Identification of regional water security issues in China, using a novel water security comprehensive evaluation model

Jiping Yao, Guoqiang Wang, Baolin Xue, Gang Xie and Yanbo Peng

ABSTRACT

In order to solve regional water security issues, such as shortage of water resources, the aggravation of water pollution, the destruction of the ecological environment, etc., this study proposed the flood control security index, resource security index and ecological security index, respectively, according to the construction principle of human development index. Based on the above security indexes, a novel water security comprehensive evaluation model is established by combining the coupling coordination degree model and the state space model. The proposed model has the advantage of simple operation and fast data speed, which is convenient for water security evaluation in different periods and regions. Taking China as an example, the water security conditions were evaluated from 2007 to 2016 for 31 provincial-level administrative regions in China, including flood control security index, resource security index, ecological security index and water security level of each region, and the specific problems of water security in each region were obtained. The evaluation results are consistent with the actual situation in each region, which provides the scientific basis for the local government authorities to formulate the corresponding regional water security policy.

Key words | ecological security index, flood control security index, regional water security, resources security index, water security evaluation model

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INTRODUCTION

Water is essential for maintaining the balance of life and the living environment. It is a basic natural resource and strategic resource to promote human economic development and social progress (Masseroni *et al.* 2019; Wang *et al.* 2019b; Yao *et al.* 2019a, 2019b). Water security refers to the capacity of water resources with quantity and quality guarantee required for human survival and development, which can maintain the basin sustainability and human and ecological environment health, and ensure people's life and property from water disasters (floods, landslides and droughts) (Ren *et al.* 2012; Fang *et al.* 2018a; Wang *et al.* 2018, 2019a; Yang *et al.* 2016; Yao *et al.* 2019c). However, in recent years, frequent floods, water shortage, pollution and water ecological damage have become serious global challenges (Parry *et al.* 2012; Emam *et al.* 2015; Awan *et al.* 2016; Han *et al.* 2018; Liu *et al.* 2018a; Ledingham *et al.* 2019). In 1972, the United Nations Conference on Environment and Development predicted that a water crisis would take place following the oil crisis (Biswas 1999). In 2000, the Hague and the World Water Week took 'water security in the 21st century' as the theme of the world Ministerial Level Conference (Falkenmark 2002). In 2009, United Nations Educational, Scientific and Cultural Organization pointed out in its World Water Resources Development Report that the contradiction between supply and demand of water resources in human society is more prominent,

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coupled with climate degradation and rapid population growth, which leads to more serious water security problems (Russo *et al.* 2014; Jiang 2015; Kumar 2015; Li *et al.* 2016; Fang *et al.* 2018b). Therefore, it is necessary to study water security and propose solutions to related issues from different perspectives.

Many scholars study water security and related issues from different perspectives. Harris & Kennedy (1999) pointed out that urban water supply should be integrated into the actual urban development planning from the perspective of water supply, and further explored the evolution of urban water security. Rijsberman & van de Ven (2000) revealed the development of urban water security from a new perspective of water resources carrying capacity. Sullivan (2002) proposed a water poverty index similar to the Consumer Price Index to reflect the impact of water shortage on human beings. Falkenmark & Lundqvist (2009) paid attention to the water quantity problem, comprehensively considering the shortage of natural water resources and water quality shortage caused by water pollution, and provided a more objective and real basis for local relevant departments to formulate water security protection policies. Ou *et al.* (2012) used the established entropy weight-fuzzy matter element model to evaluate the rural water safety situation, which effectively reduced the influence of uncertainty and fuzziness in the evaluation process on the authenticity of water safety. Tian & Gang (2012) used the pressure state response conceptual model to evaluate regional water security from the perspective of ecological security. Norman *et al.* (2013) evaluated the water security situation of a community in Canada with the method of water security index evaluation, and obtained good results. Considering the uncertainty of drought events, Dong & Xia (2014) introduced the Dempster Shafer evidence theory and evidence reasoning algorithm to assess the risk of water security during drought. Gain *et al.* (2016) put forward a framework that can quantitatively reflect the impact of human activities and natural water resources on water security by combining the factors that affect freshwater resources with the factors of social and economic development. Larson (2017) took water security as the leading mode to study natural resource policy, and comprehensively explored the situation of human water security by combining climate change with other pressing global sustainable development challenges. Actually, the water security issues are caused by the comprehensive influence of society, economy, resources, environment and ecology (Awan *et al.* 2016). However, at present, the water security evaluation is only based on the characteristics of the research area or the focus of the research problem, and puts forward the methods to solve the water security problem from different angles. The theory and methods of water security evaluation are not comprehensive enough, and the universality of the proposed evaluation method is relatively low.

