

Analysis of dynamic evolution and driving factors behind water consumption in China

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ABSTRACT

The water consumption system is a typical dissipative structure system, and its evolution can be described with information entropy. Meanwhile understanding the principal driving factors in the evolution of water consumption is essential for water consumption prediction and management. Firstly, the information entropies of water consumption in China were calculated from 1997 to 2010. Secondly, the principal driving factors were extracted using principal component analysis. Finally, based on the principal driving factors, the water consumption system was predicted. The results showed that the entropies can be divided into two stages: an entropy increasing period (1997–2002) and an entropy convergence period (2003–2010). On a national scale, the entropies in the majority of provinces are focused between 0.6 and 1.1. The principal driving factors were population, gross domestic product, food production, command irrigation area, and urban consumption levels. Chinese water consumption structure will develop an inverted 'U'-shape curve and water consumption levels are expected to plateau during 1997 to 2020. The system is gradually becoming more orderly through coordination and self-organization.

Key words | dissipative structure, driving factors, dynamic evolution, information entropy, water consumption system

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INTRODUCTION

The global water consumption system includes agricultural, manufacturing, and domestic sectors, which represent about 69%, 23%, and 8% of the total water consumption, respectively. Water usage varies greatly worldwide. In the development of European manufacturing, only 54% of the total water consumption amount is used by the agricultural sector, while in Asia and Africa, it accounts for over 81% of water consumption. In the last several decades, water consumption has increased annually between 4% and 8%. The largest increases occurred in developing countries, while in industrialized nations, water consumption remained relatively stable (Li 2002). Water in China is consumed for agricultural, manufacturing, domestic and ecological sectors. The total water consumption was approximately 602 billion m³ in 2010, and the proportions of the agricultural, manufacturing, domestic and ecological sectors are

61%, 24%, 13%, and 2%, respectively. Analyzing water consumption evolution and its driving factors is a primitive clue for water demand management (Ahmed *et al.* 2014; Fan *et al.* 2014). Currently, a number of studies have focused on domestic water consumption (Panagopoulos *et al.* 2012; Richter & Stamminger 2012; Romano *et al.* 2014). Different drivers for change have had an influence on domestic water use (Agudelo-vera *et al.* 2014), such as, for instance, technological developments, the changing perception of comfort, and energy labeling of appliances and buildings. House-Peters *et al.* (2010) considered population growth, climate change and city development to be the main factors contributing to the increase of domestic water consumption. Zhi *et al.* (2016) focused on decomposing the factors into population, consumption pattern, and per capita consumption volume. Climate variables (Slaviková *et al.* 2013) and price (Grafton

et al. 2011; Mombeni *et al.* 2015) still impacted domestic water consumption.

Water consumption structure evolves between orderliness and disorderliness. The concept of entropy in information theory describes how much information there is in a signal or event. Information entropy can reflect important structural characteristics and changes in water consumption. If information entropy is low, there will be a high degree of orderliness in water consumption. If the inverse is true, that is high information entropy, the degree of orderliness will be relatively low. Information entropy studies have focused on evolution in land usage structure and energy consumption patterns (Tan & Wu 2003). Such studies have shown that the information entropy of a large city in terms of land usage is greater than that of small cities (Chen & Liu 2001). Moreover, analyses of energy consumption in urban areas have shown that with the increase of city area, information entropy first increases before decreasing and eventually forming an inverted 'U'-shape curve (Geng *et al.* 2004). The theory of information entropy was applicable to land usage and energy consumption, and so it is to water consumption. We predict that water consumption will follow the same trend.

In this study, information entropy of water consumption was calculated from 1997 to 2010 in China, and then the driving factors were identified by principal component analysis. With these analyzed factors, the evolved trend of water consumption can be predicted by way of the back-propagation (BP) neural network model. The objective of this work is to estimate the dynamic evolution of water consumption in China to help planners and decision makers in the management of water resources.

