*Front. Agr. Sci. Eng.* 2016, **3**(3): 231–240
DOI : 10.15302/J-FASE-2016101



RESEARCH ARTICLE

# Utilization threshold of surface water and groundwater based on the system optimization of crop planting structure

**Qiang FU (✉)[1,2,3], Jiahong LI[1], Tianxiao LI[1], Dong LIU[1,2,3], Song CUI[1]**

1 School of Water Conservancy & Civil Engineering, Northeast Agricultural University, Harbin 150030, China
2 Heilongjiang Provincial Collaborative Innovation Center of Grain Production Capacity Improvement, Northeast Agricultural University, Harbin 150030, China
3 Key Laboratory of High Efficient Utilization of Agricultural Water Resource of Ministry of Agriculture, Northeast Agricultural University, Harbin 150030, China

**Abstract** Based on the diversity of the agricultural system, this research calculates the planting structures of rice, maize and soybean considering the optimal economic-social-ecological aspects. Then, based on the uncertainty and randomness of the water resources system, the interval two-stage stochastic programming method, which introduces the uncertainty of the interval number, is used to calculate the groundwater exploitation and the use efficiency of surface water. The method considers the minimum cost of water as the objective of the uncertainty model for surface water and groundwater joint scheduling optimization for different planting structures. Finally, by calculating harmonious entropy, the optimal exploitation utilization interval of surface water and groundwater is determined for optimal cultivation in the Sanjiang Plain. The optimal matching of the planting structure under the economic system is suitable when the mining ratio of the surface is in 44.13%–45.45% and the exploitation utilization of groundwater is in 54.82%–66.86%, the optimal planting structure under the social system is suitable when surface water mining ratio is in 47.84%–48.04% and the groundwater exploitation threshold is in 67.07%–72.00%. This article optimizes the economic-social-ecological-water system, which is important for the development of a water- and food-conserving society and providing a more accurate management environment.

**Keywords** economic-social-ecological, uncertainty, harmonious entropy, surface water and groundwater, utilization threshold

Received April 11, 2016; accepted May 20, 2016

Correspondence: fuqiang0629@126.com

## 1 Introduction

As an agricultural country, in China, more than 70% of the total water used is for agriculture[1]. However, the distribution of water resources over time and space is uneven in China, particularly in the northern region. This region includes 59.2% of the country's arable land but only 14.7% of the country's water resources[2]. Water is scarce in China and the tens of billions of kilogram decrease in grain production caused by water shortages each year threatens food security. Thus, water has become the most important factor affecting crop yield[3]. From the perspective of sustainable development, when a shortage of water resources occurs in the region, it can only be overcome through the rational allocation of limited water resources, in order to achieve the optimum comprehensive benefit and achieve sustainable development in agriculture[4]. Along with the rapid development of the social economy, the water use in industry, in cities and towns, and in the environment have also generated increasing competition with water use agriculture, caused the shortfall between the supply and demand for agricultural water to increase. Therefore, scientific planning of crop planting structures, establishing models of optimal allocation of water for the efficient use of the limited water resources for agriculture, and promoting the sustainable development of the agricultural ecological environment and economy are of great significance[5].

As the difference between the supply and demand of agricultural water resources increases, the development of agricultural water resources simulation and optimal allocation have been widely used. Grundmann et al.[6] presented a new simulation-based integrated water management tool for sustainable water resources management in arid coastal environments. Huo et al.[7] distributed irrigation water based on a soil moisture dynamic simulation optimization model of irrigation systems and the crop water production function. Environmental problems are triggered by the over-exploitation of groundwater; thus, joint groundwater and surface water scheduling problems are gaining increasing attention. The main methods used to solve such problems are the simulation optimization method[8], linear method[9,10], dynamic programming model[11], and numerical simulation analysis method[12].

Because the level of agricultural water use and unit cost are uncertain, and the water resources management system is an uncertain complex system, an uncertainty optimization method is suitable for solving the uncertainty factors for such a system. In recent years, this method has been widely used in many areas by, for instance, Maqsood[13]. An accurate rough interval, fuzzy linear programming method is applied to the water resources allocation of an agricultural irrigation system. Li et al.[14,15] used an interval fuzzy multistage method for water resources management and established a random two-stage interval quadratic programming model for water quality management. Xie and Fu[16–18] used two-stage stochastic programming to optimize the allocation of water resources.

However, few studies have obtained a multi-objective cultivation solution by calculating the utilization threshold of the surface water and groundwater. Therefore, this study considers the economic-social-ecological and water resources system using a multi-objective two-stage stochastic programming model with intervals and agricultural water system entropy considerations to analyses the surface water and groundwater exploitation ratio for the Sanjiang Plain to overcome the complexity and uncertainty of the agricultural water resources system and to obtain an optimization solution and use ratio threshold of surface water and groundwater in agriculture. Multi-objective optimization and two-stage interval programing model are combined to establish the objective solution function under different solutions. Moreover, it can be employed for quantitatively analyzing a variety of alternative solutions with different stream flow levels and allocation proportions. Then, the optimal scheme is obtained by the comparison of the different solutions through the harmonious entropy. Using this approach, a new method for optimizing the allocation of water resources is proposed.

## 2 Modeling

### 2.1 Optimization of the crop planting structure under each system

The agricultural system is a complex system. A crop planting structure optimization model is established based on the latest research results of crop planting structure adjustment based on the aspects of production, life and ecology to determine the areas of economic benefit, social benefit and ecological benefit target function.

One of the largest economic benefits is to make crops produce more, which involves maximizing the use of water resources to achieve the efficient utilization of water resources[19].

