Assessing the complex adaptability of regional water security systems based on a unified co-evolutionary model

Jiping Yao, Yongtai Ren, Shuai Wei and Wei Pei

ABSTRACT

A unified co-evolutionary model was developed to study the adaptability conditions of regional water security systems, which is important for the coordinated development of these systems. In this work, the main factors that affect the adaptability of regional water security systems, the contribution of each sub-problem domain to the development of the problem domain, and the fitness values of regional water security systems were analyzed based on the model. Taking Jiansanjiang as an example, the results showed that in 2002–2011, the water resources system had strong adaptability and contributed greatly to improve the adaptability of the water security system; the socioeconomic system had poor adaptability to environmental changes and contributed little to the adaptability of the water security system; and the eco-environmental system was barely able to adapt to the changing environment and contributed less to the adaptability of the water security system. Due to the influence of the socioeconomic and eco-environmental systems, the adaptability of the water security system was relatively weak. Therefore, strengthening the sustainable utilization of water resources, promoting the coordinated development of the social economy, and improving the quality of the ecological environment are effective strategies to improve the adaptability of water security systems.

Key words | adaptability, co-evolutionary model, cooperative algorithm, grey correlation analysis, problem domain, water security systems

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

Yongtai Ren (corresponding author)
College of Science, Northeast Agricultural University,
Harbin 150030,
China
E-mail: *ytren@neau.edu.cn*

Wei Pei
School of Water Conservancy & Civil Engineering,
Northeast Agricultural University,
Harbin 150030,
China

INTRODUCTION

In recent years, due to fluctuations in the natural water cycle and the destruction of the water balance, regional water security is becoming increasingly serious; water security refers to a region (or country) under certain socioeconomic conditions and includes the ability to withstand water disasters and the sustainable use of water resources to ensure sustainable economic, social, and ecological development (Petersen-Perlman *et al.* 2012; Anand *et al.* 2013; Fu *et al.* 2013). Water security systems are complex systems including water resources, socioeconomic and eco-environmental subsystems, which must be individually examined to comprehensively and systematically analyze and study the regional water security situation. Additionally, water resource systems are the basis for the development of subsystems in water security systems; socioeconomic systems aim to maximize the benefits of the subsystems. In the context of sustainable development, eco-environmental systems provide an environment for the good functioning of water security systems. Thus, water security systems are highly integrated with complex adaptive characteristics (Giacomoni *et al.* 2013; Cheng *et al.* 2015).

This paper introduces a cooperative evolutionary algorithm to study the operational mechanisms and development of water security systems. Co-evolution refers to the

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combined evolution of both organisms and the environment under long-term mutual adaptation, whereas evolution corresponds to the individual development of organisms and the environment (Ehrlich & Raven 1964). The co-evolutionary algorithm is an evolutionary computational method that was first proposed in the 1990s to simulate the co-evolution phenomenon in ecological evolution (Hillis 1990; Panait 2010). The method calculates the fitness of individuals according to the collaborative relationship between individuals. Compared with the genetic algorithm, the co-evolutionary algorithm can simulate ecological evolution more effectively, and the algorithm is more adaptive and can overcome the premature convergence of the genetic algorithm. Therefore, some researchers have introduced cooperative evolutionary computations in research on optimization problems; for example, an innovative variation of the co-evolutionary genetic algorithm (CGA) was proposed by Baek & Yoon (2002) to determine adaptive scheduling strategies in a complex multi-machine system. The CGA effectively suppressed premature convergence and produced dispatching rules for spatial adaptation that outperformed other heuristic methods. In a study of the optimal allocation of water resources, a CGA was proposed by Wang *et al.* (2014) to improve the utilization of water resources. A hybrid CGA was proposed by Korayem *et al.* (2016) to determine the optimal moving paths of concentrated nanoparticles in a complex environment. Infeasible initial paths significantly reduced the efficacy of the path planning algorithm, especially in large and complex environments. Tian & Gong (2014) proposed a new CGA that uses two types of alternating co-evolution to generate test data for path coverage. This proposed method displayed the highest success rate, lowest requirement for human evaluation, and lowest time consumption.

Based on an individual competitive relationship or partnership, co-evolutionary algorithms can be divided into competitive co-evolutionary algorithms (CCEAs) and cooperative co-evolutionary algorithms (Chandra *et al.* 2011; Nogueira Collazo *et al.* 2014). The fitness of individuals in competitive co-evolution algorithms depends on the ability of the individual to defeat an opponent in a competition, and the progress of either party in the competition will endanger the survival of the other party. This method has been used by some researchers to solve various problems. A simple, non-problem-specific framework was proposed by Sato & Arita (2009) to extend the range of CCEAs and avoid local optima by utilizing the loss of gradient. A competitive co-evolutionary multi-objective genetic algorithm (cc-MOGA) was used to approximate a Pareto front of efficient silvicultural regimes of *Eucalyptus fastigiata* based on maintaining a maximum growth rate for as long as possible for any one rotation (Chikumbo & Straka 2012). The fitness of individuals in a CCEA depends on the cooperation of individuals, and in a competition, there is a beneficial impact on the individual associated with cooperation. The progress of any party involved in cooperation is beneficial to both sides. The cooperative co-evolutionary algorithm has been widely used in various studies. A cooperative evolutionary approach was proposed for the solution of the instance selection problem, and the experimental results showed that the proposed method was robust and could effectively solve the problem using large data sets (García-Pedrajas *et al.* 2009). A new cooperative co-evolutionary algorithm for solving structural configuration and parameter optimization issues based on adaptive platform product customization (PPC) was proposed by Li *et al.* (2008). However, the method is slow to converge at the beginning of the evolutionary process. This initial slow convergence property improves its searching capability and ensures a high-quality solution. Moreover, cooperative co-evolutionary algorithms have been used to study the dynamic optimization problems of random migration and evolution strategy. The experimental results show that the method is effective in locating and tracking the optimal solution and more scalable than the evolution strategy in a dynamic environment (Au & Leung 2014). In addition, the competitive and cooperative co-evolutionary algorithms were applied to the design of a multi-objective particle swarm optimization algorithm, and the simulation results showed that the proposed algorithm was superior to other methods of competition and co-evolution (Goh *et al.* 2010). However, the fitness values of these two algorithms change for different cooperative individuals, which increases the computational time.

To solve this problem, a uniform co-evolutionary algorithm involving absolute fitness and relative fitness is adopted. The absolute fitness depends on an individual, while the relative fitness is determined by the coordination between individuals. The adaptability of individuals and their interactions based on the external environment determines the ability of the entire system to adapt to environmental change. The absolute fitness value reflects the ability of individuals to adapt to environmental change, the relative fitness value reflects the adaptability of each element in the problem domain, and the comprehensive fitness value is the comprehensive adaptability of each element based on the absolute fitness and relative fitness.

