Adaptive management of water resources based on an advanced entropy method to quantify agent information

Kun Cheng, Shuai Wei, Qiang Fu, Wei Pei and Tianxiao Li

ABSTRACT

Adaptive management is currently an important method to optimize the management of complex water resources systems. Regional water resources adaptive management was conducted based on the advanced theory of a complex system multi-agent model; the state of an agent was tracked and modified by information entropy theory, which was improved by using individual standard deviations. With the goal of optimizing the adaptation of each agent of the region, water resources in the major grain production area of China were managed under the constraints of the total annual available water resources and water use efficiency requirements for 2015 and 2030. By introducing the adaptive water resources management in 2015, the domestic benefits and economic benefits increased by 2.90% and 14.81%, respectively, with respect to observed values. The ecological benefits declined by 3.63%, but ecological water demand was fully satisfied, and the ecological water environment was improved. Given the water use efficiency targets in 2030, applying adaptive management resulted in an increase of domestic, economic, and ecological benefits of 34.29%, 21.14%, and 1.78%, respectively. The results show that the adaptive management method presented can help managers to balance the benefits of various agents to determine the direction of water resources management decisions.

Key words | adaptive agent, information entropy, simulation method, uncertainty, water resources

Kun Cheng
Wei Pei
College of Science,
Northeast Agricultural University,
Harbin 150030,
China

Shuai Wei
College of Engineering,
Northeast Agricultural University,
Harbin 150030,
China

Qiang Fu (corresponding author)
Tianxiao Li
School of Water Conservancy & Civil Engineering,
Northeast Agricultural University,
Harbin 150030,
China
E-mail: *fuqiang0629@126.com*

INTRODUCTION

Adaptive management, which originated in the 1970s, enables managers to undertake scientific actions to adjust strategies through information feedback for the enhancement of management effectiveness when facing uncertainty problems (Lessard 1998). Although research on this management method has just begun, it has attracted the attention and interest of researchers in many fields, including resource management, socio-ecological systems, and human-nature adaptation (Christopher *et al.* 2013; Peter 2014; Cheng *et al.* 2015).

A water resources management system is a complex system that integrates economic, societal, and ecological considerations, exhibiting multidimensional, dynamic, open, and nonlinear characteristics (Brookfield & Gnau 2016; Li *et al.* 2016). Adaptive management has shown good advantages in addressing these characteristics, so it has been widely used in water resources management in recent years. Geldof (1995) considered adaptive water resources management as an entire process for the integrated management of water resources, in which strategies can be adjusted and balanced through constant adaptations to changes. In view of the complexity and uncertainty of basin water resources systems, Sophocleous (2000) noted that the sustainable management of basin water resources must be based on adaptive management. Folke *et al.* (2002) undertook an integrated management of water resources based on the theme of adaptive management, which rendered results closer to the actual situation. Based on an

analysis of the adaptive mechanism of a regional water resources system, Zhao (2003) constructed a new model for analyzing a water resources adaptive management system. Wang *et al.* (2007) considered adaptive management as a dynamic adjustment process, in which system health and resource sustainability are achieved, and by focusing on the uncertainty of system management, a series of activities that include designing, planning, monitoring, and managing resources are carried out to ensure the integrity and coordination of the system. Knüppe & Pahl-Wostl (2011) introduced adaptive mechanisms into complex groundwater management and expanded the application of adaptive management in water resources systems. Fu *et al.* (2016) introduced adaptive management into reservoir-water rights transactions and applied a two-stage interval-stochastic programming model to solve the problem. These studies emphasized the important role of adaptive management in water resources management from different perspectives.

In adaptive management, it is necessary to uniformly measure the amount of information transformation in a complex system, and entropy theory (Shannon 1948) is very effective to quantify the energy flow in a given process. Bao & Zou (2018) used entropy to confirm the weight of the objective and study the degree of conflict between water shortage and human activity. Amiri *et al.* (2014) analyzed information of each parameter through information entropy in a study of groundwater quality. Wu *et al.* (2017) used entropy theory to determine the information of indicators in the study of surface water quality. Tanyimboh (2017) and Saleh & Tanyimboh (2016) used an advanced entropy model to study the optimal allocation of water resources. Malekian & Azarnivand (2016) utilized Shannon entropy to analyze flood risk. Huang *et al.* (2014) made use of entropy theory to study the temporal and spatial variation of potential evaporation in a basin in order to improve the drought resistance ability. Entropy theory is widely used in water resources research, but there are few studies that perform quantitative analysis and track management processes using entropy theory.

With the goal of the coordinated development of water resources and the social economy, under the constraints of the total annual available water resources and water use efficiency policy goals for 2015 and 2030, which were written in the 'Opinions on the practice of the strictest water resources

management system' promulgated by the State Council of China in 2012, the advanced theory of a complex system multi-agent model was used for the adaptive management of regional water resources. Information entropy was introduced to water resources adaptive management for monitoring and evaluating the management status, in order to provide countermeasure for regional water resources management.

STUDY AREA

Heilongjiang Province, China, is located in mid-latitude eastern Eurasia (see Figure 1). Its geographical coordinates are $121°11'$ to $135°05'$ east longitude and $43°25'$ to $53°33'$ north latitude. It includes the 13 administrative regions of Harbin, Qiqihar, Mudanjiang, Jiamusi, Daqing, Jixi, Shuangyashan, Yichun, Qitaihe, Hegang, Heihe, Suihua, and Daxing-anling. Within its territory is the world-famous black soil belt, and it is an important commodity grain base in China. In the study area, the average annual water resource is $8.11 \times 10^{10} \text{ m}^3$ (the amount of surface water resources and groundwater resources are added, and the amount of repetition between them is deducted). The per capita amount of water resources is $2.16 \times 10^3 \text{ m}^3$. According to Heilongjiang Provincial Bureau of Statistics & Survey Organization of Heilongjiang of NBS (2016), the total water supply was $3.55 \times 10^{10} \text{ m}^3$, the proportions of agricultural, industrial, domestic, and ecological water consumption were 0.88:0.07:0.05:0.01. As observed above, the utilization level of regional water resources was low, and agricultural production consumed most of the available water resources, with a low water resources utilization benefit (the water consumption per 10,000-yuan production value was $2.36 \times 10^2 \text{ m}^3$, and the amount of water consumption was 2.65 times the nationwide average). Therefore, it is necessary to optimize the management of water resources so that managers can make timely adjustments to their management strategies and promote the rational utilization of water resources in this region.