Social benefits arise from making the output of grain meet the demands of human society, achieving fair social distribution, meeting the social demands of people's daily consumption and increasing farmers' income to maintain social stability and raise the quality of life of individuals[19].

Ecological sustainability involves guaranteeing ecological water use to ensure the natural condition of water resource natural ecological service function and regulating human activities and allowing water to better serve humans[19].

According to the above analysis and considering the limitations of water and soil resources, a multi-objective economic, social and ecological optimization model is proposed as follows:

$$\max f(X) = [f(x)_1, f(x)_2, f(x)_3](X \in R) \quad (1)$$

$$s.t. R = \{X | G(X) \leqslant 0, X \geqslant 0\} \quad (2)$$

where decision vector $X$ refers to the crop planting area and $f(x)_1$, $f(x)_2$, $f(x)_3$ are the economic, social and ecological benefits of the objective function, respectively. The constraint conditions include water and soil resource constraints.

### 2.2 Joint surface water and groundwater configuration under uncertainty

Considering the various benefits of crop planting area, due to the importance of the water resources system and considering the joint use of surface water and groundwater to meet a variety of crop water requirements, the goal is to reduce the cost of water. Using the two-stage uncertainty interval stochastic programming method with the minimum agricultural water comprehensive cost as the objective function and the water supply in study area as the constraint conditions, the first step to determining the three solutions for crop planting area for known conditions is the introduction of the total water cost and water dynamic resources and evaluating water resources and different water costs to calculate the optimal configuration of water.

Because the water resources system contains many sources of uncertainty, the prediction of the supply of water is challenging and the early crop water supply target is uncertain. The difference between the water resources and the water supply route leads to water transfer cost and crop price changes[20]. The output of water makes the presence of a penalty coefficient uncertain. To account for this uncertainty, this research introduced the interval parameter and used the upper and lower limit based on scientific considerations and rationality. The basic two-stage interval stochastic programming model is as follows:

$$\mathrm{Min}f^{\pm}=\sum_{i=1}^{n}T_i^{\pm}W_i^{\pm}+\sum_{i=1}^{n}\sum_{k=1}^{0}p_kC_i^{\pm}S_{ik}^{\pm} \tag{3}$$

where $f^{\pm}$ is the cost of agricultural water (CNY), $T_i^{\pm}$ is the water conveyance cost (CNY), $W_i^{\pm}$ is the prediction of water under different solutions (ten thousand $m^3$), $C_i^{\pm}$ is lack of punishment coefficient, indicating that the actual water supply cannot meet the forecast (CNY), and $S_{ik}^{\pm}$ is the water deficit forecast for the year (ten thousand $m^3$). These values are significantly influenced by the amount of rainfall, which is difficult to forecast. This study predicts different years by analyzing the water deficit cases according to discrete function processing[21]. $p_k$ is the probability of the water level. $k = 1, 2, 3\ldots\ldots k$, where $k = 1$ predicts the year of minimal water deficit and high flow. When $k = 2$, water flow is moderate, and the water deficit is small. When $k = k$ there is little water and low flow, resulting in a large water deficit. Different water resources are represented (surface water and groundwater). The constraints are as follows:

(1) Minimum water demand constraints:

$$\sum_{i=1}^{n}W_i^{\pm}\geqslant W_{i\min},\forall i \tag{4}$$

where $W_{i\min}^{\pm}$ ensures the normal growth of minimum water requirement (hundred million $m^3$).

(2) Water supply capacity constraints:

$$W_i^{\pm}-S_i^{\pm}\leqslant Q_i^{\pm}+q_{ik}^{\pm},\forall i,k \tag{5}$$

where $Q_i^{\pm}$ is the amount of available water in different regions in early water planning, and $q_{ik}^{\pm}$ is the water in different regions with different inflows during the planning period; only rainfall is considered here.

(3) Maximum water consumption constraint:

$$W_i^{\pm}\leqslant W_{i\max},\forall i \tag{6}$$

(4) Variable nonnegative constraints:

$$W_i^{\pm}\geqslant S_i^{\pm}\geqslant 0 \tag{7}$$

Due to the linear programming solution of constraints, when $W_i^{\pm}$, the uncertain input parameters cannot calculate the model solution. Therefore, this article introduces another decision variable $z_i$, among $z_i\in[0,1]$, $\Delta W_i=W_i^{+}-W_i^{-}$. When $z_i=1$, $W_i^{\pm}$ reaches the upper limit value, and the corresponding water consumption is at a maximum. When $z_i=0$, $W_i^{\pm}$ reaches the lower limit value and the corresponding water consumption is expected to reach the minimum. $\Delta W_i=W_i^{+}-W_i^{-}$ is used to determine the value. With the introduction of decision variables, the optimal value $z_{iopt}$ can be solved. The water resources optimal allocation solution system cost is determined to obtain the optimal value $W^{\pm}$.

The model is transformed into two certain temperament models representing the upper and lower limits. Such a deformation process based on an interactive algorithm is different from the commonly used interval analysis and case analysis[22] because the model uses the minimum cost of water. Therefore, the first solution $f^{-}$ and its corresponding model are

$$\mathrm{Min}f^{-}=\sum_{i=1}^{n}T_i^{-}(W_i^{-}+\Delta W_iz_i)+\sum_{i=1}^{n}\sum_{k=1}^{0}p_kC_i^{-}S_{ik}^{-} \tag{8}$$

