to form an LFP model based on CCP. The model can solve multi-objective problems in multiple scenarios while simultaneously resolving conflicts of interest between upper and lower levels. The model is described as follows:

$$
\max f = \frac{\sum_{h=1}^{H} C_{ph} x_h + \alpha}{\sum_{h=1}^{H} p_h x_h + \beta} \\
\Pr \left( \sum_{h=1}^{l} x_h \leq b_{h} \right) \geq 1 - q \\
x_h \geq 0
$$

**Optimal allocation model of the water resources in Harbin**

**Overview of the research area**

Harbin is located in northeast China, is the capital of Heilongjiang Province and is one of the central cities in northeast China. Harbin is an important city in terms of political, transportation, economic, and cultural development in northeast China, and it has excellent land resources and abundant water resources. Harbin is an important food production base in China. The geographic location is shown in Figure 1.

**Research on regional climate simulation**

The climatic conditions in the study area are those of a temperate monsoon climate with distinct seasonal variations and a freezing period of up to 5 months. Summer precipitation is high and concentrated, and there are two flood seasons in the spring and summer of each year.

Temperature and precipitation are usually employed as the two main parameters in the projection of climate change impacts in water resources. This study mainly

![Figure 1](http://iwaponline.com/ws/article-pdf/20/7/2903/788768/ws020072903.pdf)

**Figure 1** | Geographic location of Harbin.
focused on GCM simulations of the temperature and precipitation performance. For more details about this dataset, we refer to Zamani & Berndtsson (2019). Next, we selected the model suitable for China and the northeast region according to the research area. Basic information on the CMIP5 models used in this study was presented in Wu et al. (2013), Meehl et al. (2012), Dufresne et al. (2013), Yukimoto et al. (2012). In summary, these four GCMs (BCC-CSM1-1, CCSM4, IPSL-CM5A-LR, and MRI-CGCM3) were selected to simulate the temperature and precipitation in Harbin.

The annual mean temperature simulation map from the four GCMs is shown in Figure 2. Figure 2 shows that the average annual temperature in Harbin was higher than that in normal years, which may be closely related to the population density and economic development.

The annual amounts of precipitation of the study area in 2050 simulated by BCC-CSM1-1, CCSM4, IPSL-CM5A-LR, and MRI-CGCM3 under the RCP4.5, RCP6.0, and RCP8.5 scenarios are shown in Figure 3. Figure 3 shows that the eastern and western parts of the study area have less precipitation, and most of the precipitation is concentrated in the southern and northern parts of the study area.

By comparing the annual average temperature and precipitation of the target year (2050) with that of the historical years, it can be seen that the average temperature in 2050 increases by 1.36 °C, and the average precipitation increases by 24 mm. The target annual temperature and precipitation
data simulated by the GCMs are entered into the hydrological model as basic data to simulate the target annual runoff.

**Prediction of available water resources**

Using the variable infiltration capacity (VIC) model to simulate runoff, the applicability of the VIC model in the study area was verified by Fu et al. (2018a, 2018b) Combined with the actual situation of surface water resource utilization in the study area, the final exploitation coefficient is determined, and the available water resources of Harbin in the target year of simulation are obtained. According to the forecasted available water resources, combined with the Harbin Statistical Yearbook and Heilongjiang Water Resources Bulletin, the available water resources of surface water and groundwater under the different RCP scenarios in the target year of 2050 are reasonably predicted. Table 1 lists the total surface (underground) water supply under the different RCP scenarios. The total water supply in the table applies only to the three sectors of municipality, industry, and agriculture considered in the study area.

<table>
<thead>
<tr>
<th>Scenarios (h)</th>
<th>Surface water ($10^8$ m$^3$)</th>
<th>Groundwater ($10^8$ m$^3$)</th>
<th>$p_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP4.5</td>
<td>50.13</td>
<td>26.82</td>
<td>0.3</td>
</tr>
<tr>
<td>RCP6.0</td>
<td>48.52</td>
<td>24.71</td>
<td>0.5</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>44.29</td>
<td>23.04</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Optimal allocation model of the water resources in Harbin

Under the condition of climate change, an optimal allocation model of water resources is established. There are three RCP scenarios to consider the available water resources in the target year 2050. To integrate the different scenarios into the LFP model, this paper introduces CCP. According to the probability of the scenarios from the Pearson type III (P-III) curve, \( p_h \) indicates the degree of likelihood that a random event will occur under level \( h \), \( p_h > 0, \sum_{h=1}^{H} p_h = 1 \).