RESEARCH METHODS AND DATA SOURCES

The adaptive management of water resources is a dynamic process such that when conducting water resources
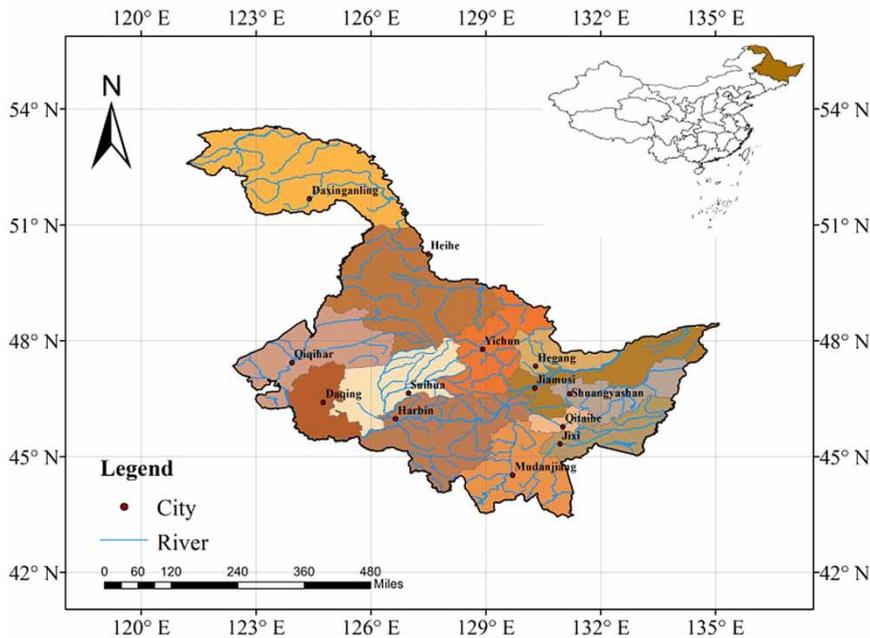
Figure 1 │ Diagram of the geographical location of the study area.

management, the needs and conflicts among different stakeholders are balanced and coordinated, and continuous learning and adjustment are adopted. In doing so, planning and management decisions directed towards water resources are improved, and the adaptability of the water resources system is increased.

In this paper, based on the decision-making process of water resources management, a multi-agent model was used to present a formal description of the management process. Based on the objectives and requirements of regional water resources management, the stakeholders of water resources systems were divided into different agents in the model. Information entropy was used to determine the weight of the objective and to quantify the adaptive performance (competition and cooperation among agents in order to realize their objectives) of each agent to evaluate the management results. The input and output methods were selected to describe the internal behaviors of the agents. A nested genetic algorithm was used to perform simulations for the agents to determine, in turn, the decision-making plan of water resources adaptive management (see Figure 2).

Model construction

The multi-agent model was proposed by the Santa Fe Institute, NM, USA, to solve practical applications of the theory of complex adaptive systems. Its essence lies in that, during the interactions between a given agent and the environment or other agents, its own behavioral rule undergoes constant changes such that it is adapted to the environment and participates in coordinated development with other agents (Holland 1995, 1998). Therefore, this approach fits the needs of adaptive management very well and is an important means of addressing the complex issues associated with water resources systems (Bazrkar *et al.* 2017).

Administrative agent

The administrative agent simulates the administrators and organizers of a water resources system. Under the premise of controlling the total amount of water resources, the administrative agent carries out resource allocation based on the principle of ceding priority to ecological environment protection, promotes the coordinated sustainable development of water resources and the social economy, and
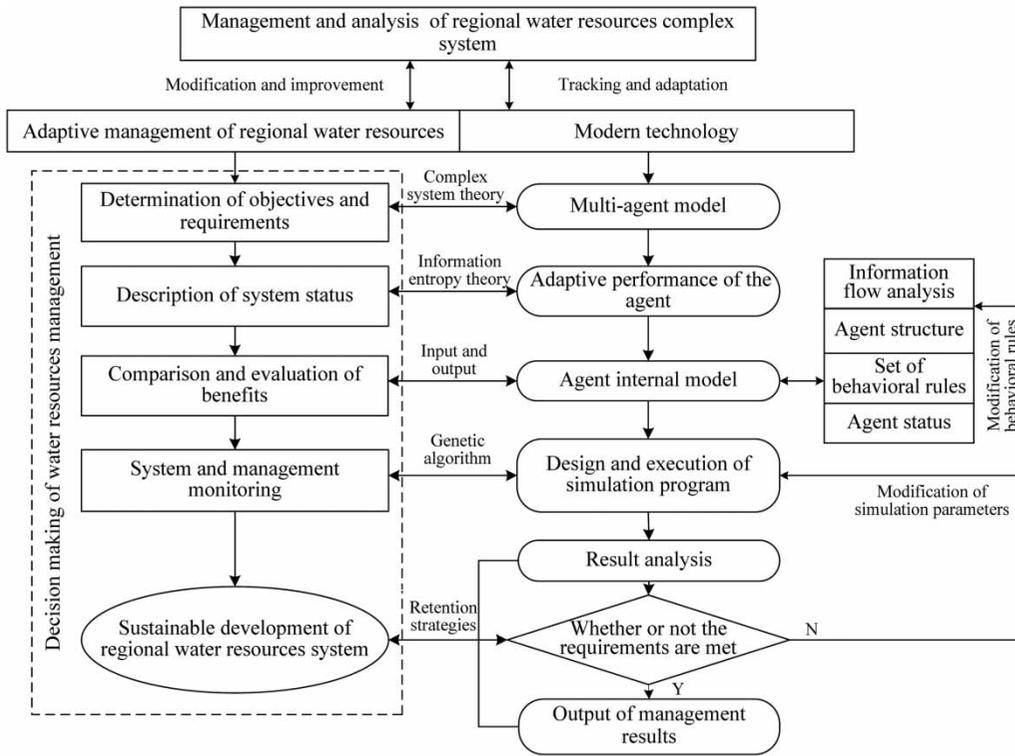
Figure 2 | Workflow of adaptive management of regional water resources.

alleviates the imbalance between the supply and demand of regional water resources.

Adaptive performance: The administrative agent would monitor all the agents and initiate the simulation process.

$$max\ SAF = d_1M + d_2X + d_3Y + d_4S_{ECO}$$
$$M = min\{M_A, M_I, M_D\}$$
$$X = max\{X_A + X_I\} \qquad (1)$$
$$Y = max\{Y_A\}$$
$$S_{ECO} = max\{S_{eco}\}$$

where SAF is the benefit function of the administrative agent; $d_i(i = 1, 2, 3, 4)$ is the weight of objective i; M is the social benefits; M_A, M_I, and M_D are the satisfaction degrees of water use of agricultural, industrial, and domestic water-demand agents; X is the regional economic benefits (yuan); X_A and X_I are the agricultural and industrial production values; Y is the grain yield (t); S_{ECO} is the ecological benefits (hm^2).

The behavioral rules are as follows.

Agent inputs: These include ecological benefits, the satisfaction degrees of water use, agricultural and industrial production value, and the grain yield.

Agent outputs: These include all the information for the water-demand agents.

Behavioral constraints: These determine the rules that must be followed in the simulation process, and the specific equations are:

$$\text{Water balance: } Q = W_A + W_I + W_D + W_O$$
$$\text{Land balance: } A = A_A + A_O \qquad (2)$$

where Q is the total amount of annual available water resources (m^3); W_A, W_I, W_D, and W_O are the amounts of water resource of the agricultural, industrial, domestic, and ecological water-demand agents (m^3); A is the main acreage of the water-demand agent (hm^2), A_A and A_O are the main acreages of the agricultural and ecological water-demand agents (hm^2).

Water-demand agents

According to the characteristics of water users and industries, the water-demand agents are divided into four types: agricultural, industrial, domestic, and ecological. The behavioral rules and constraints are shown in Table 1, and the adaptive performances are now discussed.