Subject to

$$\sum_{i=1}^{n}(W_i^{-}+\Delta W_iz_i)\geqslant W_{i\min},\forall i \tag{9}$$

$$(W_i^{-}+\Delta W_iz_i)-S_{ik}^{-}\leqslant Q_i^{+}+q_{ik}^{+},\forall i \tag{10}$$

$$W_i^{-}+\Delta W_iz_i\leqslant W_{i\max},\forall i \tag{11}$$

$$W_i^{-}+\Delta W_iz_i\geqslant S_{ik}^{-},\forall i \tag{12}$$

$$0\leqslant z_i\leqslant 1,\forall i \tag{13}$$

For the model, $z_i$ and $s_i^{-}$ are the decision variables. The definitions of $z_{i\mathrm{opt}}$ and $s_{i\mathrm{opt}}^{-}$ are the solutions for the model. The minimum value is $f_{\mathrm{opt}}^{-}$ into $W_i^{\pm}=W_i^{-}+\Delta W_iz_i$, the optimal water diversion goals can be calculated by changing $z_{i\mathrm{opt}}$ to $W_i^{\pm}=W_i^{-}+\Delta W_iz_i$. In the same manner, $z_{i\mathrm{opt}}$ is changed to the upper limit of the model:

$$\mathrm{Min}f^{+}=\sum_{i=1}^{n}T_i^{-}(W_i^{-}+\Delta W_iz_{i\mathrm{opt}})+\sum_{i=1}^{n}\sum_{k=1}^{0}p_kC_i^{+}S_{ik}^{+} \tag{14}$$

Subject to

$$(W_i^{-}+\Delta W_iz_i)-S_{ik}^{+}\leqslant Q_i^{-}+q_{ik}^{-},\forall i \tag{15}$$

$$W_i^{-}+\Delta W_iz_i\geqslant S_{ih}^{-}\geqslant 0 \tag{16}$$

$$S_{ik}^{+}\geqslant S_{ik}^{-},\forall i \tag{17}$$

$$0\leqslant z_i\leqslant 1,\forall i \tag{18}$$

After solving the calculated $s_{i\mathrm{opt}}^{+}$ and $f_{\mathrm{opt}}^{+}$ merging two sub models, the solution of the two-stage stochastic programming model is obtained as follows: $S_{i\mathrm{opt}}^{\pm}=[S_{i\mathrm{opt}}^{-},S_{i\mathrm{opt}}^{+}]$,

$z_i = z_{iopt}$, $f^{\pm}_{opt} = [f^{-}_{opt}, f^{+}_{opt}]$, $S^{\pm}_{opt} = [S^{-}_{opt}, S^{+}_{opt}]$, $z_i = z_{iopt}$. One of the most optimal allocations of water is $OPT^{-}_{i} = W^{-}_{iopt} - S^{-}_{iopt}, \forall i$

### 2.3 Computing the harmonious entropy

There are contradictions and competition between economic, societal, and ecological resources. The question of how to achieve harmoniously balanced development requires quantitative evaluation. This research established a calculation method for the entropy of the harmonious degree and determined the harmonious entropy of each subsystem. The evolution of the system direction is often determined by entropy change theory based on the maximum entropy principle, defining the system of relative entropy of harmonious entropy and using the relative harmony entropy of the agricultural system efficiency under different water utilization thresholds for comparative analysis.

The modeling process is as follows:

(1) Confirm the economic, social, ecological and water resources system parameters. For the dimensionless processing of various parameters, the optimal methods adopt the following formulas to eliminate the dimension influence on the evaluation results:

$$r^{\pm}_{ij} = (x^{\pm}_{ij} - x_{ijmin})/(x_{ijmax} - x_{ijmin}) \quad (19)$$

$$r^{\pm}_{ij} = (x_{ijmax} - x^{\pm}_{ij})/(x_{ijmax} - x_{ijmin}) \quad (20)$$

where $r_{ij}$ is the relative membership degree of the $i$ system parameters under the $j$ plan structure; $x_{ij}$ is the system parameter values of $i$ under the $j$ plan structure; and $x_{ijmin}$, $x_{ijmax}$ and $x_{ijmin}$ are the respective thresholds of the $i$ system parameters under the $j$ plan structure.

(2) Confirm the relative membership degree of each subsystem of the harmonious degree, hereinafter referred to as the subsystem relative harmony degree $u^{\pm}_{i}$:

$$u^{\pm}_{i} = \left\{ 1 + \left\{ \sum_{i=1}^{m} [w_{ij}(1 - r^{\pm}_{ij})]^2 / \sum_{i=1}^{m} (w_{ij} r^{\pm}_{ij})^2 \right\} \right\}^{-1} \quad (21)$$

where $u_i$ is the relative degree of the subsystem of $i, u_i \in [0,1]$; $m$ is the total parameter number of $i$ subsystem; and $w_{ij}$ is the weight of the $i$ system parameters under the $j$ plan structure.

(3) Confirm the relative harmony entropy of the agricultural water system $E(t)^{\pm}$:

$$E(t)^{\pm} = \sum_{i=1}^{n} k \ln u^{\pm}_{i} \quad (22)$$

where $E(t)^{\pm}$ is the relative harmony entropy of the agricultural water system under the $j$ plan structure; $n$ is the total number of the system; and $k$ is the ratio coefficient, which typically takes $k = -1$.

According to the relationship between entropy change, determine the evolution of the water resource system[23] to evaluate water resources allocation rationality: when $E(t) < E(t+1)$, the system entropy increases, there is disharmonious degree enhancement, the system is in an unstable state, the system is in the process of evolution in a vicious cycle, and the allocation of water resources is unreasonable; when $E(t) > E(t+1)$, the system entropy decreases, the disharmony degree is reduced, the system is in a state of virtuous cycle, the allocation of water resources is reasonable; when $E(t) < E(t+1)$, for a certain time interval, the system entropy has no change, the system is in a stable state, and the water resources allocation is more reasonable. By comparing various solutions of harmony entropy, where lower values indicate the solution is relatively optimal, the utilization threshold of the groundwater and surface water conditions under the solution of crop planting structure are improved.