STUDY AREA AND RESEARCH METHODS

Study area

Jiansanjiang is located on the northeastern Sanjiang Plain. It belongs to the humid monsoon climate zone (cold temperate) and is home to the largest agro-ecological park in China. Its geographical coordinates are 132°31′–134°32′E longitude and 46°49′–48°12′N latitude. The annual average temperature over the entire area is 1.0 °C to 2.0 °C, the region covers an area of 1.24×10^4 km^2, the population is 2.3×10^5, and the per capita cultivated land area is 3.33 km^2. The region contains 15 large and medium-sized state-owned farms, and there are three major rivers in the region, including the Songhua River, Heilongjiang River, and Wusu River (see Figure 1). The water area is wide and the water quality is good. The total amount of surface water resources in this area is 2.85×10^{11} m^3; the surface water transit capacity is 2.74×10^{11} m^3, including 2.14×10^{11} m^3 in the Heilongjiang River and 5.99×10^{10} m^3 in the Wusu River. The exploitable amount of groundwater resources in this area is 14.84×10^8 m^3/a, and its utilization is 13.35×10^8 m^3/a,

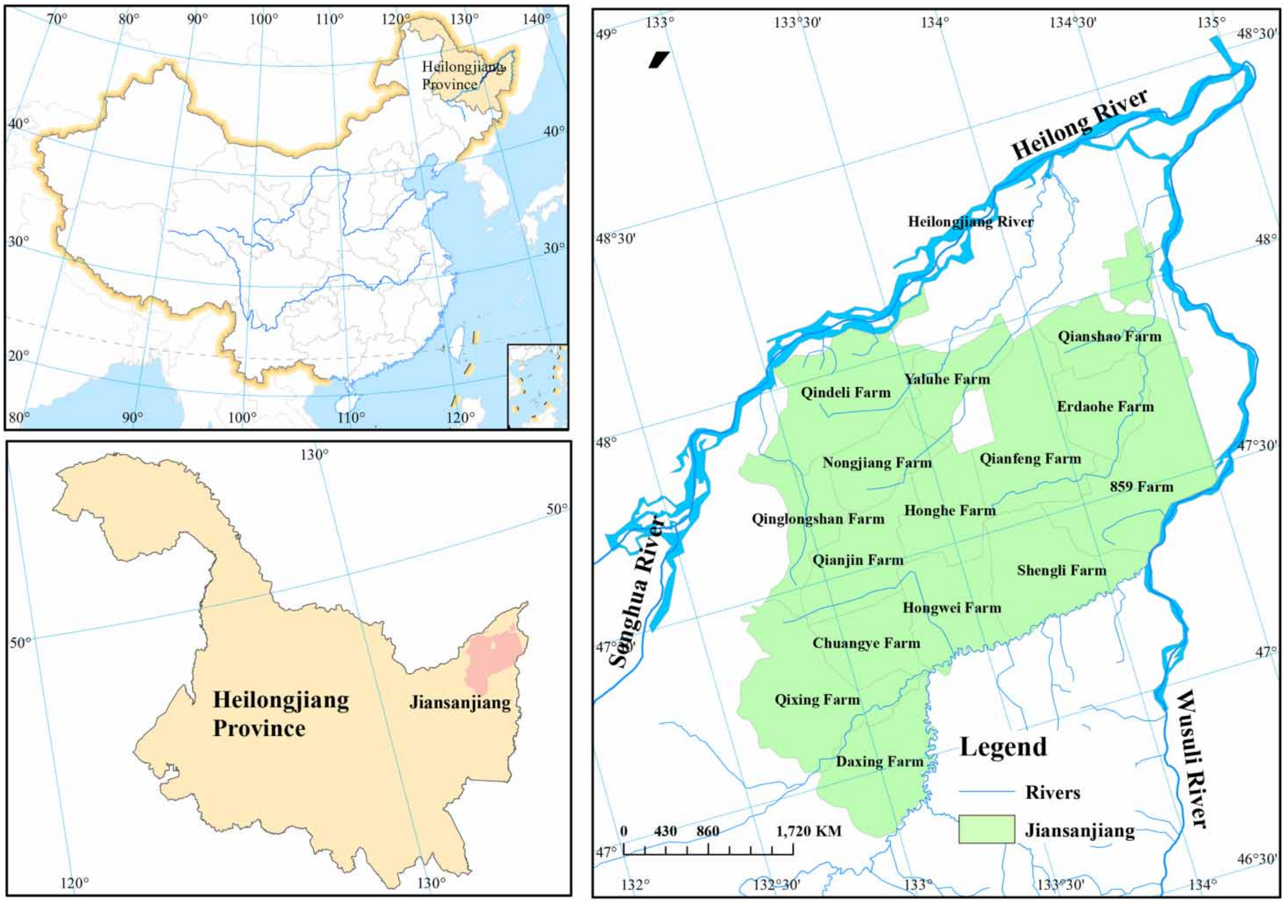

Figure 1 | Regional map of Jiansanjiang.

indicating that the region is rich in water resources and has great potential for development and utilization. However, because the region is largely populated with domestic housing, industrial water consumption is relatively small and the utilization of surface water resources is low. The rapid development of rice planting has led to a large concentration of groundwater resources in recent years, resulting in an imbalance in the supply and demand of water resources, which has seriously affected the ability of the water security system to adapt to environmental changes (Liu 2013).

Research methods

Grey relational analysis and a cooperative algorithm for regional water security systems

The grey system theory was proposed by Deng in 1982 (Morán *et al.* 2006). This theory can effectively address incomplete information and unclear problems. In the grey system, black represents the lack of system information, and white represents the complete information. A system containing incomplete and unclear information is called a grey system (Morán *et al.* 2006; Vinoth Kumar & Pradeep Kumar 2014). Grey correlation analysis uses the similarity degree of sequence curve geometry to determine the degree of correlation of a grey process development scenario. It is a quantitative method for analyzing the correlation degree of each factor in a grey system. The internal information in a water security system is incomplete, and the grey correlation degree uses the existing white information to reduce the associated error when evaluating the system (Lin & Lin 2002; Hasani *et al.* 2012). In this paper, the measured values of regional water security systems are used as comparative sequences, their ideal values are treated as reference sequences, and the grey correlation degree of each index is used as the adaptive measure value (absolute fitness).