THEORETICAL MODEL

The dissipative structure of water

A 'dissipative structure' is a non-equilibrium system that is far from the equilibrium state of the system, and should be supported by continuous material inputs and outputs in open systems (Xu & Du 2014). The behavior of the system as whole and emergent behaviors both manifest during the course of evolution. The evolution can be described with information entropy theory. A dissipative system is dynamically

sequential, which must meet the following four conditions: (1) the system must be an open system; (2) the system must be far from equilibrium; (3) there must be non-linear interactions; and (4) there must be fluctuations (Chang *et al.* 2002).

Water consumption structure accords with the fundamental characteristics of a dissipative system. First, water consumption is an open system where there is a continuing exchange of materials, energy, and information. Second, water consumption structure is far from equilibrium. 'Competition' for limited water resources creates non-equilibrium. Furthermore, water consumption structure is provided with coupled 'economic-social-ecological' complexities and their non-linear interactions with each other. Finally, water consumption structure is composed of a great number of substructures. Natural and social factors cause changes within the substructures. When the degree of these changes gets large enough, they cause mutations within the overall structure, thus leading to more orderly dissipative structures. Therefore, the water consumption system is typically dissipative, and its evolution can be analyzed by information entropy theory.

Information entropy of water consumption

Information entropy is used to quantify the amount of information in a data set (Chen 2015). Shannon (1948) proposed the concept of entropy in information theory. The concept of information as 'entropy' had been expressed since the mathematical formula for the concept is similar to the entropy function defined in statistical mechanics (Xu & Du 2014). According to the given definition of information entropy, the information entropy of continuous random variables can be defined as follows:

$$H = - \sum_x p(x) \log p(x) \quad (1)$$

where H refers to the information entropy of the continuous random variable, and $p(x)$ is represented as a continuous random distribution function.

Water consumption structure is a large and complex system which evolves closely correlated to socio-economic development. Consumption in economically less-developed regions is primarily agricultural water consumption;

following economic development, manufacturing and domestic consumption increases while agricultural decreases. Therefore, water consumption structure evolves an equilibrium (Ma *et al.* 2012). Analyses from this point of view are useful for applying the information entropy concept to study evolution in water consumption.

Supposing at a certain timescale, the total water consumption is Q , type n water consumption is (x_1, x_2, \dots, x_n) , each type of water consumption is (q_1, q_2, \dots, q_n) , and each type of water consumption as the total probability is (p_1, p_2, \dots, p_n) , where $p_i = q_i/Q$ and $\sum p_i = 1$ ($p_i \neq 0$). Then water consumption structure information entropy is defined as:

$$H = - \sum_{i=1}^n p_i \ln p_i \quad (2)$$

where H is information entropy; and for convenience in the calculations, the natural logarithm (\ln) of this value is used. Put simply, the natural logarithm of H reflects the many types of water consumption. When there is no development or utilization of water resources, the diversity index is 0, $H_{\min} = 0$. Conversely, during development, each type of water usage stabilizes and averages $q_1 = q_2 = \dots = q_n = Q/n$ at the largest diversity index, $H_{\max} = \ln(n)$. From this, we can see that with more types, the entropy increases due to the differences of each type of water consumption decrease.

The BP neural network model

The BP neural network model is a data-driven model and is highly suited to non-linear simulation (Leshno *et al.* 1993). This algorithm involves two steps: the forward propagation of information and the backward propagation of error (Firat *et al.* 2010). Neurons in the input layer receive external inputs and then transfer these inputs to neurons in the intermediate layer. The intermediate layer, where internal information is processed, transforms the information received. The intermediate layer can be designed as a configuration of single or multiple hidden layers that are structured according to the required information transformation capability. The forward propagation of the learning process is complete when information transferred to neurons within the output layer via the hidden layer is further treated, and the results are then sent

outward via the output layer. The error backward-propagation stage begins when the actual output does not correspond with the expected output. The error is backward propagated from the output layer to the hidden and input layers, with the weights of each layer corrected according to the descent gradient of the error. Information forward-propagation and error backward-propagation repeat in cycles as the weight of each layer is continuously adjusted and the neural network is constantly reconfigured (Xie *et al.* 2015). This process repeats until the network output error is reduced to an acceptable degree or the predetermined learning times are reached. The model of the BP neural network is shown in Figure 1.