The overall concept of the model can be summarized as shown in Fig. 1.

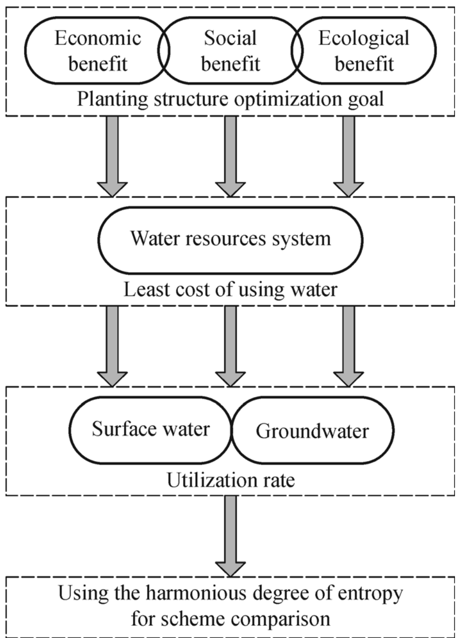


**Fig. 1** Analytic framework of the model

## 3 Case study

### 3.1 Study area

The Sanjiang Plain is located in the eastern part of Heilongjiang Province in China: 44°51′–48°28′ N, 129°12′–135°05′ E. The total area is $10.89 \times 10^4$ km$^2$, approximately one third of the cultivated land in Heilongjiang Province is China's important grain reserve base and commodity grain production base. The allocation of water resources in the Sanjiang Plain is not optimal, which results in a decrease in the capacity of regional water resources. Therefore, for the protection of national food security and based on the premise of regional ecological security, adjustments to the agricultural planting structure and the sustainable utilization of water resources are used to ensure the food security and sustainable development of the social economy in our country. The regional geographical locations are shown in Fig. 2.

### 3.2 Target of the crop planting structure under each system

The research data mainly originate from the Heilongjiang Province economic statistical yearbook, the water resources in Heilongjiang Province, the Heilongjiang Province statistical yearbook and the Heilongjiang Province yearbook. Considering the data sources and the cultivation characteristics of the Sanjiang Plain, three main crops — rice ($x_1$), corn ($x_2$) and soybean($x_3$) — are chosen for use in the surface water and groundwater joint scheduling considering the economic, social and ecological benefits. Three types of solutions are developed with the corresponding objective functions as follows:

Solution 1: economic benefit maximum ($\times 10^8$ CNY).

According to the data analysis and the comprehensive consideration of many years of rice, maize and soybean sales prices, the sales of Sanjiang Plain food produce economic benefits according to the objective function:

$$\max f(X) = 23713x_1 + 16152x_2 + 7907x_3 \tag{23}$$

Solution 2: social benefit maximum ($\times 10^8$ kg)

According to the data analysis and the comprehensive consideration of many years of rice, maize and soybean yield per unit area, the goal of maximizing the Sanjiang Plain grain output function yields the following objective function:

$$\max f(X) = 7504x_1 + 7409x_2 + 1967x_3 \tag{24}$$

Solution 3: ecological benefit maximum ($\times 10^8$ CNY)

According to the data analysis, the comprehensive consideration of the size of the agricultural land area and the relationship between the ecological service values, the following Sanjiang Plain ecological service value function is maximized:

$$\max f(X) = 55485x_1 + 1857x_2 + 3290x_3 \tag{25}$$

The constraint conditions of the objective function are as follows:

(1) The full irrigation of crops water requirement constraint ($10^4$ $m^3$)

$$11324x_1 + 5142x_2 + 3045x_3 \leqslant 1664000 \tag{26}$$

According to the data analysis and the comprehensive consideration of the Sanjiang Plain rice, maize and soybean supply situation, the amount of water available for the three crops does not exceed a maximum of $16.64 \times 10^9$ $m^3$.

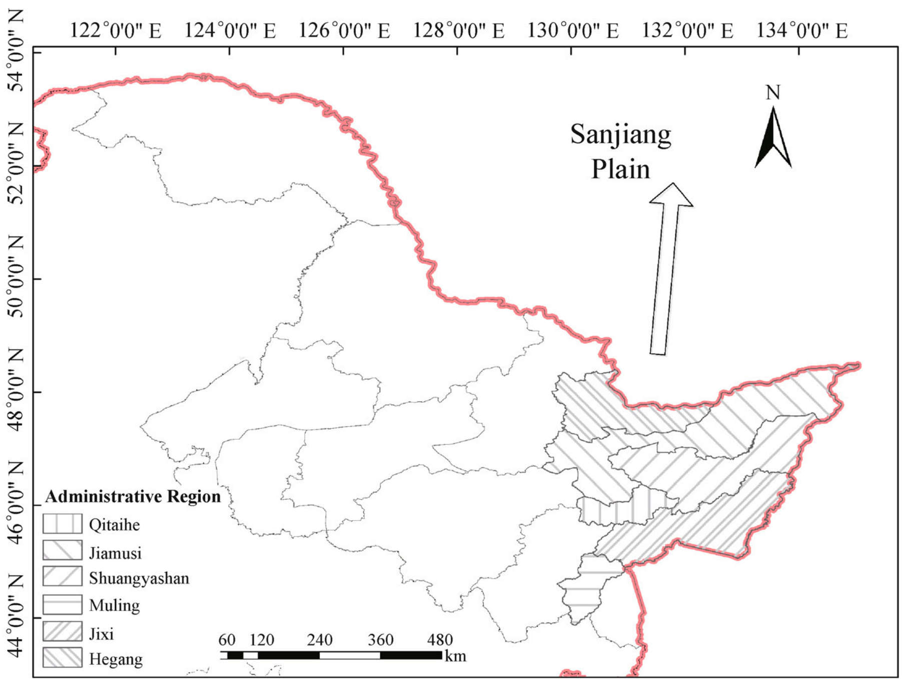


**Fig. 2** Study area of the Sanjiang Plain located in the eastern part of Heilongjiang Province in China

(2) The area constraint ($10^4$ hm$^2$)

$$\begin{cases} x_1 + x_2 + x_3 \leqslant 228.38 \\ 0 \leqslant x_1 \leqslant 95 \\ 0 \leqslant x_2 \leqslant 128 \\ 0 \leqslant x_3 \leqslant 50 \end{cases} \tag{27}$$