LFP can effectively respond to the efficiency of the system when solving multi-objective programming problems. LFP can also consider the contradiction between the interests of the upper and lower levels. Therefore, LFP has certain advantages, especially in solving the optimization of the agricultural water use structure (Li et al. 2015). CCP can distribute the probability of different scenarios in future prediction so that the probability ratio between multiple scenarios can be reasonably considered. This model regulates the direct contradiction between the economic benefits of water use and water consumption and tries to find a relatively balanced water allocation result between the two. The upper level of the fractional programming model is the net profit of the water supply, and the lower level is the total amount of the water supply. The water supply schemes of the different water sources for the different sectors under the different scenarios in the target year are solved. The model is as follows:

### Objective function:

\[
\begin{align*}
\max F &= - \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{h=1}^{H} D_{ij} p_h X_{ijh}}{\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{h=1}^{H} p_h W_{ijh}} \\
&= \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{h=1}^{H} D_{ij} p_h X_{ijh}}{\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{h=1}^{H} p_h W_{ijh}}
\end{align*}
\]  

(7)

### Constraints:

\[
\begin{align*}
\sum_{i=1}^{I} X_{ijh} &\leq T_{jh} \\
W_{ijh} &\leq W_{ijh_{\text{min}}} \\
X_{ijh} &\geq 0
\end{align*}
\]  

(8) \hspace{1cm} (9) \hspace{1cm} (10)

where \( D_{ij} \) represents the water supply benefits for the different sectors and different water source units, yuan/m³; \( X_{ijh} \) is the amount of sector \( i \) from source \( j \) under scenarios \( h \), m³; \( i \) represents the different water users with \( i = 1, 2, 3 \) representing the water supply for the municipal, industrial, and agricultural sectors, respectively; and \( j \) represents the different water sources with \( j = 1 \) and \( 2 \) representing surface water and groundwater, respectively. According to the GCM simulation, in 2050 precipitation and temperature will increase at the same time. The increase in temperature will cause the increase in evaporation. According to the Climate Change 2014 - Synthesis Report, the precipitation increase in the future is mostly due to heavy rainstorms in extreme weather (Pachauri et al. 2015). The heavy rainstorm resources are difficult to store in the river; thus, using the available runoff for regional water supplies is not feasible. The water shortages under the different RCPs in the target year are treated as discrete functions, and the probability of the different water inflow scenarios are assumed to be \( p_h \) with \( h = 1, 2, 3 \). When \( h = 1 \), the target year has an adequate water supply, which is high flow. When \( h = 2 \), the target year has a moderate water supply, which is medium flow. When \( h = 3 \), this means that the target year has very little water, which is low flow, and \( p_1 = p_2, p_3 \) with \( \sum_{h=1}^{H} p_h = 1 \). \( T_{jh} \) is the total water supply of all water sectors for the different water sources, m³. \( W_{ijh} \) is the water demand of the different sectors for the different water sources, m³. \( W_{ijh_{\text{min}}} \) is the minimum water demand of the different sectors for the different water sources, m³. \( S_{ijh} \) is the water shortage penalty of the different sectors and different water source units (Li et al. 2016; Wang et al. 2017), yuan/m³.

### Data analysis

The contributions of the water resources to the social economy were quantified using the Heilongiang Statistical Yearbook (2007–2017), Heilongiang Water Resources Bulletin (2007–2017), Water Quota (DB23/T 727-2016) and Water Use Classification (DB23/T 728-2016) according to the actual situation of Harbin and making full use of statistical records and empirical formulas. The social and economic indicators of each water user in Harbin from
2006 to 2015 are accounted for. According to the amounts of available water resources obtained in Table 1, the model parameters of the available water resources, water supply quantity and unit water supply income of each water demand sector are determined.

**Major social and economic indicators**

This paper mainly focuses on the optimal allocation of water resources for Harbin’s three major water users, namely, the municipal sector, the industrial sector and the agricultural sector. Through the analysis of the data above over the years, the parameters needed in the model were calculated to ensure the reliability of the parameters in the model. For the municipal sector, the indicators of population, water consumption and economy were mainly analysed to determine the parameters of water supply income. For the industrial sector, mainly the indicators of economy, energy consumption, and pollutant discharge were analysed. When calculating the unit water supply income and water shortage penalty, while considering the benefits of industrial enterprises, the expenditure on the treatment of industrial pollutants should not be neglected (Wang et al. 2019). The agricultural sector, as a large water-demanding household, mainly considers the crop planting area, grain yield, economic benefits, and irrigation facilities to quantify the unit water supply income and water shortage penalty. These data are introduced in the supplementary material.