Agricultural agent

Adaptive performance: Under the control of the administrative agent, the agricultural agent would allocate resources to users and organize daily production. The water-demand amount was determined according to users' irrigation quotas, the yield of grain crops was predicted using the Douglas production function (Wang & Zhou 2012), the economic benefits were calculated based on the actual per-unit-area yield and unit prices of crops in 2015, and finally, the optimal benefit of the agent was obtained.

$$
\begin{aligned}
max \ AAF &= d_1 M_A + d_2 X_A + d_3 Y_A \\
M_A &= max\{MA(s)\} \\
X_A &= \sum_{s=1}^{s'} XA(s) \\
Y_A &= \sum_{s=1}^{s'} YA(s) \\
MA(s) &= wa_s / wa_s' \\
XA(s) &= \sum_{s=1}^{s'} u(s) YA(s) \\
\ln YA(s) &= \sum_{k=1}^{k'} h_k \ln x_k(s) + \varepsilon
\end{aligned}
\tag{3}
$$

where AAF is the benefit function of the agricultural agent; s' is the total number of users; $MA(s)$, $XA(s)$, and $YA(s)$ are the satisfaction degrees of water use, production value (yuan), and grain yield for user s, respectively; wa_s and wa_s' are, respectively, the amount of water use and demand for user $s(m^3)$; $u(s)$ is the unit price for user s(yuan); h_k is a parameter to be estimated; $x_k(s)$ is the impacting factor of production for user s; k' is the number of major factors affecting the grain yield; and ε is the residual ($0 < \varepsilon < 1$).

Industrial agent

Adaptive performance: Under the control of the administrative agent, the industrial agent would organize daily production. Indicators of industrial production in the region were counted, the amount of water demand was determined according to water use efficiency, and the economic benefit was calculated based on the amount of water demand per 10,000-yuan production value. The average annual growth rate of production value was used to predict the change in the production value for the industrial agent, and the optimal benefit of the agent was obtained.

$$
\begin{aligned}
max \ IAF &= d_1 M_I + d_2 X_I \\
M_I &= max\{MI(e)\} \\
X_I &= \sum_{e=1}^{e'} XI(e) \\
MI(e) &= wi_e / wi_e' \\
XI(e) &= \frac{wi_e(1 + \eta(e))}{R(e)}
\end{aligned}
\tag{4}
$$

where IAF is the benefit function of the industrial agent; e' is the total number of users; $MI(e)$ and $XI(e)$(yuan) are, respectively, the satisfaction degrees of water use and the production values for user e; wi_e and wi_e' are the amount of water use and demand for user $e(m^3)$, respectively; $\eta(e)$ and $R(e)(m^3)$ are the water resource reuse rate and the amount of water demand per 10,000-yuan production value for user e.

Domestic agent

Adaptive performance: Under the control of the administrative agent, with the goal of achieving national water quota per capita, the domestic agent would allocate resources to users for meeting their daily water needs. In considering the change of regional population policy, population growth was predicted using the logistic model. The amount of water demand was determined by the national water quota per capita, and the optimal benefit of the agent was obtained.

$$
\begin{aligned}
M_D &= max\{MD(g)\} \\
MD(g) &= wd_g / wd_g'
\end{aligned}
\tag{5}
$$

Table 1 | Inputs and outputs for behaviors of water-demand agents

Water-demand agents	Behavioral rules			Network connection in the system	Behavioral constraints
	Type	Parameter	Variable		
Agricultural	Input	User's minimum planting area User's yield parameters to be estimated User's market price Presence/absence of multiple cropping User's irrigation quota Rate of minimum guaranteed water use	User's planting acreage User's yield User's production value User's water consumption User's water-demand amount	Input of the last iteration for agricultural agent	$\sum\limits_{s=1}^{s'} A(a,s) \leq A_A$ $\sum\limits_{s=1}^{s'} wa_s \leq W_A$
	Output		Satisfaction degrees of water use Amount of water consumption Acreage of land occupied Total yield Total production values	Output to administrative agent	
Industrial	Input	Amount of water-demand per 10,000-yuan production value Water use efficiency Reuse rate of water resources Average annual growth rate of production value Rate of minimum guaranteed water use	User's total water consumption User's production value Amount of water demand for each user	Input of the last iteration for industrial agent	$\sum\limits_{e=1}^{e'} wi_e \leq W_I$ $X_I(n) = X_I(1+r)^n$
	Output		Total production values Amount of water consumption Satisfaction degrees of industrial water use	Output to administrative agent	
Domestic	Input	National water quota per capita Population Saturation value of population Rate of minimum guaranteed domestic water use	 Amount of domestic water consumption Amount of domestic water demand	Input of the last iteration for domestic agent	$\sum\limits_{g=1}^{g'} wd_g \leq W_D$ $R = \dfrac{k}{1+me^{-at}}$
	Output		Total amount of water consumption Satisfaction degrees of domestic water use	Output to administrative agent	
Ecological	Input	Equivalent factor of user Minimum land acreage occupied by users Rate of optimal guaranteed ecological water use	Acreage of land occupied by user Ecological benefit of user Amount of water demand	Input of the last iteration for ecological agent	$\sum\limits_{t=1}^{t'} A(o,t) \leq A_O$
	Output		Total acreage of land occupied Amount of water consumption Total ecological benefits	Output to administrative agent	

Notes: $A(a,s)$ is the planting acreage of user s of the agricultural agent (hm^2); $X_I(n)$ is the industrial production value of year n (yuan); and r is the average annual growth rate of the industrial production value (%); g' is the total number of users of the domestic agent; t is the time variable in the population prediction model (year); a and m are the coefficients to be determined; and k is the given population saturation value of the case study area, which was set to $k = 4.5 \times 10^7$ people (Cheng *et al.* 2015).

where $MD(g)$, wd_g, and wd_g' are the satisfaction degrees of water use, amount of water use, and demand amount (m^3) for user g, respectively.

Ecological agent

Adaptive performance: Under the control of the administrative agent, priority is given to guarantee the water consumption of the ecological agent; an equivalent factor (Wackernagel & Rees 1996) was used to determine the ecological benefits in order to obtain the optimal benefit for this agent.

$$S_{eco} = \sum_{t=1}^{t'} s_{eco}(t)$$
$$s_{eco}(t) = b_t A(o, t) \tag{6}$$

where $s_{eco}(t)$, b_t, and $A(o, t)$ are, respectively, the ecological benefits (hm^2), equivalence factor, and acreage of land occupied (hm^2) for user t, and t' is the total number of users.

Weight determination

Quantifying information in the management process is the basis for choosing a management strategy. According to information entropy (Shannon 1948), an advanced theory to quantify the information uncertainty, the information of individuals in the model simulation process was first quantified. The weight of each objective was then accordingly determined, and the benefits of a given agent were obtained. To effectively overcome the influence of the large objective difference and prevent the occurrence of objective weight 0, the interaction between objectives was considered fully, and the individual standard deviation σ_i was introduced to improve the traditional entropy method.