The relationships among the three methods are as follows. Firstly, the evolution of ‘dissipative structure’ can be described with ‘information entropy’. The water consumption system is a typical dissipative system, and its evolution can be analyzed by information entropy. This can describe the current evolution of water consumption structure. Secondly, the ‘BP neural network model’ is used to forecast water consumption structure, and then to forecast the evolution of water consumption structure by ‘information entropy’.

DYNAMIC EVOLUTION OF WATER CONSUMPTION

Quantifying changes in water consumption

The total amount of water consumption in China in 1997 was 556.6 billion m^3 , and it increased to 602.2 billion m^3

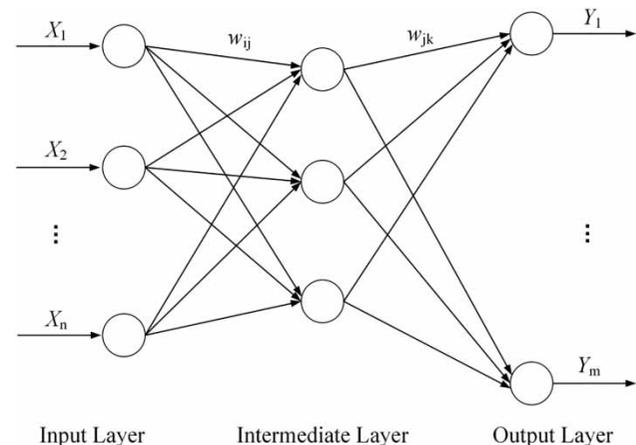


Figure 1 | Model of the BP neural network.

in 2010. This represents a 14-year increase of 45.6 billion m^3 . The changes in water use for all types from 1997 to 2010 are shown in Figure 2. Climate change has affected agricultural water use and there was an overall slight decreasing trend for agricultural water during this period; agricultural consumption reached its lowest level in 2003 when it was 343.1 billion m^3 . In contrast, manufacturing and domestic water use increased, and the growth rate was 3.95% and 3.28%, respectively. Data collection for ecological use began in 2003, and its amount was from 7.98 billion m^3 in 2003 to 12 billion m^3 in 2010. The increase of water consumption types enhanced the function of the water consumption system.

Water consumption information entropy

Water consumption structure from 1997 to 2010 in China was calculated according to the concept of information entropy. When ecological water consumption started in 2003, information entropy leapt significantly. Therefore, the information entropy was divided into two phases: (1) 1997–2002 and (2) 2003–2010. During 1997–2002, a stable increase in information entropy was observed. The information entropy was lowest in 1997 when orderliness was highest. Afterwards, with steady development, there was an increase in information entropy and the structural orderliness decreased. The primary cause was that agricultural

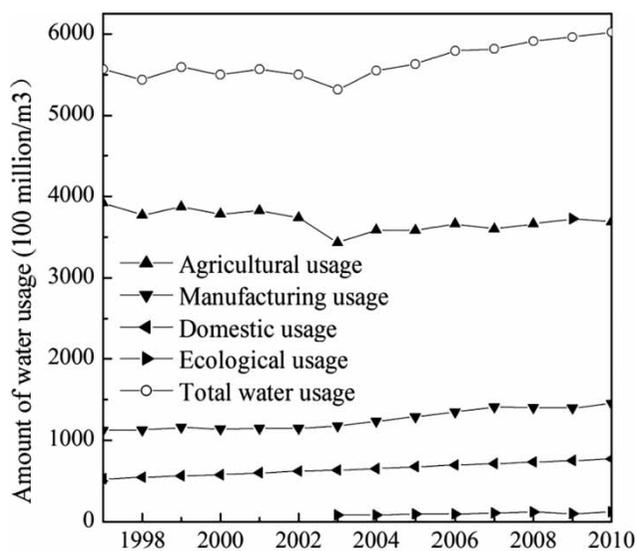


Figure 2 | The dynamic changes in water consumption from 1997 to 2010.

water consumption decreased while manufacturing and domestic water consumption continually increased. During 2003–2010, after a slight increase in information entropy, the narrowing trends also converged. Thus, water consumption structure passed through self-organization towards orderly development.