**Model parameter determination**

Among the constraints of the model, the maximum and minimum water demands of each water user have the greatest impacts on the optimal water allocation results. *Water Quota (DB23/T 727-2016)* and *Water Use Classification (DB25/T 728-2016)* were used as references, and the determination method of the water demand quota are mentioned in these standards. According to the actual situation and the per capita water consumption of the residents, the maximum (minimum) water demand of the municipal sector in the target year is predicted by considering the ways and conditions of urban and rural water uses. The industrial water demand, reclaimed water reuse and industrial water quota are also considered, and the maximum (minimum) water demand of the industrial sector in the target year is forecasted. The maximum (minimum) water demand of the agricultural sector in the target year is forecasted according to the crop types, planting areas, irrigation methods, and agricultural water facilities in Harbin. *Table 2* lists the maximum and minimum water supply targets for each water user in the study area.

In water resource planning and allocation, if the amount of available water resources can meet the users’ water demand, the economic benefit obtained is the net income. If the amount of available water resources fails to meet the maximum water demand of users, a corresponding penalty of water shortages will occur. The minimum water requirement set by the water demand department is to maintain the minimum water requirement for the normal operation of the department. Only meeting the minimum water requirement cannot produce great benefits. The maximum water requirement set is the maximum water requirement to ensure the steady development of the economy without wasting the limited water resources. Generally, Harbin, as the capital city of Heilongjiang Province, located along the main stream of the Songhua River Basin. The purpose of further optimizing the water resources is to adjust the water structures of groundwater and surface water and to ensure the functional water use of various departments on the premise of satisfying the sufficient ecological water quantities of rivers. The treatment costs of wastewater and COD discharge in Table 3 are considered, combined with the calculation index of the treatment cost of a sewage treatment plant adopted by Fu et al. (2018a, 2018b), and the treatment costs shown in the supplementary material are included in the upper benefits of the model.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Source of water</th>
<th>Maximum water requirement (10^8 m³)</th>
<th>Minimum water requirement (10^8 m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipal</td>
<td>Surface water</td>
<td>3.96</td>
<td>2.98</td>
</tr>
<tr>
<td></td>
<td>Groundwater</td>
<td>1.93</td>
<td>0.95</td>
</tr>
<tr>
<td>Industrial</td>
<td>Surface water</td>
<td>3.92</td>
<td>2.73</td>
</tr>
<tr>
<td></td>
<td>Groundwater</td>
<td>1.42</td>
<td>0.98</td>
</tr>
<tr>
<td>Agricultural</td>
<td>Surface water</td>
<td>44.77</td>
<td>36.91</td>
</tr>
<tr>
<td></td>
<td>Groundwater</td>
<td>24.70</td>
<td>19.15</td>
</tr>
</tbody>
</table>
The income of unit water supply is mainly determined according to the social and economic indicators and the gross domestic product of each sector. Since fractional programming has an objective function that solves for the maximum value, the denominator value should be maximized, and the calculated value should be the lowest. To ensure fairness of water allocation among the sectors, the penalty strategy of water shortage should be introduced. When water allocation in the agricultural sector is reduced, the allocation of municipal and industrial sectors should be improved. When the benefits of water increase, increasing the penalty of water shortage in the agricultural sector can ensure the fairness of water allocation in the agricultural sector. Table 3 shows the unit water supply income and unit water shortage penalty for each water user based on Li et al. (2016); Wang et al. (2017) define the penalty for water shortage and ladder water price. To ensure fair water distribution among users with more and less benefits from the same water demand, users with high benefits have a higher penalty for water shortage, and users with low benefits have a lower penalty for water shortage. The penalty for water shortage is a relative concept. When the minimum water supply of each department cannot be met, there is a water shortage for each department; when the minimum water supply can be met, it is water shortage for each department to pursue to meet the maximum water supply.

### Analysis of the Results

According to Equations (7)–(10), the optimal allocation model of regional water resources is established. The optimal water supply targets of surface water and groundwater for the different users are calculated in Table 4.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Source of water</th>
<th>Unit water supply income (yuan/m³)</th>
<th>Unit water shortage penalty (yuan/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipal</td>
<td>Surface water</td>
<td>250</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>Groundwater</td>
<td>220</td>
<td>190</td>
</tr>
<tr>
<td>Industrial</td>
<td>Surface water</td>
<td>230</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>Groundwater</td>
<td>200</td>
<td>210</td>
</tr>
<tr>
<td>Agricultural</td>
<td>Surface water</td>
<td>190</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>Groundwater</td>
<td>160</td>
<td>230</td>
</tr>
</tbody>
</table>

The results show that under the RCP4.5 scenario, to satisfy the minimum water supply requirements of the departments, the remaining available water resources are allocated to departments based on ensuring fair water distribution through the water shortage penalty. The economic efficiency of each department must be improved to pursue the maximum water supply. In the RCP6.0 scenario, when meeting the minimum water supply requirements of departments, there is still a small amount of available water resources. The model weighs the benefits and penalties between departments, and the agricultural department can receive the smallest penalty. Under the RCP8.5 scenario, when meeting the minimum water supply demand of each department, little available water resources remain. At this point, the pursuit of development becomes the primary goal of the model; thus, the remaining water resources are allocated to the municipal and industrial sectors.