According to the data analysis and the comprehensive consideration of the Sanjiang Plain crops with a planting area for rice, maize and soybean of no more than 2.2838 × $10^4$ hm$^2$ over many years, the largest acreage was less than 95 × $10^4$ hm$^2$, 128 × $10^4$ hm$^2$ and 50 × $10^4$ hm$^2$ for rice, maize, and soybean, respectively.

The benefit of each system for crop planting area and the corresponding benefit value are calculated[24], and the results are shown in Table 1.

### 3.3 Optimal allocation of surface water and groundwater under uncertainty

With more than three solutions for planting area under known conditions, an interval, two-stage, stochastic programming model has been developed using the method of interval two-stage stochastic programming and having the minimum comprehensive cost of the Sanjiang Plain water as the goal. Groundwater and surface water are optimized; then, the water resources system status is analyzed according to the result of the optimal configuration and analysis of the surface water and groundwater exploitation utilization.

Table 2 lists the allowable water usage in the irrigation of the three crops in Sanjiang Plain for different forecast years. The research of the future water levels is divided into three categories, namely, low, medium, and high, according to the historical statistical rainfall and runoff data of Sanjiang Plain. The probability of medium is higher than the high flow and low flow, and the high flow and low flow have similar probabilities. Therefore, this article assumes water level probabilities of 0.2, 0.6, and 0.2.

In water resources planning, if the amount of water available is expected to meet the water demand, there are only water costs; if the amount of water fails to meet the water demand, there are punishment costs. Table 3 shows the different cost of water diversion, the water shortage penalty coefficient and the amount of water available in early planning[25].

### 3.4 Optimal allocation results for water resources

The solutions are obtained using Matlab and Excel. The optimal water supply of surface water and groundwater under different solutions can be obtained by, ${W_{iopt}}^{\pm} = W_i^- + \Delta W_i z_{iopt}$. The water deficit is forecast according to the model calculation results, which are shown in Table 4. Then, the optimal allocation of water resources under different solutions is calculated for different levels of water. The value is the available water quantity minus the water deficit $OPT^{\pm} = W_{iopt}^{\pm} - S_{iopt}^{\pm}$, as shown in Fig. 3.

The results in Table 4 show that each solution in the optimal water resources allocation has a certain water shortage. The difference between the supply and demand of water resources is significant in the study area. Research

**Table 1** Crop planting area and corresponding efficiency values under each solution

| Solution | Rice/(×$10^4$ hm$^2$) | Corn/(×$10^4$ hm$^2$) | Soybean/(×$10^4$ hm$^2$) | Economic benefits /(×$10^8$ CNY) | Food production /(×$10^8$ kg) | Ecological benefits /(×$10^8$ CNY) |
|---|---|---|---|---|---|---|
| 1 | 84.46 | 128.00 | 15.92 | 419.61 | 161.35 | 497.63 |
| 2 | 88.74 | 128.00 | 0.00 | 417.17 | 161.42 | 516.14 |
| 3 | 95.00 | 83.38 | 50.00 | 399.48 | 142.90 | 559.04 |

**Table 2** Allowed water use for Sanjiang Plain under different water levels

| Study area | Water level | Surface water/(×$10^8$ m$^3$) | Groundwater/(×$10^8$ m$^3$) | Probability |
|---|---|---|---|---|
| Sanjiang Plain | low | [64.0, 75.1] | [27.8, 36.9] | 0.2 |
| | medium | [76.8, 91.5] | [33.5, 47.5] | 0.6 |
| | high | [93.7, 105.7] | [48.3, 60.7] | 0.2 |

**Table 3** Initial period of allowed water use (×$10^8$ m$^3$) and related economic data (CNY·m$^{-3}$)

| Surface water | | Groundwater | | Allowable water use/(×$10^8$ m$^3$) | |
|---|---|---|---|---|---|
| Unit cost of water diversion/ (CNY·m$^{-3}$) | Penalty coefficient | Unit cost of water diversion/ (CNY·m$^{-3}$) | Penalty coefficient | Surface water | Groundwater |
| [3.9, 4.3] | [4.5, 4.8] | [5.2, 5.5] | [5.7, 6.0] | [25.13, 37.83] | [8.15, 17.83] |