Ehrlich and Raven proposed the concept of co-evolution in ecology in 1964 (Hillis 1990). This concept refers to the ability of several related populations to interact with each other, adapt to environmental changes and promote their ability to adapt to these changes. The co-evolutionary algorithm is a global optimization algorithm that was inspired by the co-evolution phenomena associated with the interactions between individuals in nature (Nogueira Collazo *et al.* 2014). According to the principle of constructing the problem domain of the co-evolutionary algorithm (Zhang *et al.* 2010), the adaptability of water security systems is studied based on the entire problem domain and several sub-problem domains. The factors that affect the adaptability of water security systems are considered the elements of the problem domain, and the relative fitness between individuals is calculated using the improved co-evolutionary algorithm.

The division of the problem domain

In this paper, the adaptability of the water security systems in the study area is considered the research domain, and it is divided into water resource system adaptability, socioeconomic system adaptability, and eco-environmental system adaptability. The adaptability of water resources systems is based on the water resource content, water use efficiency, and human control. The influence of regional, social, and economic development on the sustainable development of water security systems is the concentrated embodiment of the adaptability of socioeconomic systems. The adaptability of eco-environment systems reflects the adaptability of water security systems to changes in environmental conditions related to water and soil resources, natural disasters, man-made factors caused by climate change, and the destruction of the water and soil environment. The evaluation elements of each sub-problem domain are selected according to the 'International water management standards for the promotion of sustainable use of freshwater' issued by the Global Water Management Partnership (GWP), the 'World environmental assessment report' issued by the United Nations Environment Program (UNEP), the 'Annual report on water resources management' issued by the Water Resources Department of Ministry of Water Resources in China, and the principles of being objective, systematic, dynamic, data-focused, and attentive to regional characteristics (see Table 1).

A unified co-evolution model of water security systems

The weight of each element (index) is determined using the improved entropy weight method. The absolute fitness of

Table 1 | Evaluation index system of the adaptability of water security systems

Problem domain	Sub-problem domain	Element (Index)	Index type
Water security system adaptability	Water resources system adaptability	Total water resources (X_1) ($1\times10^8\,m^3$)	P
		Stream runoff volume (X_2) ($1\times10^8\,m^3$)	P
		Surface water resources (X_3) ($1\times10^8\,m^3$)	P
		Groundwater resources (X_4) ($1\times10^8\,m^3$)	P
		Volume of groundwater exploitation (X_5) ($1\times10^8\,m^3$)	N
		Comprehensive supply of groundwater (X_6) ($1\times10^8\,m^3$)	P
		Total annual precipitation (X_7) (mm)	P
		Water environment and public facilities (X_8) ($1\times10^4\,t\cdot d^{-1}$)	P
		Industrial water recycling rate (X_9) (%)	P
		The processing capacity of wastewater treatment facilities (X_{10})	P
		Urban sewage concentrated treatment rate (X_{11}) (%)	P
		Drainage and irrigation stations (X_{12}) (PCS)	P
		Tap water penetration rate (X_{13}) (%)	P
		Wastewater treatment facilities operating costs (X_{14}) (1×10^8 *yuan*)	P
	Socioeconomic system adaptability	Total population (X_{15})	N
		Natural population growth rate (X_{16}) (%)	N
		GDPPC (X_{17}) (*RMB yuan*)	P
		Water use amount per ten thousand Yuan of GDP (X_{18}) ($m^3/10^4$ *RMB yuan*)	N
		The proportion of investment in environmental protection accounted for by GDP (X_{19}) (%)	P
		Grain yield per unit area (X_{20}) (hm^2)	P
		Regional agricultural production density (X_{21}) (%)	P
	Eco-environmental system adaptability	Food crop planting area (X_{22}) (hm^2)	P
		Effective irrigation area (X_{23}) (hm^2)	P
		Actual irrigation area (X_{24}) (hm^2)	P
		Land area (X_{25}) (hm^2)	P
		Agricultural acreage (X_{26}) (hm^2)	N
		Drought disaster proportion (X_{27}) (%)	N
		Flood disaster proportion (X_{28}) (%)	N
		Vegetation coverage rate (X_{29}) (%)	P
		Pesticide application amount (X_{30}) (t)	N
		Fertilizer application amount (X_{31}) (t)	N
		Livestock fence amount (X_{32}) (PCS)	P
		Forested area (X_{33}) (hm^2)	P

'P' represents a positive index based on a 'larger is better' index value. 'N' represents a negative index based on a 'smaller is better' index value.

each index is determined using improved Euclidean grey weighted correlation analysis, and the relative fitness of each element is obtained using the improved co-evolutionary algorithm. According to the absolute fitness and relative fitness of each element (index), a unified co-evolution model is constructed, and the comprehensive fitness of each index is obtained. Simultaneously, the influence of the sub-problem domain on the overall problem domain is analyzed based on the comprehensive fitness and coordination index of each sub-problem domain. Then, the fitness of the entire problem domain is determined according to the projected weight value of the comprehensive fitness of each index. According to an assessment of urban water security systems, the ability of regional water security systems to adapt to environmental change is analyzed. The specific process is shown in Figure 2, and the model operation procedure is as follows.

Step 1: Numerical normalization processing of evaluation indexes

Assume that the sample matrix of the evaluation indexes is $(x_{ij})_{m\times n}$, where x_{ij} denotes the i^{th} index of the j^{th} sample, and m and n denote the number of indexes and sample size, respectively. The specific process of the index is