In the 1990 Human Development Report, the United Nations proposed the Human Development Index (HDI), which comprehensively reflects the level of human development among different countries and regions by using three variables: human life index, education level index and GDP index (Kawada *et al.* 2019). The index plays an important role in guiding the development strategies of developing countries. Therefore, this paper puts forward a flood control security index, resource security index and ecological security index similar to HDI from flood control, resources and ecology, and establishes an evaluation model that can comprehensively reflect the regional water security situation. The water security of the 31 provinces of China is analyzed and evaluated by the proposed water security evaluation model, and the distributions of flood control security index, the resource security index and the ecological security index are respectively obtained. Additionally, the distributions of water security index which can comprehensively reflect the water security status of each region are obtained. All of the above indexes provide a scientific and reliable basis for a comprehensive understanding of water security problems in various regions of China and for the formulation of targeted strategies to solve water security problems.

MATERIALS AND METHODS

Study area and data

According to the three key factors of water security, namely flood control security, resource security and ecological security, the current situation and changes of water security in China from 2007 to 2016 are comprehensively evaluated. In this paper, 31 administrative regions in mainland China are taken as the research units of regional water security to study the temporal and spatial evolution of water security in China (Figure 1), and the key factors affecting the water security status of China and each research unit are analyzed. Due to the lack of relevant data, Taiwan, Hong Kong and Macao were not included in the study. The dataset of this study came from the China Water Conservancy Bulletin, China Water Development Statistical Yearbook, China Statistical Yearbook, China Environmental Statistical Yearbook and the China Flood and Drought Disaster Bulletin during the period 2007–2016 (Liu *et al.* 2018a).

Methods

Determination of security indexes of the regional water security evaluation model

Based on the three key factors of flood control safety, resource security and ecological security, which can comprehensively reflect the regional water security, this paper establishes the flood control security index, resource security index and ecological security index respectively. The three indexes are used to establish the water security evaluation model. The specific calculation methods are discussed below.

The key points of flood control security are casualties caused by flood, economic loss of water conservancy facilities and disaster area loss caused by flood in the region. Therefore, the flood control security index (*FS*) established includes three data sets: loss rate of disaster area R_a, regional flood disaster population rate R_c and the ratio of economic loss of water-saving facilities to direct economic loss R_e, which reflects the regional social development water. The specific calculation formula is as follows:

$$\begin{cases} R_a = \frac{R_{ad}}{R_{as}} \\ R_c = \frac{R_{cf}}{R_{cp}} \\ R_e = \frac{R_{ew}}{R_{ed}} \end{cases} \tag{1}$$

where R_{ad} denotes flood damage areas (km^2), R_{as} denotes flood disaster areas (km^2), R_{cf} denotes the number of flood-affected population (10,000 people), R_{cp} denotes the number of population affected by disasters (10,000 people), R_{ew} denotes economic loss of water-saving facilities

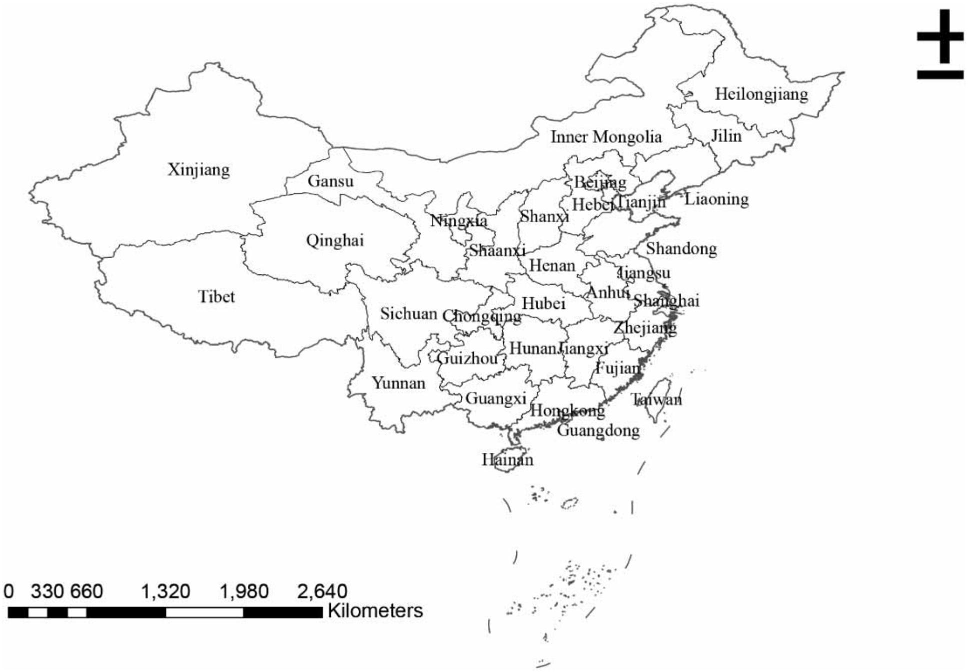

Figure 1 | Overview of the study area.