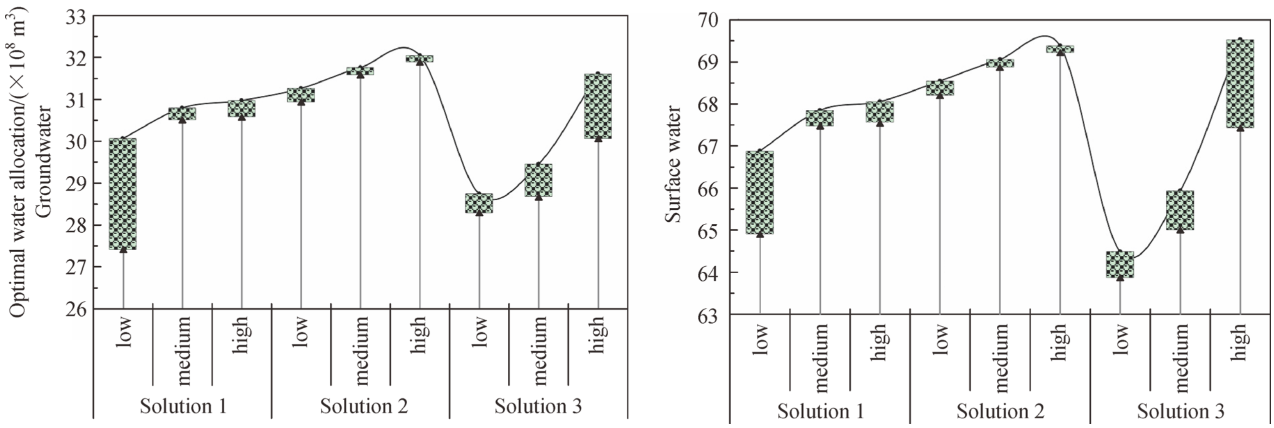


**Fig. 3** Optimal allocation of surface water and groundwater under different solutions and water levels

**Table 4** Water supply target and shortage under different solutions

| Solution | Water | Water level | Probability | Optimal water supply/($\times 10^8$ m$^3$) | Water deficit/($\times 10^8$ m$^3$) |
|---|---|---|---|---|---|
| Solution 1 | Surface water | low | 0.2 | 68.17 | [1.31, 3.28] |
| | | medium | 0.6 | 68.17 | [0.34, 0.71] |
| | | high | 0.2 | 68.17 | [0.13, 0.64] |
| | Groundwater | low | 0.2 | 31.09 | [1.03, 3.68] |
| | | medium | 0.6 | 31.09 | [0.30, 0.58] |
| | | high | 0.2 | 31.09 | [0.12, 0.51] |
| Solution 2 | Surface water | low | 0.2 | 69.42 | [0.89, 1.23] |
| | | medium | 0.6 | 69.42 | [0.38, 0.56] |
| | | high | 0.2 | 69.42 | [0.16, 0.22] |
| | Groundwater | low | 0.2 | 32.08 | [0.82, 1.14] |
| | | medium | 0.6 | 32.08 | [0.32, 0.49] |
| | | high | 0.2 | 32.08 | [0.14, 0.19] |
| Solution 3 | Surface water | low | 0.2 | 69.84 | [5.37, 5.98] |
| | | medium | 0.6 | 69.84 | [3.92, 4.85] |
| | | high | 0.2 | 69.84 | [0.33, 2.42] |
| | Groundwater | low | 0.2 | 32.41 | [3.67, 4.12] |
| | | medium | 0.6 | 32.41 | [2.96, 3.73] |
| | | high | 0.2 | 32.41 | [0.80, 2.35] |

Note: z(1,1) = 0.10, z(1,2) = 0.10; z(2,1) = 0.13, z(2,2) = 0.13; z(3,1) = 0.14, z(3,2) = 0.14. Minimum overall cost [432.08, 477.05], [441.71, 481.30], [471.84, 521.79] ($\times 10^8$ CNY). z(1,1) and z(1,2) are the decision variables of surface water and groundwater, respectively, under the first solution, z(2,1) and z(2,2) are the decision variables of surface water and groundwater, respectively, under the second solution and so on.

into water-saving irrigation and improving the efficiency of water use has a profound significance for the Sanjiang Plain. Reducing the total cost of water is also important to further increase income among regions and to reduce the losses caused by the exploitation of water; thus, the solutions of water resources allocation are smaller. Figure 3 shows that the changing trends of the optimal configuration of water under different water levels in Solutions 1 and 2 are small. The change in the third solution of the optimal allocation of water under different water levels is larger, which indicates that the considerations for the economic system and social system in the natural and outside factors of water are small, whereas the ecosystem response to the external system is large, which results in a larger change.

To further understand the exploitation of surface water and groundwater, this research used the optimal allocation of water resources determined above as the foundation and the medium water level was selected to calculate the proportion of surface water and groundwater available for each situation and to calculate the surface water and groundwater proportions of the total water use of each situation. The reasonable proportion of surface water and groundwater usage is determined. The calculation result is shown in Fig. 4.

As seen from Fig. 4., the overall surface mining ratio of Sanjiang Plain is [40%, 55%], and the groundwater exploitation threshold is [50%, 80%], which indicates a higher percentage of groundwater exploitation but reasonable control (within 80%). Reasonable development of groundwater can greatly improve the efficiency of groundwater; in each region, the surface water use ratio is approximately 70%, and the groundwater use ratio is approximately 30%. For the Sanjiang Plain agricultural irrigation to achieve economic-social-ecological optimization and for the sound development of the water resources system, the manager should give priority to surface water, with groundwater being complementary.

### 3.5 Using the entropy of the harmony degree to compare solutions

According to the characteristics of the Sanjiang Plain and the related system principle of determining the parameters, the output of the three crops is chosen as the order parameter of the economic system, per capita gain is chosen as the parameter for the social system, the per capita ecological service value is chosen as the ecological order parameter, and the extraction threshold of groundwater and surface water utilization are chosen for the water resources system parameters. The weight of each of the economic-social-ecological-water systems is 0.25, which embodies the principle of balanced and harmonious development. Finally, the harmonious entropy of each solution and corresponding exploitation of groundwater and surface water utilization are calculated, as shown in Fig. 5.