Table 4 shows that (1) under the RCP4.5 scenario, the surface water and groundwater allocations constitute the maximum water demand of the municipal sector. Under the RCP6.0 scenario, the surface water allocation is the minimum water requirement of the municipal sector, and the groundwater allocation tends to the maximum water allocation required by the sector. Under the RCP8.5 scenario, the allocations of surface water and groundwater are between the maximum water demand and the minimum water demand of the municipal sector. Generally, the three scenarios can meet the basic water demand of the municipal sector.
municipal sector. Under the RCP4.5 scenario, the maximum water demand of the municipal sector can be met. Under the other two scenarios, when water needs to be used by the other departments, surface water quantities of 298 million m³ and 386 million m³ and groundwater quantities of 192 million m³ and 189 million m³ are allocated, which takes into account the maximum economic benefits and the minimum penalty. Under the three scenarios, the water allocations of the municipal sector arranged from large to small were those under RCP4.5, RCP8.5, and RCP6.0.

(2) For the industrial sector water allocation, under the RCP4.5 scenario, surface water and groundwater allocations constitute the maximum water demand of the industrial sector. Under the RCP6.0 scenario, the surface water allocation is the minimum water requirement of the industrial sector, and the groundwater allocation tends to be the maximum water allocation required by the sector. Under the RCP8.5 scenario, the water allocations of surface water and groundwater are between the maximum water demand and the minimum water demand of the industrial sector. Under the three scenarios, the water allocations of the industrial sector arranged from large to small are those under RCP4.5, RCP8.5, and RCP6.0.

(3) The surface water and groundwater allocations under the three scenarios are between the maximum and minimum water demand of the agricultural sector. Neither can meet the maximum water demand. Under the three scenarios, the water allocations of the industrial sector arranged from large to small are those under RCP6.0, RCP4.5, and RCP8.5.

**DISCUSSION**

Due to the shortage of water resources and the low economic benefits of the agricultural sector, the traditional water allocation model will minimize the allocation of water to the agricultural sector. When considering the maximum economic benefits, the model used in this study will guarantee the fairness of water allocation for the agricultural sector according to the established penalty constraints for water shortage. The two models for water allocation to the agricultural sector are contrasted, as shown in **Table 5**. The results show that the water shortage of surface water resources according to the model without considering the water shortage penalty under the RCP6.0 scenario is 217 million m³ less than that of the model considering the water shortage penalty. The surface water resources cannot satisfy the water allocation under the three scenarios, especially under the RCP4.5 scenario, and the most serious shortage of water is 432 million m³. Therefore, it is necessary to introduce the restriction of the water shortage penalty into the model.

**CONCLUSION**

Taking Harbin as an example, an LFP model based on CCP for the optimal allocation of regional water resources under different RCP scenarios was established, and the regional water allocation scheme was studied. Through model calculations, the following conclusions can be drawn: (1) under the RCP4.5 scenario, the water supply is sufficient, which can ensure the maximum water supply allocated to the municipal and industrial sectors. Under the RCP6.0 scenario, the model provides water allocation to the agricultural sector, reduces the economic penalty, and reduces the water supply of the municipal and industrial sectors. Under the RCP8.5 scenario, the total water supply is smaller. The model can satisfy water allocation as much as possible for each sector while taking into account economic benefits by increasing water allocation to the municipal and industrial sectors and reducing water allocation to the agricultural sector. (2) The model pursues the two problems of maximizing the economic benefits and minimizing the water supply. To prevent the model from blindly allocating water to users with high economic benefits, a penalty decision is introduced for users with high profits, and high penalties.
penalties are introduced for water shortage and low profits. In addition, the penalty for water shortage is low to ensure fair water allocation of the model. (3) Harbin is situated along the main stream of the Songhua River, and the water quantity is relatively sufficient. Protecting the water source security is also a key concern in Harbin’s water resource planning. In the model design, considering the treatment of wastewater and COD emissions, treatment costs are included in the upper model layer to make the regional water resource allocation model more practical.

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DATA AVAILABILITY STATEMENT

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

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