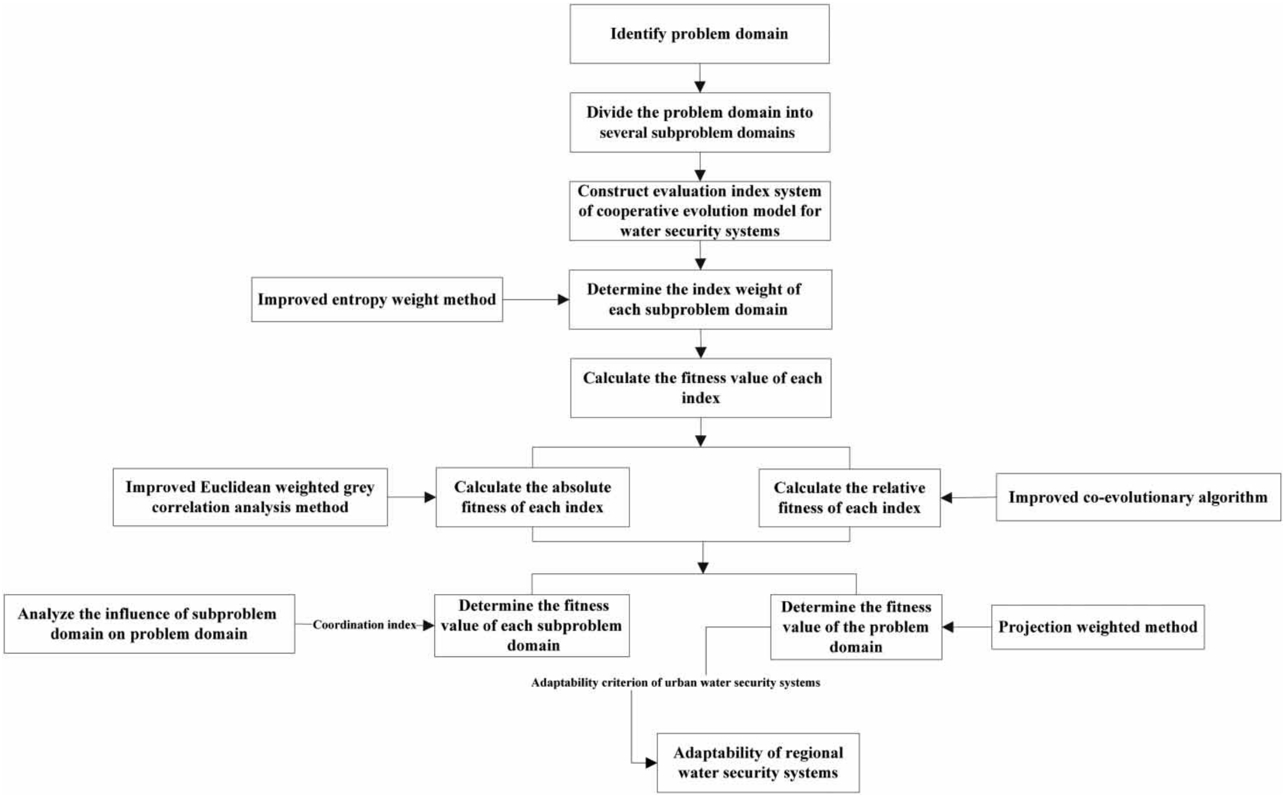

Figure 2 | Flow chart of the co-evolution model of regional water security systems.

shown in Equation (1):

$$\begin{aligned}&\text{The positive index: } r_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}\\&\text{The negative index: } r_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})}\end{aligned} \tag{1}$$

where $\max(x_{ij})$ and $\min(x_{ij})$ indicate the maxima and minima of x_{ij}, respectively, of the i^{th} index of the j^{th} sample.

Step 2: Determine the weight of the evaluation index in the sub-problem domain

The weight of each index is determined using the improved entropy weight method. This method overcomes the shortcoming that the index weight is affected by the difference coefficient and prevents an index weight of 0 from being assigned. Additionally, this approach fully considers the influence of the interactions between the indexes.

Assume that H_i is the entropy value of the i^{th} evaluation index, and n is the number of evaluation objects. The entropy information of the i^{th} evaluation index can be calculated as follows:

$$H_i = -\frac{1}{\ln(n)}\sum_{j=1}^{n} f_{ij}\ln(f_{ij}) \tag{2}$$

where

$$f_{ij} = \frac{1 + r_{ij}}{\sum_{j=1}^{n}(1 + r_{ij})}(i = 1, 2, \ldots, m\ j = 1, 2, \ldots, n).$$

Assume that $\bar{w}_i$ is the entropy weight value of the i^{th} evaluation index, and m is the number of indexes. Additionally, $g_i = 1 - H_i$. The standard deviation of the sample σ_i is introduced to preserve the objectivity of the traditional entropy method, and the computational formula for $\bar{w}_i$ is as follows:

$$W_{m\times 1} = \bar{w}_i = \frac{g_i + \sigma_i \sum_{i=1}^{m}\frac{\sigma_i}{\bar{r}_i}}{\sum_{i=1}^{m} g_i + \sum_{i=1}^{m}\sigma_i \cdot \sum_{i=1}^{m}\frac{\sigma_i}{\bar{r}_i}} \tag{3}$$

where

$$\sigma_i = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(r_{ij}-\bar{r}_i)^2}$$

Step 3: Calculate the absolute fitness of the index in the sample information matrix using the improved Euclidean grey weighted average correlation method

Set $(y_{ij})_{n\times m} = (x_{ij})'_{m\times n}$ as the initialization decision matrix, and select $y_{0j}(j = 1, 2, \ldots, m)$ as the reference sequence based on the index attributes and $y_{ij}(i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m)$ as a comparison sequence. The decision matrix is obtained by the dimensionless processing of the grey correlation factor matrix: $Y_{ij} = y_{ij}/y_{0j}$ (for positive indicators), $Y_{ij} = y_{0j}/y_{ij}$ (for negative indicators). The correlation coefficient between the comparison sequence and the reference sequence at each point is as follows:

$$\begin{cases} \xi_{ij} = \dfrac{\min\limits_i \min\limits_j |Y_{0j}-Y_{ij}| + \rho \max\limits_i \max\limits_j |Y_{0j}-Y_{ij}|}{|Y_{0j}-Y_{ij}| + \rho \max\limits_i \max\limits_j |Y_{0j}-Y_{ij}|} \\ Y_{0j} = [1, 1, \ldots, 1]_{1\times m} \end{cases} \tag{4}$$

where ρ denotes the resolution coefficient, which is generally equal to 0.5. The average grey correlation degree is as follows:

$$\bar{\xi}_{ij} = \frac{1}{n}\sum_{i=1}^{n}\xi_{ij}.$$

Let A_i indicate that y_{ij} is related to y_{0j}, namely, $A_i = (\xi_{i1}, \xi_{i2}, \ldots, \xi_{in})$. For any pair $A_i, A_l(i, l = 1, 2, \ldots, m)$ close to each other, the following expression reflects the grey Euclid closeness:

$$N(A_i, A_l) = 1 - \frac{1}{\sqrt{n}}\left[\sum_{i=1}^{n}(\xi_{ij}-\xi_{lj})^2\cdot\bar{w}_i\right]^{1/2}.$$

$A_e = (1, 1, \ldots, 1)$ indicates that Y_{ij} has the greatest correlation with Y_{0j}. Therefore, taking the closeness of A_i and A_e as the correlation between Y_{ij} and Y_{0j} yields the following expression:

$$\zeta_{ij} = 1 - \frac{1}{\sqrt{n}}\left[\sum_{i=1}^{n}(\xi_{ij}-1)^2\cdot\bar{w}_i\right]^{1/2} \tag{5}$$

Assume that the fluctuation in the comparison series y_{ij} and the reference sequence y_{0j} at each point can be reflected by the correlation coefficient ξ_{ij} relative to the weighted average value of $\bar{\xi}_{ij}$. Thus, $\varepsilon_{ij} = \xi_{ij} - \bar{\xi}_{ij}$, and ξ_{ij} can be denoted as follows:

$$\xi_{ij} = \bar{\xi}_{ij} + \varepsilon_{ij} \tag{6}$$

The improved Euclidean grey weighted average correlation can be calculated using Equations (7) and (8), and it is used as the absolute fitness of each sub-problem domain for water security systems:

$$f_i^c(t) = \xi_{ij}^* = 1 - \left[\left(\bar{\xi}_{ij}-1\right)^2 + \sum_{i=1}^{n}\varepsilon_{ij}^2\cdot\bar{w}_i\right]^{1/2} \tag{7}$$