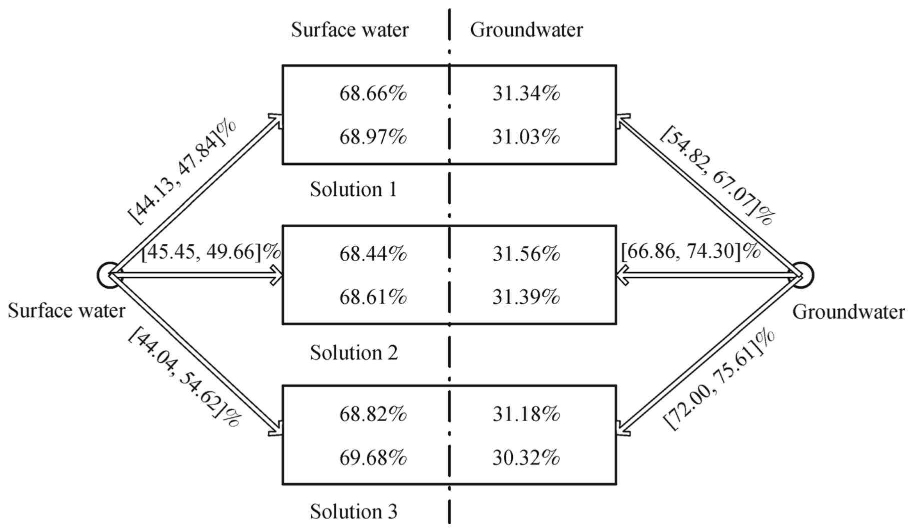


**Fig. 4** Exploitation and utilization ratio of surface water and groundwater under each solution

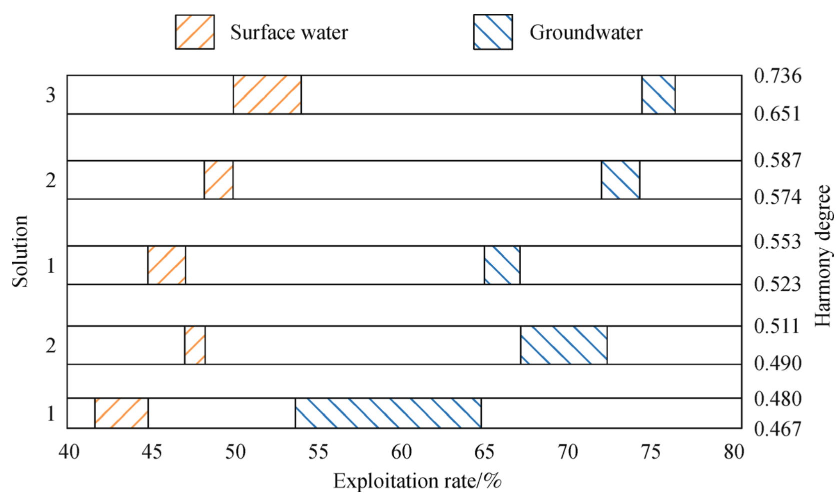


**Fig. 5** Utilization threshold of groundwater and surface water and corresponding entropy of harmony degree under the three solutions

Figure 5 shows that the entropy of harmony degree of the third solution is the largest, the corresponding surface water and groundwater exploitation utilization ratio is the largest, the agricultural system is relatively unstable, and the planting structure is not suitable. For the first and second solutions, due to the mining of groundwater and the surface water use ratio of a certain interval, with the surface water utilization within 44.13%–45.45% and the threshold of groundwater exploitation within 54.82%–66.86%, the minimum entropy value of harmony degree and the corresponding crop planting structure of the first solution are more suitable. For surface water utilization within 47.84%–48.04% and a threshold of groundwater exploitation within 67.07%–72.00%, the entropy of the harmonious degree of the second solution is smaller, and the corresponding crop planting structure is more reasonable.

Figure 5 shows that the three solutions of surface water and groundwater exploitation are better than the current usage. Solution 1 considers the economic benefit most and the mining quantity and costs less. The optimal solution 2 maximizes the social benefits, and the exploitation of water and cost are greater. Solution 3 maximizes the ecological benefits. The mining quantity is greater, the cost is the largest, and the entropy of harmonious degree is the maximum, which indicates the system is the least stable. The solution cannot blindly pursue economic-social-ecological benefits, causing the water resources system to face excessive risk. The solution also cannot only consider the existence of risk and ignore the development of the society. Therefore, the benefits and water resources system must be balanced to select the appropriate solution.

## 4 Conclusions

This research establishes an objective optimization model for the benefit of the comprehensive agricultural planting structure and the corresponding water cost minimum target optimization model considers the sustainable development of agriculture. The objective functions of the model represent the four aspects of economy, society, ecology and water resources.

After a variety of crop planting structures were determined, a reasonable allocation of water resources was studied, with the objective function of minimizing the cost of crop water. A two-stage uncertainty interval stochastic programming model was applied for the optimal allocation of agricultural water resources in the Sanjiang Plain. After the introduction of water cost and shortage cost to the cost of water, the optimal allocation of surface water and groundwater under various solutions can be calculated under different water levels, which helps policy makers save water and improve the use efficiency of water.

The greatest advantage of this model is using the entropy of harmonious degree to evaluate the social-economic-ecological-water resources system comprehensively for each solution. Through the harmonious entropy, this research provides the optimal allocation of surface water and groundwater in the rational mining range. When the utilization threshold of surface water is within 44.13%–45.45% and the exploitation threshold of groundwater is within 54.82%–66.86%, the structure of crop planting is based on achieving the maximum benefits of the economic system. When surface water utilization is within 47.84%–48.04% and the groundwater exploitation threshold is within 67.07%–72.00%, the structure of crop planting is based on achieving the maximum benefits of the social system. This reasonable exploitation is an important reference value and theoretical basis for agricultural policy, which is useful for the sustainable utilization of water resources in the Sanjiang Plain.