in floods (100,000,000 yuan), R_{ed} denotes direct economic losses in floods (100,000,000 yuan). Since floods are driven by disasters caused by natural and human events, the five-year moving average value is calculated based on the above data to reduce the impact of the annual flood control security index. The regional flood control security index (*FS*) is defined as:

$$FS = \begin{cases} 1, & R_i \le 0.01 \\ 0.2 - 0.4 \times \dfrac{\sum \lg R_i}{3}, & 0.01 < R_i \le 0.1 \\ 0.3 - 0.3 \times \dfrac{\sum \lg R_i}{3}, & 0.01 < R_1 \le 1 \\ 0, & R_i > 1 \end{cases} \quad (i = a, c, e) \tag{2}$$

The resource security index (*RS*) reflects the coordination between the per capita water resources, urban and rural development level and water supply capacity. The index shows the relative guarantee strength among regional basic resources, economic development level and water supply capacity. The resource security index (*RS*) includes per capita water resources, urbanization rate and per capita water demand, and its calculation formula is as follows:

$$RS = \begin{cases} 1, & Wr \ge 2\overline{W} \\ 1 - \left\{\dfrac{1}{3} \times [(1-W)^2 + (1-U)^2 + (1-C)^2]\right\}^{1/2}, & Wr < 2\overline{W} \end{cases} \tag{3}$$

where W denotes the normalized water resource factor (see Equation (4)), U denotes the urbanization rate (%), and C is the per capita water storage capacity.

$$W = \begin{cases} 1, & Wr > 2\overline{W} \\ \lg \dfrac{Wr}{Wr_{\min}} / \lg \dfrac{2\overline{W}}{Wr_{\min}}, & Wr_{\min} < Wr \le 2W \\ 0, & Wr \le Wr_{\min} \end{cases} \tag{4}$$

where Wr denotes the per capita water resources volume, $\overline{W}$ is the global per capita water resources volume (6,123 m^3), and $Wr_{\min}$ is the lower limit of global per capita water resources volume. The per capita water resources of Israel (a country with a serious water shortage), 97 m^3, is taken as the lower limit of per capita water resources in this study (Liu *et al.* 2018b).

The ecological security index (*ES*) focuses on the environmental conditions related to water, which reflects the security of water ecology through the ecological conditions of rivers, lakes and reservoirs. The index includes the ratio of the length of a river above Class III to total river length (*RW*) and the ratio between the number of non-eutrophication lakes to the total number of lakes (*RE*). The calculation formula for the ecological security index (*ES*) is as follows:

$$ES = \sqrt{\frac{RW^2 + RE^2}{2}} \tag{5}$$

Construction of regional water security model

Based on the flood control security index, resource security index and ecological security index, the water security index is proposed to reflect regional water security. Due to the complementary relationship among flood control, resources and ecology (Wilkinson & Bathurst 2018), this paper introduces the coupling coordination model (Cheng *et al.* 2019) to characterize the interaction between flood control, resources and ecology, and the specific calculation formula is as follows:

$$\begin{cases} D_{FS\leftrightarrow RS} = \sqrt{[FS \times RS/(FS+RS)^2]^{1/2} \times (a \times FS + b \times RS)} \\ D_{RS\leftrightarrow ES} = \sqrt{[RS \times ES/(RS+ES)^2]^{1/2} \times (b \times RS + c \times ES)} \\ D_{FS\leftrightarrow ES} = \sqrt{[FS \times ES/(FS+ES)^2]^{1/2} \times (a \times FS + b \times ES)} \end{cases} \tag{6}$$

where $D_{FS\leftrightarrow RS}$, $D_{RS\leftrightarrow ES}$ and $D_{FS\leftrightarrow ES}$ respectively represent the coupling coordination degree of the interaction between the flood control security and the resource security, the coupling coordination degree of the interaction between the resource security and the ecological security, and the coupling coordination degree of the flood control security and the ecological security interaction. *a, b* and *c* are the undetermined coefficients of the flood control security index, resource security index and ecological security index respectively, the value of which should be $a = b = c = \frac{1}{2}$ (Cheng *et al.* 2019).