Step 4: Calculate the relative fitness of each index using the improved co-evolutionary algorithm, and the comprehensive fitness is obtained by combining the relative fitness and absolute fitness

The relative fitness of indexes in the system depends on their Hamming distance and average Hamming distance. Considering the importance of the indexes in the system, the weight is added to the calculation of the relative fitness. Additionally, the comprehensive fitness is related to the adaptive ability of the index itself and affected by other indexes that are related to the synergy. The associated computational formula is as follows:

$$\begin{cases} f_i^s(t) = \bar{w}_i\cdot f_i^c(t) + (1-\bar{w}_i)\cdot c_i(t) \\ c_i(t) = \dfrac{0.5 + HD_i(t) - AHD}{0.5 + AHD} f_i^c(t) \\ HD_i(t) = \sum\limits_{j=1}^{m}(W_{m\times 1})^T\cdot|f_j^c(t) - f_i^c(t)| \\ AHD = \dfrac{1}{m-1}\sum\limits_{i=1}^{m}(HD_i(t))' \end{cases} \tag{8}$$

where $f_i^s(t)$ denotes the comprehensive fitness of index i at t time, $f_j^c(t) - f_i^c(t)$ denotes the difference in the absolute fitness between index j and index i at t time, $c_i(t)$ denotes the relative fitness of index i affected by other indexes at t time, $HD_i(t)$ denotes the weighted Hamming distance of elements i and j in the problem domain, AHD denotes the weighted average Hamming distance of all elements, and 0.5 denotes the smoothing factor, which is used to avoid severe effects on the system associated with small AHD values.

Step 5: Calculate the adaptability of each sub-problem domain, and analyze the importance of each sub-problem domain to the problem domain based on the coordination index

Assume that S_v is the adaptability of each sub-problem domain and that CI_v is the coordination index of each sub-problem domain. The computational formula is as follows:

$$\begin{cases} s_v = \sum\limits_{t=1}^{k} f_i^s(t) \cdot R^* \\ CI_v = \sqrt{\sum\limits_{t=1}^{k} (f_i^s(t) - s_v)^2} / s (v = 1, 2, 3) \\ s = \sum\limits_{v=1}^{3} s_v \end{cases} \tag{9}$$

where $R^* = y_{ij} / \sum_{j=1}^{m} y_{ij}$.

Step 6: Calculate the adaptability of the entire problem domain

Assume that the comprehensive fitness projection value of each element is $\bar{f}_i^s(t)$. The adaptability of the entire problem domain can be obtained by the weighted summation of the weight of each element. The specific calculation formula is as follows:

$$\begin{cases} \bar{f}_i^s(t) = \dfrac{(f_i^s(t))^2}{\sqrt{\sum_{i=1}^{m} (f_i^s(t))^2}} \\ D_j = \sum\limits_{i=1}^{m} \bar{f}_i^s(t) \cdot R^* \end{cases} \tag{10}$$

Adaptive grade threshold division of water security systems

Based on the Chinese city water security system indexes and grading standards (Liu 2011; Shao *et al.* 2013), project survey statistics, the relevant literature regarding index classification methods (Xiang 2011), and the regional characteristics of the study area (Li & Ma 2015), the adaptability is divided into four levels. The grade threshold of each element is shown in Table 2. According to the threshold of each element of water security systems, the adaptability criterion is obtained by the unified co-evolution model (see Table 3).

Data source

The evaluation index system for water security systems was established based on the index values between 2002 and 2011 in the study area (see Table 4). Our research data were primarily obtained from the 'Jiansanjiang Statistical Yearbook (2002–2011)', the 'Heilongjiang Reclamation Area Statistical Yearbook (2002–2011)', and a field study conducted during this research project.

RESULTS AND DISCUSSION

Model verification

In this paper, based on the data of the water security system evaluation index for the period 2002–2011 and using Matlab2012a software, the weights, absolute fitness values, relative fitness values, and comprehensive fitness values of the elements in each sub-problem domain (see Table 5) are obtained by the unified co-evolution model (steps 1–4; Equations (1)–(8)). According to the comprehensive fitness value of each element, the fitness degree and coordination index of each sub-problem domain of the water safety system in the study area (see Table 6) are obtained using operation step 5 (Equation (9)), and the fitness of the entire problem domain (see Table 7) is obtained using step 6 (Equation (10)).

Adaptability analysis of the water safety system in the study area

According to the absolute fitness, relative fitness, and comprehensive fitness values in Table 5, the fitness bar graph of each element of the study area's water security system is obtained (see Figure 3). Based on the data in Table 6, the comprehensive fitness and coordination index change

Table 2 | Element level thresholds of water security systems

	Level threshold					Level threshold			
Element (index)	**UA**	**BA**	**A**	**VA**	**Element (index)**	**UA**	**BA**	**A**	**VA**
X_1	18	30	46	54	X_{18}	1,050	650	480	210
X_2	2,400	3,500	4,580	5,100	X_{19}	0.35	0.72	1.2	1.8
X_3	2	9	15	20	X_{20}	2,035	3,265	4,576	6,630
X_4	1.2	7.5	12	16	X_{21}	10.5	20	38.5	65
X_5	18	14	9.2	5.2	X_{22}	125,000	320,000	550,000	750,000
X_6	2.5	7.6	12.8	16.5	X_{23}	12.5	20	45	70
X_7	150	385	575	750	X_{24}	9.5	18.6	42	68
X_8	650	2,120	4,500	6,500	X_{25}	350,000	855,000	1,250,000	1,460,000
X_9	50	70	80	90	X_{26}	800,000	630,000	450,000	180,000
X_{10}	0.0089	0.02	0.08	0.15	X_{27}	0.15	0.095	0.055	0.01
X_{11}	20	35	65	90	X_{28}	0.152	0.105	0.075	0.008
X_{12}	3.5	10	15	20	X_{29}	10	15	30	50
X_{13}	70	80	90	98	X_{30}	5,000	4,500	3,800	2,050
X_{14}	1.2	3.5	5.5	8.5	X_{31}	90,000	70,000	45,000	10,000
X_{15}	305,000	253,500	152,500	95,000	X_{32}	255,000	420,000	600,000	720,000
X_{16}	10	6	4	1.76	X_{33}	500	1,250	3,850	4,730
X_{17}	6,500	12,600	18,700	28,000					

UA, under adaptation; BA, basic adaptation; A, adaptable; VA very adaptable.

curves of each sub-problem domain are also obtained (see Figure 4). Finally, the comprehensive fitness change curve of the study area's water security system problem domain is determined (see Figure 5).