**Acknowledgements** This research has been supported by funds from National Natural Science Foundation of China (51179032, 51479032, 51579044); Yangtze River Scholars in Universities of Heilongjiang Province and Water Conservancy Science and Technology Project of Heilongjiang Province (201318, 201503); The Outstanding Youth Fund of Heilongjiang Province (JC201402).

**Compliance with ethics guidelines** Qiang Fu, Jiahong Li, Tianxiao Li, Dong Liu, and Song Cui declare that they have no conflict of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

## References

1. Li R R, Li X. Advance of research on utilization coefficient of irrigation water. *Water Saving Irrigation*, 2011, (11): 56–58 (in Chinese)
2. Yang D J. Study on the soil hydrodynamics model for the soil-plant-atmosphere continuum (SPAC) system. Hangzhou: *Zhejiang University*, 2009 (in Chinese)
3. Yuan B Z, Lu G H. LI Y Y. Analysis of driving factors for water demand. *Advances in Water Science*, 2007, **18**(3): 404–409 (in Chinese)
4. Gao M J, Luo Q Y. Study on cropping structure optimization in region short of water: a case study of north China. *Journal of Natural Resources*, 2008, **23**(2): 204–210 (in Chinese)
5. Wang Y, Li Y Y. Irrigation distribution optimization models: a review. *Water Saving Irrigation*, 2014, (**10**): 74–79 (in Chinese)
6. Grundmann J, Schütze N, Lennartz F. Sustainable management of a coupled groundwater agriculture hydro system using multi-criteria simulation based optimization. *Water Science and Technology*, 2012, **67**(3): 689–698
7. Huo J J, Shang S H. Optimization method for crop irrigation scheduling based on simulation technique and genetic algorithms. *Transactions of the Chinese Society of Agricultural Engineering*, 2007, **23**(4): 23–28 (in Chinese)
8. Smout I K, Gorantiwar S D. Productivity and equity of different irrigation schedules under limited water supply. *Journal of Irrigation and Drainage Engineering*, 2006, **132**(4): 349–358
9. Vedula S, Mujumdar P P, Chandra Sekhar G. Conjunctive use

modeling formulticrop irrigation. *Agricultural Water Management*, 2005, **73**(3): 193–221
10. Khare D, Jat M K, Sunder J D. Assessment of water resources allocation options: conjunctive use planning in a link canal command. *Resources, Conservation and Recycling*, 2007, **51**(2): 487–506
11. Wang J F, Cheng G D, Gao Y G, Long A H, Xu Z M, Li X, Chen H, Barker T. Optimal water resource allocation in arid and semi–arid areas. *Water Resources Management*, 2008, **22**(2): 239–258
12. Singh A. Simulation–optimization modeling for conjunctive water use management. *Agricultural Water Management*, 2014, **141**: 23–29
13. Maqsood I, Huang G, Huang Y, Chen B. ITOM: an interval–parameter two–stage optimization model for stochastic planning of water resources systems. *Stochastic Environmental Research and Risk Assessment*, 2005, **19**(2): 125–133
14. Li Y P, Huang G H, Yang Z F, Nie S L. IFMP: Interval-fuzzy multistage programming for water resources management under uncertainty. *Resources, Conservation and Recycling*, 2008, **52**(5): 800–812
15. Li Y P, Huang G H. Two-stage planning for sustainable water-quality management under uncertainty. *Journal of Environmental Management*, 2009, **90**(8): 2402–2413
16. Xie Y L, Huang G H, Li W, Li J B, Li Y F. An inexact two-stage stochastic programming model for water resources management in nansihu lake basin, China. *Journal of Environmental Management*, 2013, **127**(2): 188–205
17. Fu Q, Zhao K, Liu D, Jiang Q, Li T, Zhu C. Two-stage interval-parameter stochastic programming model based on adaptive. *Water Resources Management*, 2016, **30**(6): 2097–2109
18. Fu Q, Zhao K, Liu D, et al. The application of a water rights trading model based on two-stage interval-parameter stochastic programming. *Water Resources Management*, 2016, **30 (7)**: 2227–2243
19. Gan H, Wang L, Cao Y B, You J J, Gan Z G, Qin C H, He S, Xu K. Multi-dimensional overall regulatory modes and threshold values for water cycle of the Haihe River Basin. *Chinese Science Bulletin*, 2013, **58**(27): 3320–3339 (in Chinese)
20. Chinnasamy P, Bharati L, Bhattarai U Khadka A , Dahal V , Wahid S. Impact of planned water resource development on current and future water demand in the Koshi River basin, Nepal. *Water International*, 2015, **40**(7): 1004–1020
21. Fu Y H, Guo P, Fang S Q, et al. Optimal water resources planning based on interval-parameter two-stage stochastic programming. *Transactions of the Chinese Society of Agricultural Engineering*, 2014, **30**(5): 73–81 (in Chinese)
22. Huang G H. Ipwm: an interval parameter water quality management model. *Engineering Optimization*, 1996, **26**(2): 79–103
23. Mishra A K, Özger M, Singh V P. Association between uncertainties in meteorological variables and water resources planning for the state of texas. *Journal of Hydrologic Engineering*, 2011, **16**(12): 984–999
24. Hack J. Application of payments for hydrological ecosystem services to solve problems of fit and interplay in integrated water resources management. *Water International*, 2015, **40**(5–6): 1–20
25. Jiang W, Marggraf R. Bilateral virtual water trade in agricultural products: a case study of Germany and China. *Water International*, 2015, **40**(3): 483–498