Step 1: Normalize the information of the individuals.

$$p_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \qquad i = 1, 2 \cdots m; j = 1, 2 \cdots n \tag{I}$$

where x_{ij} is the value of individual j under objective i in the simulation process for a given agent, m is the total number

of objectives in the adaptive performance for the agent, and n is the total number of individuals.

Step 2: Calculate the entropy of each objective.

The role of the individual in the comprehensive assessment is determined by the entropy value.

$$E_i = -\frac{1}{\ln n} \sum_{j=1}^{n} P_{ij} \ln P_{ij} \quad 0 < E_i < 1$$
$$P_{ij} = \frac{1 + p_{ij}}{\sum_{j=1}^{n} (1 + p_{ij})} \tag{II}$$

where E_i is the entropy value of objective i.

Step 3: Calculate the weight of each objective.

$$d_i = \frac{1 - E_i + \sigma_i \sum_{i=1}^{m} \frac{\sigma_i}{\bar{p}_i}}{\sum_{i=1}^{m} (1 - E_i) + \sum_{i=1}^{m} \sigma_i \sum_{i=1}^{m} \frac{\sigma_i}{\bar{p}_i}}, \quad i = 1, 2, \cdots, m$$
$$\sigma_i = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (p_{ij} - \bar{p}_i)^2} \tag{III}$$

where d_i is the weight of objective i.

Step 4: Calculate the benefits of the individuals.

$$U = \sum_{i=1}^{m} d_i P_{ij} \tag{IV}$$

Model solution

Based on the model characteristics, a nested genetic algorithm, i.e., another genetic algorithm embedded in a genetic algorithm, was used to solve the model (Cheng *et al.* 2015; see Figure 3). The inner-layer genetic algorithm was used to simulate the water-demand agents, and the outer-layer genetic algorithm was used to simulate the administrative agent. The individual comprehensive evaluation value was confirmed according to formulas (I)–(IV), the favorite individual required by agent was selected (see formula (V)), and the optimal benefit of the administrative agent was achieved when the algorithm converges. Matlab 2012a was used to implement the algorithms, the hybrid operator $P_c = 0.8$ and the mutation operator $P_m = 0.2$ come from
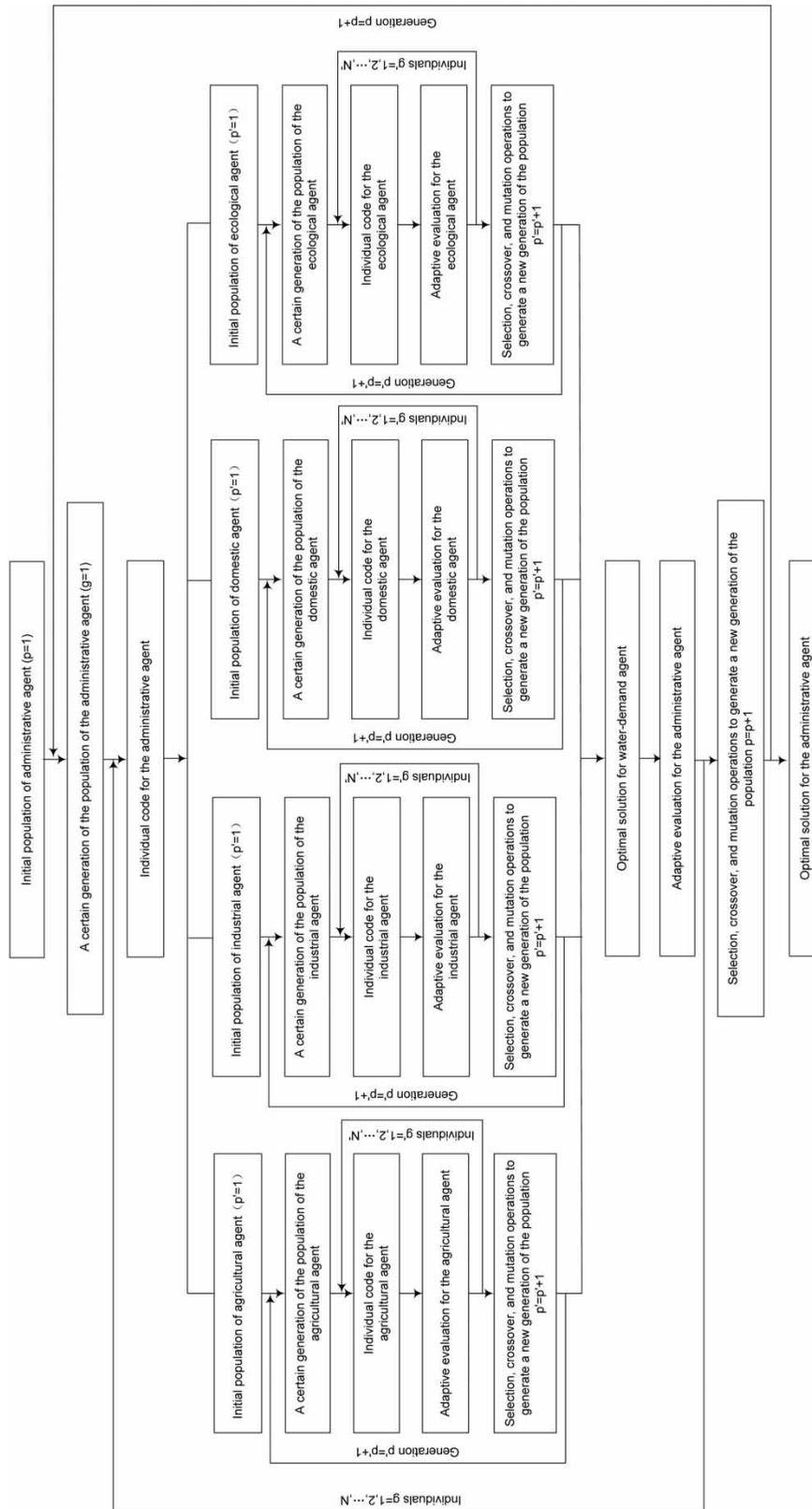
Figure 3 │ Nested genetic algorithm used to solve the simulation process in the multi-agent model.

Fu *et al.* (2012).

$$bestx_i(j+1) = \begin{cases} x_i(j+1) & U(x_i(j+1)) \geq U(bestx_i(j)) \\ x_i(j) & U(x_i(j+1)) < U(bestx_i(j)) \end{cases}$$

$$(V)$$

Data sources

The initial data for the water-demand agents are shown in Table 2. The amounts of water consumption, production values, grain yield, and acreage of land occupied were obtained from the Heilongjiang Provincial Bureau of Statistics & Survey Organization of Heilongjiang of NBS (2016) and National Bureau of Statistics of China (2016). The net irrigation quota were derived from the water quota for local standards in Heilongjiang Province, China (DB23/T 727-2010). The production value of the agricultural agent was taken from the Ministry of Agriculture of the People's Republic of China (2016). The irrigation water use coefficient, water use efficiency of industrial agent, and the reference

amount of initial water consumption of the agents in 2030 were taken from the stipulation in 'Opinions on the practice of the strictest water resources management system (http://www.gov.cn/zhengce/content/2012-02/15/content_2311.htm)' and 'Assessment methods on the practice of the strictest water resources management system (http://www.gov.cn/zwgk/2013-01/06/content_2305762.htm)'. The initial satisfaction degree of water use for the water-demand agents were obtained based on the water consumption amounts and initial water-demand amounts.