Previous perspectives helped to form the dynamic evolution in water consumption of China. Detailed data on the information entropy of 31 provinces are shown in Figure 3, which does not include the information entropy for Hong Kong, Macau, or Taiwan. The average information entropy for the majority of provinces from 2003 to 2009 fluctuated between 0.6 and 1.1. The highest values were observed in Beijing and Zhejiang, and the lowest values were observed in Xinjiang, Tibet, and Ningxia.

The analysis data for Beijing, Zhejiang, Henan, Hubei, Yunnan, and Xinjiang (which are demonstrative of both coastal and inland regions and both developed and underdeveloped regions) highlight the changing links between water consumption structure and information entropy. From 2003 to 2009, the major changes in water consumption were as follows. (1) In Beijing, agricultural and manufacturing water use decreased while domestic and ecological water use increased. (2) In Zhejiang, agricultural water use decreased, then in 2009, it recovered slightly. Meanwhile, manufacturing water consumption first rose before declining in 2008 and 2009. Domestic and ecological water use rose with fluctuations. (3) In Henan, agricultural water use decreased with fluctuations and increased slightly in 2008 and 2009. Manufacturing and ecological water use increased, while domestic water use showed little change. (4) In Hubei, agricultural water use fluctuated, decreasing before increasing slightly in 2008 and 2009. Manufacturing water use increased, while domestic water use and ecological water use showed little change. (5) In Yunnan, agricultural water use decreased. Conversely, manufacturing, domestic, and ecological water use increased. (6) In Xinjiang, agricultural water use increased as well as manufacturing and domestic water use. However, ecological water use decreased. Water consumption and information entropy of typical provinces are shown in Table 1 and Figure 4.

China is a major agricultural country, and 60%–70% of all water consumption is in the agricultural sector.



Figure 3 | Map of provincial information entropy.

Table 1 | Water consumption (%) and information entropy (nat) of typical provinces from 2003 to 2009

Province/City	Regional characteristics	Agricultural water consumption proportional range	Agricultural, manufacturing, domestic, and ecological ratio	Information entropy range
Beijing	High Income, Northern Coast	30%–40%	35:18:42:5	1.15–1.25
Zhejiang	Medium Income, Eastern Coast	45%–55%	50:27:15:6	1.10–1.25
Henan	Mid–High Income, Middle Region of the Yellow River	55%–65%	62:21:15:2	0.95–1.05
Hubei	Mid–High Income, Yangzi River Region	50%–55%	53:36:11:0	0.93–0.96
Yunnan	Mid–Low Income, Southwest Region	65%–75%	71:15:13:1	0.75–0.91
Xinjiang	Mid–Low Income, Northwest Region	90%–95%	92:2:2:4	0.35–0.40
Whole country	–	60%–70%	65:22:12:2	0.93–0.98

Agricultural water use is relatively low in economically developed regions where people focus on quality of life and there is a higher domestic water consumption rate. Take Beijing for

example, where domestic water consumption is as high as 42% of the total water use. Hence, the demand for agricultural water use has decreased in developed regions and the