Element (index)

Figure 3 shows that the absolute fitness values of each element are significantly greater than their relative fitness values. This indicates that each element itself has a strong adaptability to the environment, which is directly related to the good natural foundation in the study area (Liu 2013). The ability of the elements to interact with each other to adapt to environmental change is weak, which is due to the various elements focusing on their own development; mutual interaction is caused by the effects of production. The comprehensive fitness value can fully reflect the ability of each factor to adapt to environmental changes. The result shows that the comprehensive fitness values of X_1, X_2, X_4, X_6, X_7, X_{11}, X_{13}, X_{15}, X_{25}, X_{29}, and X_{32} all exceeded 0.5 (mean value of 0.701), which is because the absolute fitness (mean value of 0.863) and relative fitness (mean value of 0.698) of these elements are higher; these elements also have a stronger ability to recover themselves and resist external disturbances. However, the overall fitness values of the remaining factors are below 0.5 (mean value of 0.444), which is due to the absolute fitness (mean value of 0.613) and relative fitness (mean value of 0.438) of these elements being low; these elements tend to mutate when subjected to external conditions or other elements. Therefore, it is an effective measure for improving the comprehensive fitness of each element to strengthen the construction of each element and to improve the coordinated development relationship among the various factors.

Table 3 | Adaptability criterion of water security systems

Adaptation degree	**Under adaptation (I)**	**Basic adaptation (II)**	**Adaptation (III)**	**Very adaptable (IV)**
Discriminate criterion	<0.528	0.528–0.661	0.661–0.862	0.862–1

Table 4 | The original data of evaluation index of the study area's water security system

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
X_1	46.575	47.543	47.993	43.626	39.598	39.564	51.332	37.113	40.0566	41.616
X_2	50,139	50,106	50,668	49,077	47,486	47,486	47,486	47,156	47,148	47,051
X_3	16.02	13.09	15.08	11.1	10.38	10.74	15.06	10.74	10.39	10.9
X_4	14.81	15.19	12.08	14.23	14.23	13.43	15.21	11.41	12.83	13.39
X_5	6.489	7.603	8.498	9.448	9.642	9.800	10.770	9.494	11.080	11.672
X_6	11.145	15.563	15.333	15.296	14.988	15.394	15.562	14.963	14.837	15.336
X_7	450	460.5	467.3	487.4	487.2	491.1	580.5	572.7	503.1	405.9
X_8	1,996	2,430	2,819	5,844	6,522	5,684	5,585	6,014	5,480	7,065
X_9	27.23	28.1	28.1	27.84	21.07	20.68	47.8	46.88	28.74	44.5
X_{10}	0.02	0.02	0.02	0.02	0.09	0.1	0.19	0.19	0.19	0.19
X_{11}	49.75	50.62	54.21	52.69	50.53	49.87	50	51.18	57.4	57.4
X_{12}	11	12	12	13	14	14	14	14	14	21
X_{13}	55.3	77.5	96.8	96.8	97.3	98.1	98.1	98.5	98.9	100
X_{14}	3.5	3.5	3.5	3.5	4	7	8.3	8.3	8.3	8.3
X_{15}	190,795	194,873	198,997	200,135	200,319	203,819	206,600	207,695	209,692	240,604
X_{16}	3.86	2.68	2.2	2.28	2.44	2.23	1.54	0.84	1.07	1.14
X_{17}	11,017	14,244	18,340	16,382	26,419	30,386	37,478	50,880	64,282	79,390
X_{18}	297	290.04	302.63	1,100	241.43	242	242	1,100	1,050	1,050
X_{19}	64	71	72	104	104	104	104	100	100	125
X_{20}	4,065	4,589	5,640	6,534	6,649	7,702	7,586	7,559	8,311	8,661
X_{21}	0.321	0.315	0.315	0.432	0.432	0.441	0.545	0.575	0.590	0.597
X_{22}	369,147	345,411	369,291	385,051	511,675	530,225	614,290	707,098	726,908	736,633
X_{23}	22.24	20.62	27.85	30.85	39.84	49.37	45.34	49.94	64.41	69.97
X_{24}	20.41	20.6	23.71	24.83	35.76	43.8	44.92	49.22	57.64	63.34
X_{25}	1,237,514	1,237,514	1,237,514	1,237,514	1,237,514	1,237,514	1,237,514	1,234,694	1,234,694	1,238,164
X_{26}	396,955	390,053	389,553	534,666	535,069	545,393	674,150	710,244	728,710	738,922
X_{27}	0.018	0.508	0.110	0.035	0.012	0.119	0.043	0.028	0.003	0.001
X_{28}	0.040	0.029	0.082	0.037	0.052	0.050	0.007	0.152	0.049	0.008
X_{29}	15.2	15.3	15.6	16.6	16.7	16.9	17	17.1	17.2	17.2
X_{30}	1,283	1,330	1,404	1,320	1,841	2,139	2,917	3,303	3,851	4,309
X_{31}	48,695	49,097	53,190	57,311	72,600	88,600	99,661	11,562	12,388	10,815
X_{32}	485,010	483,907	624,312	655,375	640,189	715,149	721,147	676,944	581,774	552,398
X_{33}	3,704	3,581.5	3,459	1,749	989	809	1,465	3,309	2,184	1,178

Sub-problem domain

For the period 2002–2011, Figure 4(a) shows that the average annual comprehensive fitness values of the water resources, socioeconomic, and eco-environmental system in the study area are 0.795, 0.345, and 0.619, respectively, indicating that the water resources system has good adaptability. The adaptability of the ecological environment system at the medium level during this period, and the adaptability of the socioeconomic system is low. The comprehensive fitness of the studied water resources system shows a rising trend, with an average annual increase of 5.03%, which is

Table 5 | Weight and fitness of each element in the study area water security system