RESULTS

Initial data for the water-demand agents in the study area are shown in Table 2. During model execution, each agent would undergo adaptive evolution by following the behavioral rules and undergo reorganization through continuous learning and feedback. The results converge when the allocation of available water is stable, and a way emerges

Table 2 │ Initial data for the water-demand agents in the study area

Water-demand agents	Amount of water consumption (10^8 m³)		Water-demand prediction	Initial amount of water demand (10^8 m³)		Other	
	Year 2015	**Year 2030**		**Year 2015**	**Year 2030**	**Year 2015**	**Year 2030**
Agricultural agent	312.50	311.66	$\sum\limits_{s=1}^{s} R_s A(a, s)$	423.66	366.10		
Domestic agent	16.20	16.16	$T \times R$	24.31	26.19	$T = 0.17$ $R = 3.81 \times 10^7$	$T = 0.17$ $R = 4.11 \times 10^7$
Industrial agent	23.80	23.74	$kWE_{2010}X_I$	29.36	46.71	$K = 0.65$	$K = 0.50$
Ecological agent	2.60	18.50	$0.05 \times Q$	17.77	18.50		

Land usage type (year 2015 and 2030)	Agricultural agent					Ecological agent		
	Rice	**Corn**	**Soybean**	**Wheat**	**Other**	**Forests land**	**Grassland**	**Wetland**
Land acreage (10^4 hm²)	384.30	772.30	248.60	7.50	20.10	2,183.70	206.30	431.48
Net irrigation quota (m³/hm²)	4,800	800	950	900	1,000			
Irrigation water use coefficient	0.7, 0.8	0.55, 0.65	0.55, 0.65	0.55, 0.65	0.55, 0.65			
Per unit area yield (t/hm²)	5.72	4.59	1.76	2.91	6.02			
Unit-price (10^4 yuan/t)	0.48	0.23	0.45	0.25	6.91			
Equivalent factor						1.1	0.5	0.2

Notes: R_s is the irrigation quota (m³/hm²) for crop *s*, it is the ratio of net irrigation quota to irrigation and water use coefficient; X_I is the industrial production value; *Q* is the total amount of annual available water resources (m³); *T* is the national water quota per capita (m³/day); *R* is the population; WE_{2010} is the amount of water consumption per 10,000-yuan production value in the study area in 2010 (m³); and *k* is the industrial water use efficiency.

to coordinate water use with other agents and the environment, which is the result of adaptive management (see Figure 4). The adaptive management result for water resources allocation in 2015 was obtained. The validity of the result was verified by comparing it with the real data for 2015 (see Figure 5). Then, considering the 'Opinions on the practice of the strictest water resources management system', the data of 2030 in Table 2 were input into the model, and the adaptive management results in the study area were compared under the two conditions of changeless

and increased water use efficiency (see Figure 6). The required improvement in water use efficiency for meeting the above policy goal in 2030 was achieved.

Comparative analysis before and after water resources adaptive management in the study area in 2015

In Figure 5(a), the water consumption of the ecological agent in the study area for 2015 was fully guaranteed after adaptive management: the lowest satisfaction degrees of water use
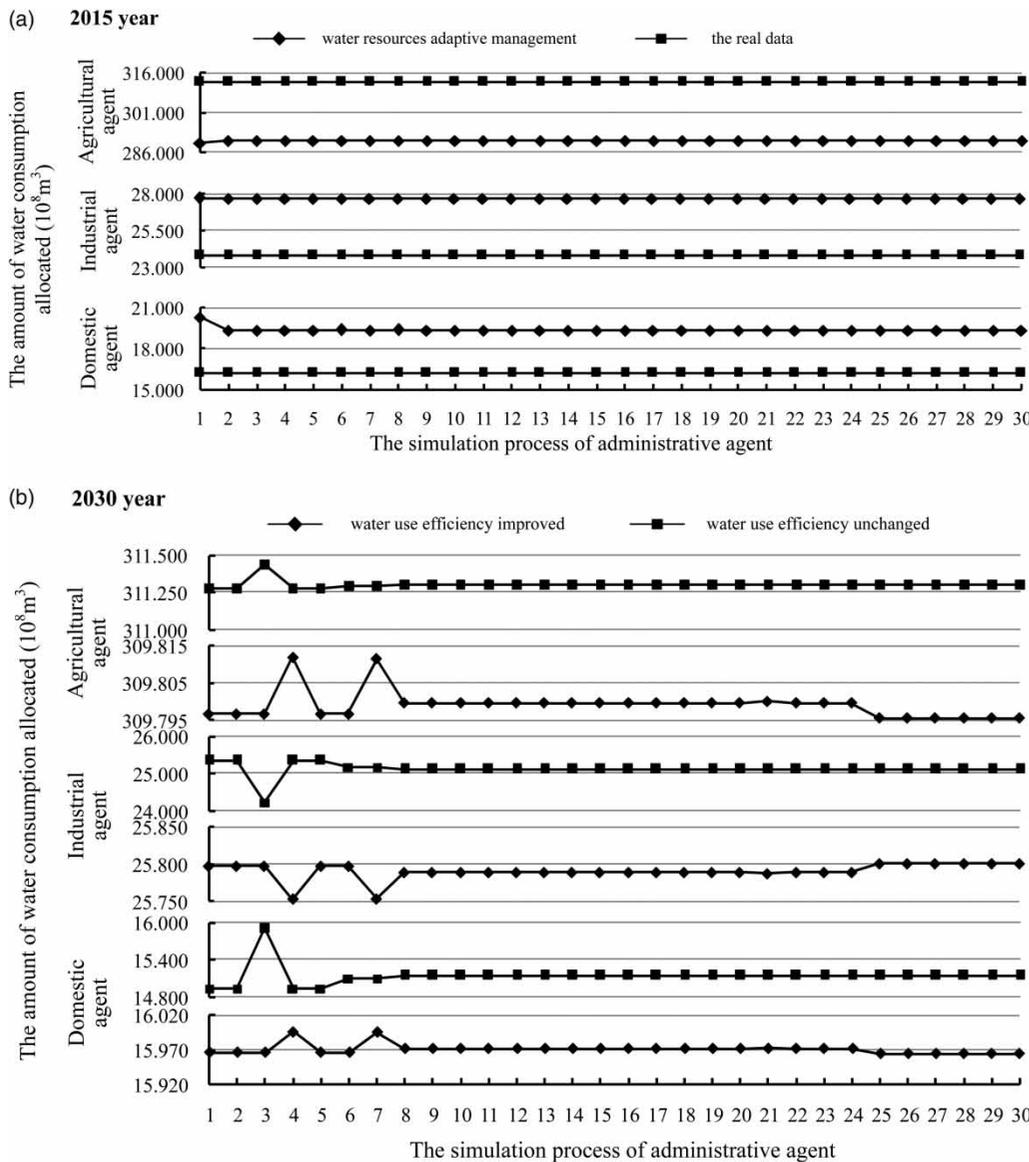