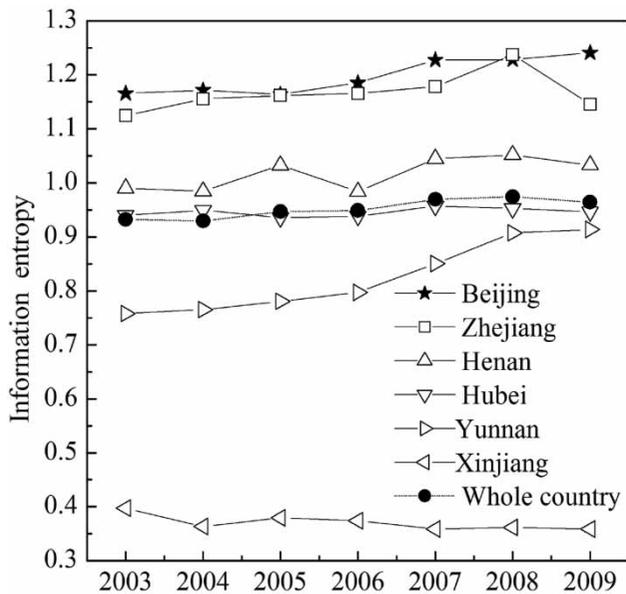


Figure 4 | Dynamic changes in information entropy of typical provinces from 2003 to 2009.

gaps between all usage sectors have narrowed. The stability of water consumption structure in such regions has increased and information entropy is relatively high. Taking out Xinjiang province, the trends of the remaining five provinces encountered were mostly rising with fluctuations. In 2009, information entropy decreased in Zhejiang, Henan, and Hubei. The water consumption information entropy of the Xinjiang Autonomous Region was consistently low. This may explain the orderliness at low levels, which consisted of a single water type. The information entropy for Beijing, Zhejiang, and Henan were larger than the national average, while those of Hubei, Yunnan, and Xinjiang were lower than the national average. The evolution trend in Henan was consistent with the national and Hubei approached the national average.

ANALYSIS OF THE DRIVING FACTORS BEHIND WATER CONSUMPTION

Driving factors

The factors that can influence evolution in water consumption structure include population size, economics, society, technology, and the inner links among these factors.

Precipitation is a main factor affecting water resources, but its influence on water consumption structure is not large. So in this study, precipitation is not regarded as a driving factor. Thus, we chose 12 factors that were representative of population growth, economic development, and social advancement to drive the evolution of water consumption structure, as shown in Figure 5.

Analysis of the principal driving factors

The dimension of a huge data set can be trimmed down by using principal component analysis, which is considered as one of the most prevalent and useful statistical methods for uncovering the potential structure of a set of variables. This method is used for explaining the variance of a large set of interrelated variables by transforming them into a new, smaller set of uncorrelated (independent) variables, namely the principal components (Azid *et al.* 2014). Principal component analysis was performed, using SPSS (Statistical Product and Service Solution) software, to reduce the number of the 12 factors to a smaller number without loss of essential information. The variance and covariance of all involved factors were determined based on standardized data. The score coefficient matrix of the 12 factors is listed in Table 2.

The extracted driving factors for the evolution in water consumption are as follows. (1) The first main component explained 70% of the evolution, and this component included the population, command irrigation area, gross domestic product (GDP), plantation proportion, manufacturing proportion, service proportion, urbanization level, water conservation area, city parks, and urban consumption levels. Hence, these socio-economic factors, which represent population growth, water conservation technology, and industry, show a close relationship with the change in water consumption. (2) The second component explained 23% of the evolution, and this component included agricultural information such as cropland and food production. Agricultural structure has a principal influence on water consumption. Therefore, the driving factors influencing water consumption in China can be divided into two categories: socio-economic development variables and agricultural structural variables, and the former has a more significant influence.