Element (Index)	Weight	Absolute fitness	Relative fitness	Comprehensive fitness	Element (Index)	Weight	Absolute fitness	Relative fitness	Comprehensive fitness
X_1	0.0275	0.773	0.555	0.558	X_{18}	0.0409	0.637	0.435	0.449
X_2	0.0338	0.915	0.779	0.784	X_{19}	0.0265	0.692	0.469	0.474
X_3	0.0335	0.700	0.476	0.486	X_{20}	0.0283	0.715	0.491	0.494
X_4	0.0286	0.836	0.643	0.650	X_{21}	0.0343	0.704	0.480	0.488
X_5	0.0257	0.645	0.438	0.444	X_{22}	0.0341	0.670	0.452	0.462
X_6	0.0252	0.913	0.776	0.780	X_{23}	0.0289	0.589	0.423	0.427
X_7	0.0255	0.771	0.553	0.556	X_{24}	0.0308	0.594	0.424	0.429
X_8	0.0301	0.664	0.448	0.454	X_{25}	0.0300	0.988	0.944	0.941
X_9	0.0320	0.634	0.434	0.437	X_{26}	0.0342	0.678	0.458	0.470
X_{10}	0.0397	0.597	0.424	0.434	X_{27}	0.0254	0.401	0.386	0.387
X_{11}	0.0329	0.850	0.664	0.677	X_{28}	0.0243	0.472	0.406	0.404
X_{12}	0.0229	0.610	0.427	0.430	X_{29}	0.0336	0.917	0.784	0.790
X_{13}	0.0270	0.868	0.693	0.688	X_{30}	0.0317	0.644	0.438	0.445
X_{14}	0.0416	0.668	0.451	0.468	X_{31}	0.0299	0.514	0.413	0.416
X_{15}	0.0231	0.882	0.718	0.721	X_{32}	0.0305	0.780	0.565	0.570
X_{16}	0.0253	0.536	0.417	0.419	X_{33}	0.0338	0.611	0.427	0.448
X_{17}	0.0284	0.508	0.412	0.410					

mainly due to the abundant water resources (average annual water resources amount of 4.35×10^9 m^3) in the study area. Moreover, over the studied period, the comprehensive supply of groundwater increases (maximum increase of 39.64%), the processing capacity of wastewater treatment facilities increases (average annual growth rate of 85%), and the cost of wastewater treatment facilities increases (average annual increase was 13.71%), improving the adaptability of the water resources system. The comprehensive fitness of the socioeconomic system shows an upward trend, with an average annual increase of 6.94%; this is due to the decrease in the natural growth rate of the population (an average annual decrease of 5.33%), which reduces the pressure on the social and economic development of the study area. Moreover, the proportion of investments in environmental protection accounted for by the GDP increases with an average annual growth rate of 2.02%, which reduces the pollution level of the enterprises in the study area. The grain yield per unit area and regional agricultural production density increases with an average annual growth rate of 3.26% and 3.81%, respectively, which improves the efficiency of agricultural economic development. However, due to the small change in each element and their low comprehensive fitness values, the adaptability of the sub-problem domain is low. The

Table 6 | Comprehensive fitness and coordination index of each sub-problem domain in the study area water security system

Year	*WA*	*SA*	*EA*	*WAC*	*SAC*	*EAC*
2002	0.646	0.278	0.500	0.404	0.439	0.404
2003	0.693	0.265	0.703	0.413	0.395	0.521
2004	0.714	0.271	0.600	0.470	0.406	0.405
2005	0.736	0.366	0.524	0.497	0.261	0.353
2006	0.756	0.317	0.565	0.532	0.326	0.365
2007	0.776	0.327	0.654	0.534	0.290	0.424
2008	0.953	0.333	0.640	0.811	0.258	0.372
2009	0.858	0.401	0.737	0.610	0.179	0.479
2010	0.845	0.425	0.651	0.609	0.164	0.385
2011	0.971	0.471	0.616	0.791	0.129	0.325

'*WA*' denotes the comprehensive fitness of the water resources system; '*SA*' denotes the comprehensive fitness of the socioeconomic system; '*EA*' denotes the comprehensive fitness of the eco-environmental system; '*WAC*' denotes the adaptive coordination index of the water resources system; '*SAC*' denotes the adaptive coordination index of the socioeconomic system, and '*EAC*' denotes the adaptive coordination index of the eco-environmental system.

Table 7 | Fitness values of the problem domain of the study area water security system

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Fitness value	0.453	0.528	0.503	0.517	0.520	0.558	0.600	0.634	0.610	0.632

comprehensive fitness of the eco-environmental system fluctuates upward and downward. In 2002–2003, the comprehensive fitness of the system shows a rising trend due to a decrease in the extent of flood damage (decrease of 26.08%) and an increase in vegetation coverage (increase of 0.66%), which reduces the amount of soil erosion in the study area. In 2004–2005, the comprehensive fitness of the system shows a downward trend due to the increase of cultivated land area (increase of 37.25%), which leads to an increase in the fertilizer application rate (increasing range of 7.75%) and an increase in the content of soil toxic substances in the study area; the number of local livestock increases (increase of 4.98%); and the afforestation area decreases (decrease of 49.44%), aggravating the degree of desertification in the study area. In 2006–2011, the comprehensive fitness of the system increases with a maximum increase of 40.65%; the effective irrigation area and the actual irrigation area in the study area increases (average annual increases of 12.60% and 12.85%, respectively), reducing the ecological environment carrying capacity; the local drought and flood disaster degree decreases (average annual decreases of 14.12% and 15.81%, respectively); and the number of livestock grazing decreases (average annual decrease of 2.28%), improving the ability of the eco-environmental system to protect itself against natural disasters.

Figure 4(b) shows that in 2002–2011, the contribution degree of water resources system to the study area's water security system adaptability increases (average annual increase of 9.58%), and the average annual coordination index value is 0.567. The contribution degree of the socio-economic system to the water security system adaptability decreases (average annual decrease of 7.06%), and the average annual coordination index value is 0.285. The contribution degree of the eco-environmental system to the water security system adaptability exhibits a fluctuating downward trend (maximum decrease of 37.62%), and the average coordination index value is 0.403. The results show that the water resources system enhances the ability of the study area's water security system to adapt to the

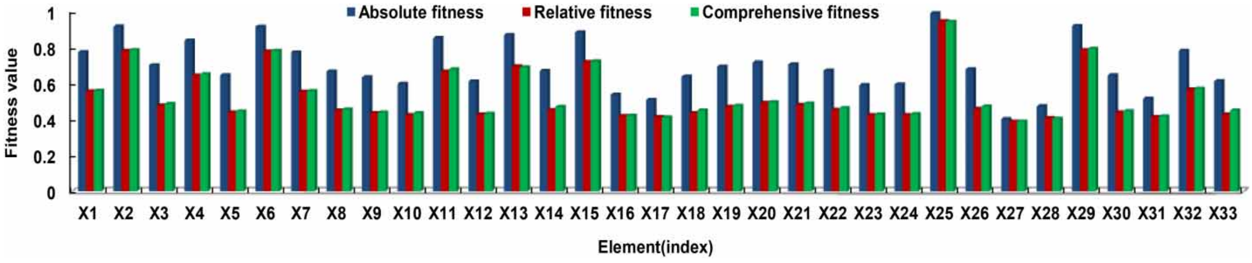

Figure 3 | Bar chart of each fitness value of each element in the problem domain of the study area's water security system.