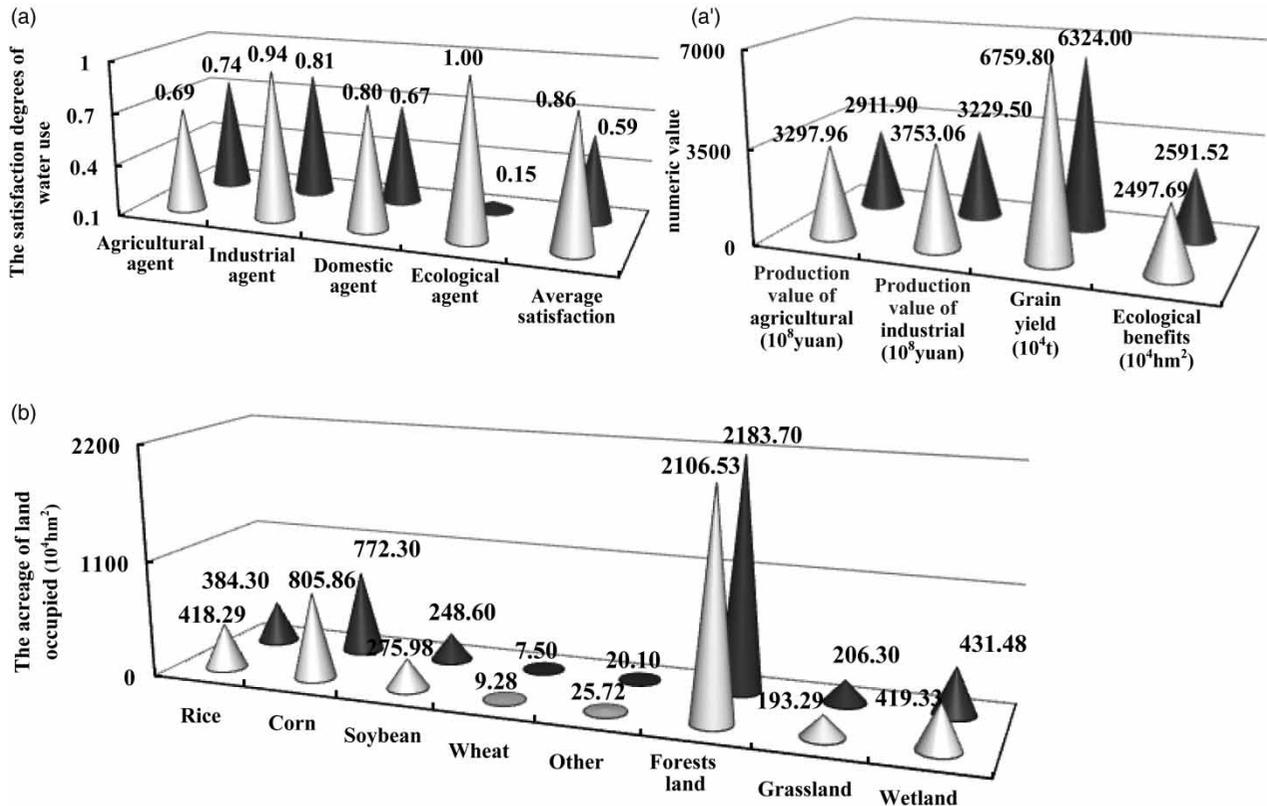**Figure 4** │ The amount of water consumption allocated during model execution.

Figure 5 │ Comparative analysis of water resources adaptive management results before and after adaptive management for the year 2015 (black: before; gray: after).

increased from 0.67 for the domestic agent to 0.69 for the agricultural agent (an increase of 2.90%); the satisfaction degrees of water use of the agricultural agent decreased from 0.74 to 0.69; and the satisfaction degrees of water use of the industrial agent, domestic agent, and ecological agent increased from 0.81, 0.67, and 0.15 to 0.94, 0.80 and 1.00, respectively. In Figure 5(a′), the production value of the agricultural agent increased from 2.91×10^{11} yuan to 3.30×10^{11} yuan; the production value of the industrial agent increased from 3.23×10^{11} yuan to 3.75×10^{11} yuan; the grain yield increased from 6.32×10^{7} t to 6.76×10^{7} t; and the ecological benefit decreased from 2.59×10^{7} hm^2 to 2.50×10^{7} hm^2 (a decrease of 3.63%). In Figure 5(b), the land acreage for rice, corn, soybean, wheat, and other crops of the agricultural agent increased from 3.84×10^{6} hm^2, 7.72×10^{6} hm^2, 2.49×10^{6} hm^2, 7.50×10^{4} hm^2, and 2.01×10^{5} hm^2 to 4.18×10^{6} hm^2, 8.06×10^{6} hm^2, 2.76×10^{6} hm^2, 9.28×10^{4} hm^2, and 2.57×10^{5} hm^2 (after the adaptive management, it increased by 8.84%, 4.35%, 11.02%, 23.76%, and 27.97%, respectively). The land acreage for forest land, grassland, and wetland

of the ecological agent decreased from 2.18×10^{7} hm^2, 2.06×10^{6} hm^2, and 4.31×10^{6} hm^2 to 2.11×10^{7} hm^2, 1.93×10^{6} hm^2, and 4.19×10^{6} hm^2 (after the adaptive management, it decreased by 3.53%, 6.31%, and 2.82%, respectively).

After adaptive management in 2015, the economic benefit of the whole region, namely, the total production value of industry and agriculture, increased from 6.14×10^{11} to 7.05×10^{11} yuan. Combined with the amount of water consumption allocated of the agricultural and industrial agent (2.90×10^{10} m^3 and 2.77×10^{9} m^3), the benefit of water use was calculated to be 22.17 yuan/m^3, which is 14.81% higher than the 19.31 yuan/m^3 before the adaptive management. The amount of water consumption allocated of the agricultural agent was 7.10% less than that before adaptive management. The major reason is that the study area is one of the important commodity grain bases in China, and agricultural water consumption is always high in order to ensure national food security (Ren *et al.* 2018), which, to a certain extent, limits the development of other industries in the region and also leads to the overall economic development

of the region below the national level. Under the constraints of water balance of the administrative agent, this part of water resources was transferred to other water-demand agents, resulting in improvement of the satisfaction degrees of water use of the industrial, domestic, and ecological agents (after the adaptive management, it increased by 16.3%, 19.5%, and 585.0%, respectively), which effectively promotes the balance between supply and demand. This is conducive to the development of other industries in the region and the rationalization of industrial structure. The grain yield increased by 6.89% after adaptive management; the stable growth of the grain yield is of great significance for ensuring national food security. Under the constraints of land balance of the administrative agent, the increase in land acreage of the agricultural agent resulted in a reduction in the land acreage of the ecological agent; the formula for the ecological benefit shows that this is the reason for the decline in the ecological benefit. However, the adaptive management implemented provision of ecological compensation to the ecological agent, the water consumption allocated of the ecological agent increased to $1.78 \times 10^9 \, \text{m}^3$, making the satisfaction degree of water use of the ecological agent increase from 0.15 to 1, thus achieving the Pareto optimum of water resource management (Nouiri 2014). In practice, ensuring ecological water demand to be met for 100% can be accomplished by means of comprehensive implementation of the 'river chief system' (Ren 2015) and other regulatory means to control river water intake, prevent and control water pollution, improve water environment, and restore water ecology.