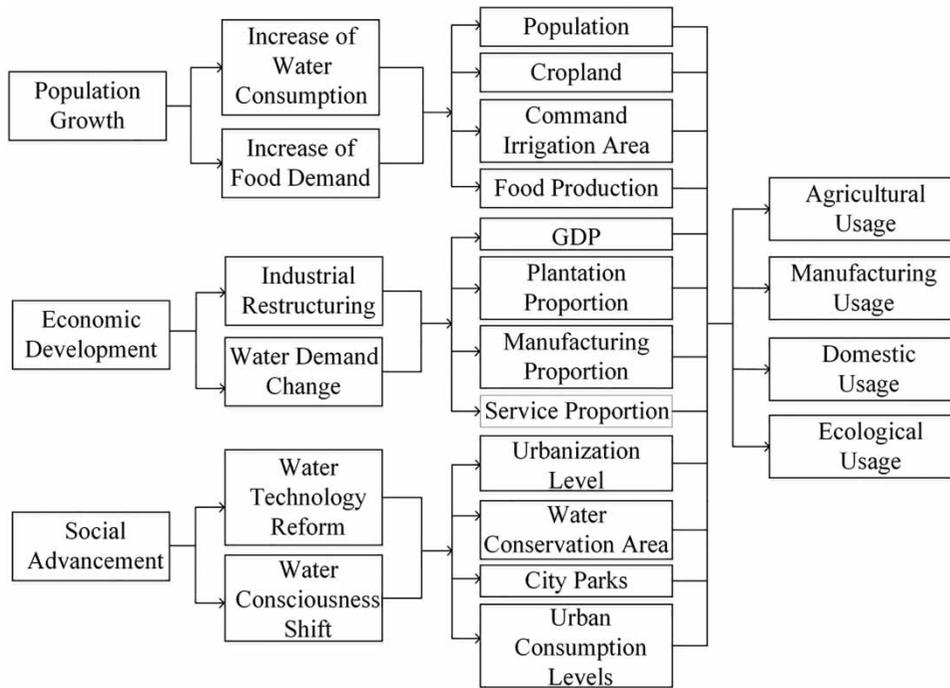


Figure 5 | Driving factors for the change in water consumption.

Table 2 | Component score coefficient matrix

	Component			Component	
	1	2		1	2
Population x_1	0.118	-0.019	Manufacturing proportion x_7	0.022	-0.316
Cropland x_2	-0.056	0.302	Service proportion x_8	0.097	-0.156
Command irrigation area x_3	0.110	0.081	Urbanization level x_9	0.117	-0.026
Food production x_4	0.044	0.317	Water conservation area x_{10}	0.117	0.024
GDP x_5	0.112	0.112	City parks x_{11}	0.116	0.024
Plantation proportion x_6	-0.106	0.085	Urban consumption levels x_{12}	0.113	0.106

According to the component score coefficient matrix, we determined the relationship between the two main components and factors as follows:

$$F_1 = 0.118x_1 - 0.056x_2 + 0.110x_3 + 0.044x_4 + 0.112x_5 - 0.106x_6 + 0.022x_7 + 0.097x_8 + 0.117x_9 + 0.117x_{10} + 0.116x_{11} + 0.113x_{12}$$

$$F_2 = -0.019x_1 + 0.302x_2 + 0.081x_3 + 0.317x_4 + 0.112x_5 + 0.083x_6 - 0.316x_7 - 0.156x_8 - 0.026x_9 + 0.024x_{10} + 0.024x_{11} + 0.106x_{12}$$

The first main contributing component value was 70% and the second was 23%. The multiple linear regression equation of the driving factors can be obtained by weighted

contributing component values:

$$F = 0.70F_1 + 0.23F_2 = 0.078x_1 + 0.030x_2 + 0.095x_3 + 0.104x_4 + 0.104x_5 - 0.055x_6 - 0.057x_7 + 0.032x_8 + 0.076x_9 + 0.087x_{10} + 0.086x_{11} + 0.103x_{12}$$

Therefore, the greatest factors influencing China's water consumption structure are population, command irrigation area, food production, GDP, water conservation area, city parks, and urban consumption levels. Based on the maximum factor score and factor non-repetition, the principal driving factors are population, GDP, food production, command irrigation area, and urban consumption levels.