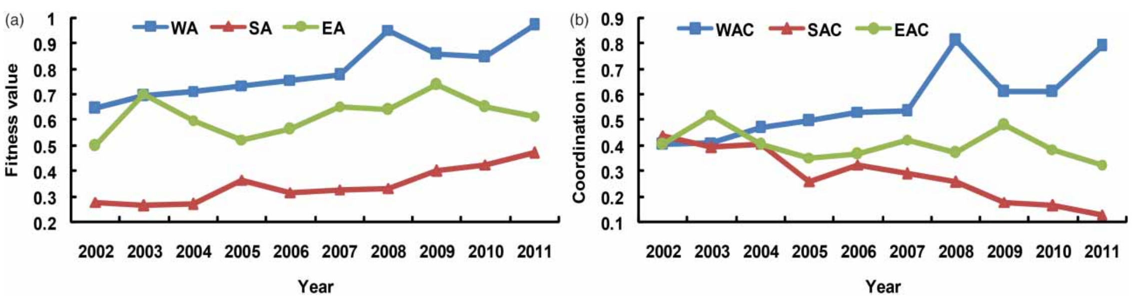

Figure 4 | Sample fitness value and coordination index value in each sub-problem domain.

environmental changes, while the socioeconomic system and the eco-environmental system decrease annually.

Problem domain

Figure 5 shows that in 2002–2011, the comprehensive fitness of water security system in the study area fluctuates upward (maximum increase of 39.96%), and the annual comprehensive fitness is 0.556, which indicates the system adaptability is at level II. The system is barely able to adapt to changes in the environment. Despite the comprehensive fitness of the water resources system and the contribution degree to the problem domain being high, the comprehensive fitness of the socioeconomic and the eco-environmental system (especially the socioeconomic system) and their contribution degree to the problem domain are low; and their contribution to the problem domain decreases each year, which further decreases the comprehensive fitness of the water security system in the study area. Therefore, to improve the water security system adaptability, the healthy development of the water resources system should be promoted. Moreover, vigorous improvements in the sustainable development of the society and economy and the protection and improvement of the quality of the ecological environment are needed.

Suggestions and measures

This study shows that the main reason for the reduced adaptability of the water security system to the changing environment is the low comprehensive fitness of the socioeconomic and the eco-environmental system, and the two systems' contributions to the sustainable development of the water safety system decrease every year. Therefore, effective measures should be taken to improve the fitness and contribution of these two systems; the specific suggested measures are as follows:

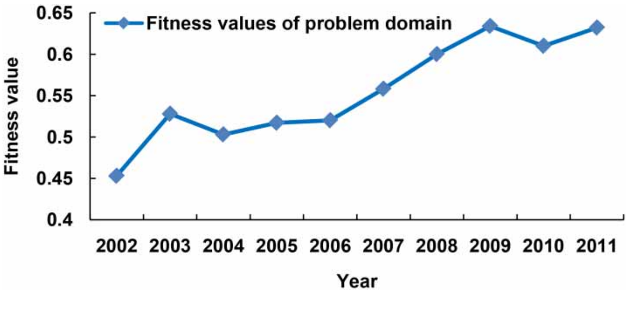

Figure 5 | Line chart of the problem domain fitness values for the study area's water security system.

1. Based on the low comprehensive adaptability of the socioeconomic system and the low contribution of the system to the problem domain, the study area should adjust the three major industrial structures and diversify the production methods, which can increase the per capita GDP and reduce the pressure on the water security system caused by the rapid socioeconomic development. The study area also needs to mobilize all social forces to enhance environmental protection and water conservancy construction funds for diversified, multi-channel, and multi-level financing mechanisms related to environmental protection and water conservancy investments. Moreover, the area should improve the relationship between economic development and the use of water resources and the protection of the ecological environment in the study area.
2. According to the relatively low comprehensive adaptability of the eco-environmental system and the relatively low contribution of the system to the problem domain, the local government should carry out practical farmer fertilizer technical guidance and scientific breeding training, improve farmer fertilizer application technology and grain pest disaster prevention level, and promote farmers to use pollution-free organic fertilizer on farmland, improve soil organic matter content, and increase the effective area of cultivated land. In the fenced grazing areas, controlling livestock grazing quantity, increasing afforestation efforts, continuing to reclaim wasteland, reducing land desertification degree, and reducing the loss of water and soil are all needed.
3. Although the comprehensive adaptation degree of the study area's water resources system is high in the study period, if we ignore the development scenario of the water resources system, the ability of the water security system to adapt to the changing environment will be seriously hindered. Therefore, to strengthen the social and economic development and ecological environmental protection at the same time, the study area needs to rely on scientific and reasonable development and utilization of water resources, make full use of

rainwater resources to replace groundwater surface water, improve the quality and yield of rice using surface water irrigation, and store surface runoff decreased by groundwater exploitation (the groundwater to vertical replenishment effect can also improve the local ecological environment). Moreover, the way in which wastewater is discharged should be addressed, and the construction of farm sewage treatment facilities should be strengthened. Centralized wastewater treatment emissions act to scatter emissions; strictly controlling new pollution sources of water and a finite period of governance are needed.

CONCLUSIONS

Based on the complex adaptive features in water security systems, the co-evolution theory has been introduced. The adaptability of water security systems is defined as the problem domain, and 33 elements (indicators) and sub-problem domains based on water resources, the social economy, and ecological environment are used. An evaluation index system of water security systems is established. Based on reliable survey data, the unified co-evolution model is used to study the adaptability conditions of a water security system. The results show that the adaptability of the water security system in the study area is low, and the comprehensive fitness shows an upward trend. In the sub-problem domains, the adaptability of the water resources system is high, and the comprehensive adaptability of the system increases every year. Moreover, the adaptability of the socioeconomic and the eco-environmental system is low, the comprehensive fitness of the socioeconomic system exhibits an increasing trend, and the comprehensive fitness of the eco-environmental system fluctuates (average increasing trend). The Euclidean grey weighted correlation method is used to calculate the absolute fitness of each element; this method considers the importance of each element in the system and the fluctuation coefficient, which is the fluctuation in each point correlation coefficient based on its average value. The method fully reflects the influence of the correlation degree between the reference sequence and comparison sequence on the overall correlation degree. The relative fitness of each element is used in the improved co-evolution method, and the method is based on the individual variation in each element in the system based on the principles of competitive exclusion and feature substitution (Shang 2002).

In summary, the unified co-evolutionary model proposed in this paper has good practical significance for studying the adaptability of regional water security systems. Moreover, it provides a reliable basis for improving the adaptability of water security systems.

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