In a word, adaptive management in the study area coordinates water use of each water-demand agent, and effectively alleviates the regional water use imbalance. At the same time, after the adaptive management of the agricultural agent in the study area, the amount of water consumption was reduced, but there was still an increase in the water demand caused by the increase in the land acreage of the grain crops; thus, it is necessary to improve the efficiency of irrigation water use.

Comparative analysis of water resource adaptive management before and after the improvement of water use efficiency of the water-demand agents in 2030 in the study area

In Figure 6(a), the water consumption of the ecological agent in the study area before and after the improvement

of water use efficiency was fully guaranteed: the lowest satisfaction degrees of water use increased from 0.41 to 0.55 for the industrial agent (an increase of 34.29%), and the satisfaction degrees of water use of the agricultural agent and domestic agent increased from 0.73 and 0.58 to 0.85 and 0.61 (increases of 16.44% and 5.17%), respectively. In Figure 6(a′), the production value of the agricultural agent decreased from 3.33×10^{11} to 3.28×10^{11} yuan, the production value of industrial agent increased from 2.84×10^{11} to 4.19×10^{11} yuan, the grain yield decreased from 7.04×10^7 to $6.81 \times 10^7 \, \text{t}$, and the ecological benefit increased from 2.50×10^7 to $2.54 \times 10^7 \, \text{hm}^2$. In Figure 6(b), the land acreages of rice, corn, soybean, wheat, and other crops of the agricultural agent changed from $4.59 \times 10^6 \, \text{hm}^2$, $8.31 \times 10^6 \, \text{hm}^2$, $2.45 \times 10^6 \, \text{hm}^2$, $8.90 \times 10^4 \, \text{hm}^2$, and $2.37 \times 10^5 \, \text{hm}^2$ to $4.53 \times 10^6 \, \text{hm}^2$, $7.87 \times 10^6 \, \text{hm}^2$, $2.51 \times 10^6 \, \text{hm}^2$, $8.96 \times 10^4 \, \text{hm}^2$, and $2.39 \times 10^5 \, \text{hm}^2$, the land acreages of rice and corn decreased by 1.25% and 5.29%, and those of soybean, wheat, and other crops increased by 2.53%, 0.69%, and 0.88%, respectively. The land acreage of main crops increased or decreased, reflecting changes in planting structure. The land acreages of forest land, grassland and wetland of the ecological agent increased from $2.11 \times 10^7 \, \text{hm}^2$, $1.86 \times 10^6 \, \text{hm}^2$, and $3.89 \times 10^6 \, \text{hm}^2$ to $2.15 \times 10^7 \, \text{hm}^2$, $1.90 \times 10^6 \, \text{hm}^2$, and $3.90 \times 10^6 \, \text{hm}^2$, respectively (increases of 1.8%, 2.34%, and 0.16%).

After improvement in the water use efficiency in 2030, the economic benefit of the whole region, namely, the total production value of industry and agriculture, increased from 6.16×10^{11} to 7.47×10^{11} yuan. Combined with the amount of water consumption allocated of agricultural and industrial agents ($3.10 \times 10^{10} \, \text{m}^3$ and $2.57 \times 10^9 \, \text{m}^3$), the benefit of water use was calculated to be 22.18 yuan/m^3, which is 21.14% higher than the 18.31 yuan/m^3 before improving the water use efficiency. The satisfaction degrees of water use of all water-demand agents were improved. Under the policy of the changeless total amount of water consumption, the water consumption of each water-demand agent in the region was effectively coordinated, promoting socioeconomic development. The ecological benefit in the study area increased by 1.78% relative to that when water use efficiency was unchanged; combined with the decrease in the ecological benefit in 2015, it can be concluded that constant water resources adaptive management can improve the
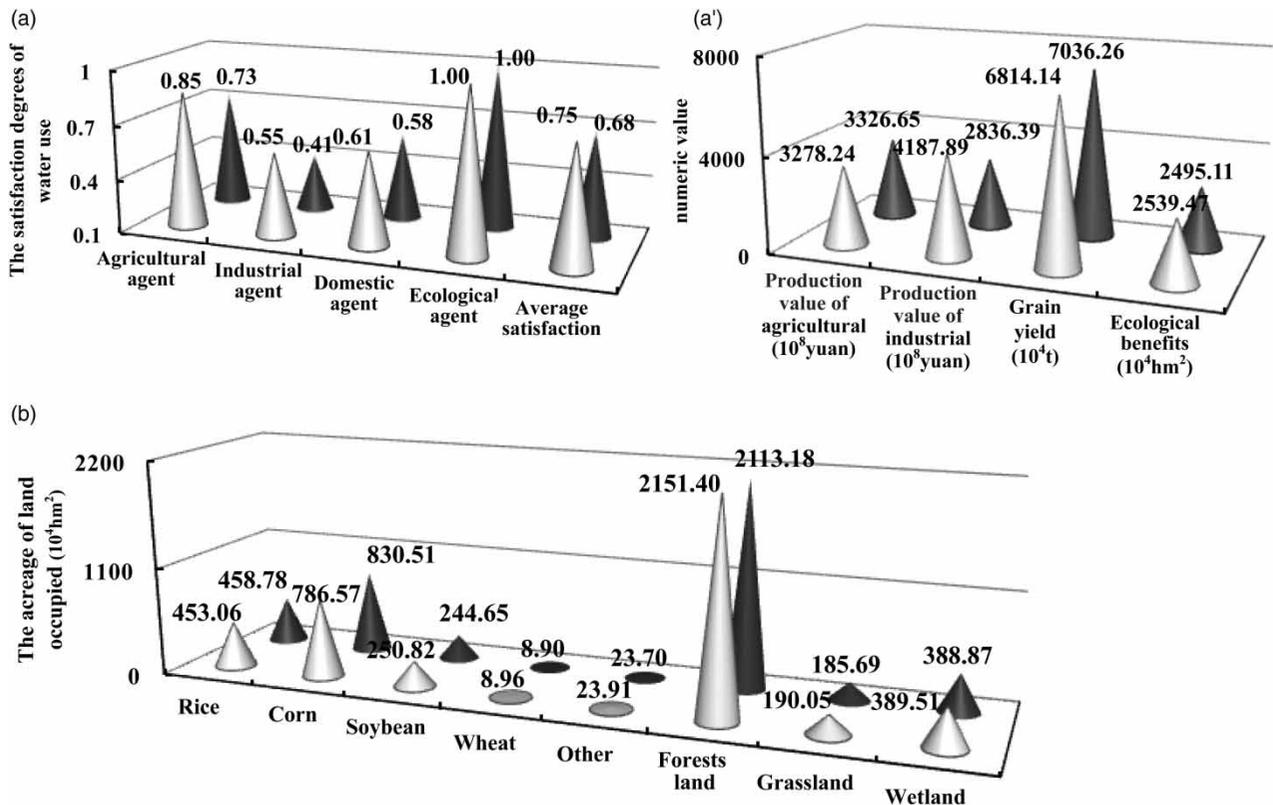
Figure 6 | Comparative analysis of water resources adaptive management results before and after improving the water use efficiency for the year 2030 (black: water use efficiency unchanged; gray: water use efficiency improved).