PREDICTING WATER CONSUMPTION STRUCTURE

BP neural network theory was used to predict water consumption structure. The BP neural network of water consumption structure contained five inputs including the principal driving factors, namely population, GDP, food production, command irrigation area, and urban consumption levels. The outputs of the BP model were agricultural consumption proportion, manufacturing consumption proportion, domestic consumption proportion, and the total water consumption. The data from 2011 to 2020 of five inputs were predicted, for example, the population was predicted by a logistic retarded growth model. On the

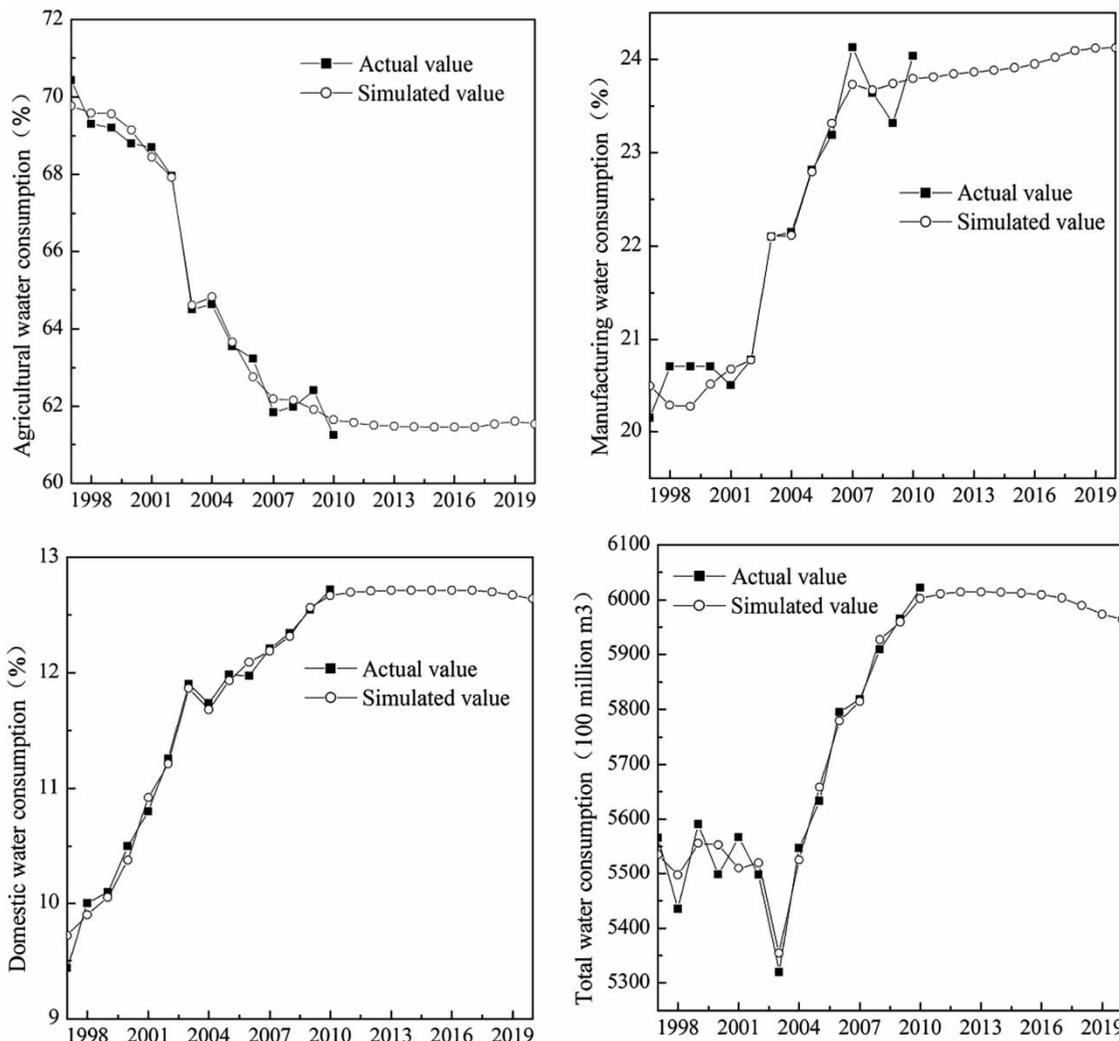


Figure 6 | Simulation and prediction of water consumption structure.

basis of predicting the inputs, the outputs were predicted by the BP model. These data are shown in Figure 6.