ecological benefit in 2030. Clearly, the adaptive management of water resources while improving water use efficiency not only helps realize policy goals but also improves the ecological environment of the study area. After improving the water use efficiency, the amount of water consumption of agricultural agent decreased by 0.59% relative to that when the water use efficiency was unchanged, and the total land acreage for agriculture decreased by 4.32×10^5 hm^2 (a decrease of 2.76% relative to that when the water use efficiency was unchanged); at the same time, the grain yield decreased by 3.16%, and the change rates of the grain yield relative to the amount of water consumption and land acreage were 5.28 and 1.14, respectively. The grain yield was greatly affected by the amount of water consumption. Considering the loosening of China's population policy, the population will inevitably increase, and since the volume of international grain trade is limited, the demand for grain is bound to exhibit a rigid growth trend. Therefore, improving the efficiency of agricultural irrigation water is necessary to ensure national

food security. Combining the amount of water consumption with the production value of the industrial agent, the amount of water consumption per 10,000-yuan production value was 61.37 m^3, a decrease of 16.73% relative to the value of 73.90 m^3 in 2015. Therefore, in order to achieve the policy goal, the industrial agent must ensure that the annual decrease in the amount of water consumption per 10,000-yuan production value is 1.21%. The total amount of water consumption of the domestic agent increased by 4.64% relative to that when the water use efficiency was unchanged, but according to the logistic model for population growth in this paper, the population of the study area will reach 4.11×10^7 in 2030, so the water quota per capita was decreased from 0.12 m^3 to 0.11 m^3 per day. Therefore, we should encourage people to save water via adaptive management.

In conclusion, the adaptive management of water resources by improving water use efficiency is conducive to realizing policy goals, to promote the sustainable

development of society, the economy, and ecology, and to providing direction for managers to make water resources management decisions.

Weights of the objectives in the benefits function

Formulas (I)–(III) were used to calculate the weights of the objectives before and after adaptive management for the year 2015, and before and after improving the water use efficiency for the year 2030 (see Table 3). In Table 3, when the agent has one or two targets, the weights of the objectives are essentially equal (e.g., industrial agents) during the model execution. When there are more than three objectives, the weights vary greatly (e.g., the weight of agricultural agent production value has changed from 0.315 to 0.448 for the year 2015). For the same agent, the order of the weights of each objective are also different (e.g., in 2015 and 2030, the order of the objectives for the administrative agent are $d_4 > d_3 > d_1 > d_2$ and $d_4 > d_3 > d_2 > d_1$). This shows that no matter what the conditions, the ecological benefit of the study area is vitally important. The second most important is grain yield, the reason for this being that the study area is one of the important commodity grain bases in China. The weight order of satisfaction degree and production value have changed before and after adaptive management for the year 2015, and before and after improving the water use efficiency for the year 2030; this is related to the strict requirement of the total annual available water resources in the region and after improving the water use efficiency, the administrative agent pays more attention to production value than water. In total, under the condition of improving the ecological environment and not affecting

the grain yield too much, the study area should actively improve the water use efficiency of the water-demand agent, and find ideas and measures to promote the development of a high-quality economy.

It can be seen from the above that the weights given according to individual information entropy are different from the previous weighting methods, and can better reflect the differences between the objectives of the agent during model execution. Moreover, the imbalance between supply and demand of water resources has been improved in the water resources management of the study area in 2015 and 2030, which verifies the feasibility and rationality of the method in practical application.

Potential applicability of research methods

In this paper, a research method for adaptive management of regional water resources is proposed. The information entropy is used to solve the problem of information transmission during the model execution. The traditional information entropy is improved by using the standard deviations of individuals, the interference of the abnormal value to the agent evolution information is reduced, the state of the agent is tracked and modified, and a nested genetic algorithm is employed to perform the simulation of each agent. The method can effectively coordinate the benefit conflict among the water-demand agents and the benefit conflict between the water-demand agents and administrative agent. A water allocation scheme with high comprehensive benefits is obtained through individual selection, crossover, and mutation. This research about water resources management provides a valuable solution to the whole water

Table 3 │ Comparative analysis of the weight of the agent's objectives during model execution

Agent	Before and after adaptive management for the year 2015				Before and after improving the water use efficiency for the year 2030			
	Satisfaction degree (d_1)	Production value (d_2)	Grain yield (d_3)	Ecological benefit (d_4)	Satisfaction degree (d_1)	Production value (d_2)	Grain yield (d_3)	Ecological benefit (d_4)
Administrative	0.094/0.016	0.014/0.020	0.229/0.238	0.663/0.726	0.084/0.033	0.025/0.051	0.220/0.219	0.671/0.697
Agricultural	0.001/0.001	0.315/0.448	0.684/0.552		0.001/0.001	0.342/0.508	0.657/0.491	
Industrial	0.500/0.500	0.500/0.500			0.500/0.500	0.500/0.500		
Domestic	1.00/1.00				1.00/1.00			
Ecological				1.00/1.00				1.00/1.00

resources management problem, which is applicable to the optimization and simulation of regional water resources management and other complex systems. However, the model does not reflect the impact of socioeconomic development on the crop unit price and irrigation water efficiency, nor does it provide a detailed analysis of the uncertain relationship between conservation of the ecological environment and ecological water use. This will be an important direction to improve the method in future work.

CONCLUSION

In this paper, regional water resources adaptive management research is conducted based on the advanced theory of complex systems, which is applicable to the optimization and simulation of regional water resources management and other complex systems. Under the condition of giving priority to ecological water use, the benefits relationship among different agents are considered from two aspects: administrative agent and water-demand agents. The adaptive management model is tested by using the actual data of Heilongjiang Province in 2015. After adaptive management, the proportions of agricultural, industrial, domestic, and ecological water consumption changes to 0.817:0.078:0.055:0.050, which alleviates the imbalance of regional water use, and the validity of regional water resources adaptive management has been confirmed. According to strict control requirement of the regional total annual available water resources in 2030, water resources adaptive management before and after improving the water use efficiency are conducted. It was concluded that water resources adaptive management can change the proportions of agricultural, industrial, domestic, and ecological water consumption to 0.835:0.069:0.046:0.050, which further shows that the constant water resources adaptive management coordinates the water use among the water-demand agents.

The traditional information entropy is improved by introducing the standard deviation of individuals, which reduces the interference of abnormal value to the agent evolution information, prevents the occurrence of weight '0', and quantifies the states of agents so that managers can track and manage. Unlike previous ones, the differences among the objectives of agents during the model execution can be reflected well, and a new method to determine the weight of multi-objectives is provided.

In addition, taking Heilongjiang Province, the main grain-producing region in China as an example, after adaptive management for the year 2015, the weight of production value increased by 42.22%, indicating that the agricultural agent pays more attention to production value than grain yield, but the weight of grain yield still accounted for 55.2%. When improving the water use efficiency for the year 2030, the weight difference between the two is only 0.017. Therefore, in order to realize adaptive management, the study area needs to continuously improve agricultural production value under the condition of ensuring grain yield, and create a good external environment for regional agricultural products' processing industry.

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