The simulated values were consistent with the actual values during 1997 to 2010, especially for domestic water consumption. The total water consumption will decrease slightly from 2011 to 2012. Agricultural water consumption will greatly decrease, while manufacturing and domestic will increase. According to information entropy theory, the values of actual and simulated information entropy data are illustrated in Figure 7.

As shown in Figure 7, simulated and actual information entropy for water consumption from 1997 to 2010 fitted with high precision. Compared with 2010, the calculated 2011 information entropy dropped slightly, and afterwards, it remained stable. There was an obvious drop after the peak at 0.980 in 2014, thus indicating an inverted 'U'-shape curve. This demonstrated that water consumption is progressively becoming orderly.

The inverted 'U'-shape of water consumption structure evolution has also emerged in land (Chen & Liu 2001), energy (Geng *et al.* 2004), and other scarce resource development processes. This suggests that information entropy can be used as a reliable approach to describe the development process of the water consumption system. Moreover, it validates the predicted results of water consumption structure.

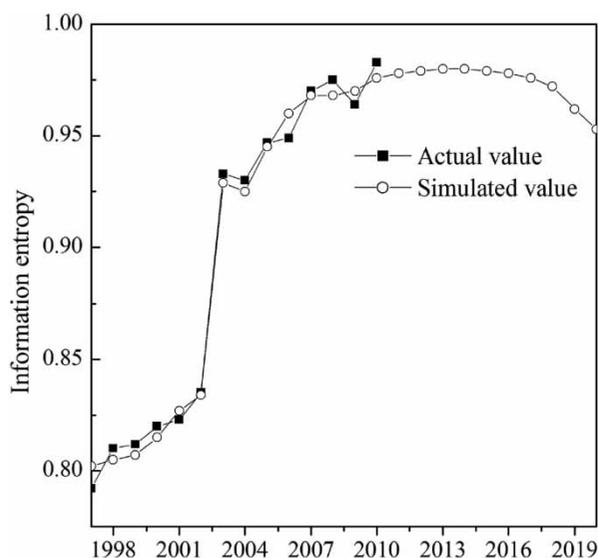


Figure 7 | Comparison of simulated and actual information entropy for water consumption.

CONCLUSIONS

The water consumption system has typical characteristics of dissipative structures, and its evolution can be described by information entropy. Meanwhile, the driving factors of water consumption were analyzed to predict the evolution of water consumption. The main conclusions were as follows.

1. The information entropy of water consumption structure experienced an increasing period and convergence period from 1997 to 2010. The convergence of the entropy demonstrated that there was a gradual orderliness in the system's development. Analysis of the information entropy for 31 provinces in China found that the majority of provinces experienced fluctuations between 0.6 and 1.1.
2. The principal driving factors influencing water consumption were population, command irrigation area, food production, GDP, water conservation area, city parks, and urban consumption levels. These results suggest that controlling population growth, improving economic efficiency, and increasing the use of water-conservation technologies in the agricultural sector would be the most beneficial for solving water scarcity issues in China.
3. Five principal factors were used as inputs of a BP neural network model to predict water consumption from 2011 to 2020. The results demonstrate that the total amount of water consumption will be changed slightly. Specifically, agricultural water consumption will decrease, while both manufacturing and domestic water consumption will increase. The information entropy was further calculated based on the predicted water consumption structure, which presented an inverted 'U'-curve. This evolution trend accords with land, energy, and other scarce resource development processes.
4. The research analysed the dynamic evolution and driving factors of water consumption in China. On this basis, the evolved trend of water consumption was predicted. According to the research, driven by the driving factors, the water consumption system will be more reasonable during the coming period. Decreasing agricultural water and increasing manufacturing and domestic water will optimize water consumption allocation, which made the limited water resources produce the maximum socio-economic values.

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