On the basis of the above-mentioned security interactions, the state space model (Li *et al.* 2019) is used to obtain a water security index (*WSI*) that can comprehensively consider the impact of flood control security, resource security and ecological security interaction on water security. Based on the above steps, a water security evaluation model is established. The specific calculation formula is as follows:

$$WSI = \sqrt{\frac{D^2_{FS\leftrightarrow RS} + D^2_{RS\leftrightarrow ES} + D^2_{FS\leftrightarrow ES}}{3}} \tag{7}$$

In order to scientifically and effectively show the advantages and disadvantages of water security in various regions, this paper classifies water security into five levels: unsafe, relatively unsafe, general security, relative security and security according to the water security classification standard (Ren *et al.* 2017) (see Table 1).

RESULTS AND DISCUSSION

Considering that the flood control security index, resource security index and ecological security index are affected by interannual changes, only relying on the evaluation results of a single year to determine the current situation of water security in each region of the study area will lead to a large deviation between the evaluation results and the actual situation. Consequently, based on the average values of the water security evaluation indexes data for 2007–2016, the proposed water security evaluation model is used to obtain the flood control security index, the resource security index, the ecological security index and the water security index (Tables 2–4). The spatial distribution characteristics of water security status in 31 administrative regions of the study area were analyzed (Figures 2–5).

Table 1 | Water security evaluation standards

Water security level	Unsafe	Relatively unsafe	Generally safe	Relatively safe	Safe
Level threshold	[0,0.2)	[0.2,0.4)	[0.4,0.6)	[0.6,0.8)	[0.8,1.0]

Table 2 | Average values of flood control security index in the study area from 2007 to 2016

Region	R_a	R_c	R_e	FS
Beijing	0.5150	0.5031	0.2132	0.4258
Tianjin	0.7343	0.1358	0.1840	0.4737
Hebei	0.5656	0.0428	0.1871	0.5344
Shanxi	0.6055	0.0531	0.0718	0.5636
Inner Mongolia	0.6150	0.2719	0.0954	0.4797
Liaoning	0.6164	0.1722	0.2212	0.4629
Jilin	0.5247	0.0649	0.2144	0.5137
Heilongjiang	0.6584	0.0154	0.0943	0.6020
Shanghai	0.3654	0.0321	0.0611	0.6145
Jiangsu	0.3190	0.0010	0.0613	0.7709
Zhejiang	0.4632	0.0084	0.1338	0.6285
Anhui	0.5147	0.0137	0.2187	0.5813
Fujian	0.4454	0.0580	0.1926	0.5303
Jiangxi	0.5247	0.0234	0.2297	0.5549
Shandong	0.5712	0.0092	0.0783	0.6385
Henan	0.2643	0.0064	0.2314	0.6406
Hubei	0.3644	0.0454	0.1936	0.5494
Hunan	0.5185	0.0356	0.2318	0.5369
Guangdong	0.4352	0.0585	0.1526	0.5410
Guangxi	0.3543	0.0485	0.1351	0.5634
Hainan	0.5439	0.0399	0.0818	0.5750
Chongqing	0.4053	0.0854	0.1641	0.5246
Sichuan	0.5295	0.0612	0.1723	0.5253
Guizhou	0.4664	0.1050	0.1298	0.5197
Yunnan	0.5745	0.1935	0.1744	0.4712
Tibet	0.4157	0.2733	0.1922	0.4661
Shaanxi	0.6509	0.1643	0.1837	0.4707
Gansu	0.7150	0.1307	0.1260	0.4929
Qinghai	0.5609	0.6281	0.2317	0.4088
Ningxia	0.4540	0.2043	0.3703	0.4464
Xinjiang	0.6254	0.3694	0.3534	0.4088

Characteristics of flood control security in the study area

Table 2 shows the average value of flood control security index (*FS*) of each administrative region in the study area

Table 3 | Average values of resources security index in the study area from 2007 to 2016

Region	W	U	C	RS
Beijing	0.0869	0.8584	0.1194	0.2630
Tianjin	0.0523	0.8030	0.0834	0.2303
Hebei	0.1883	0.4642	0.1379	0.2496
Shanxi	0.2657	0.4687	0.0943	0.2602
Inner Mongolia	0.6706	0.5648	0.2053	0.4434
Liaoning	0.2861	0.6396	0.4130	0.4273
Jilin	0.5264	0.5404	0.5955	0.5531
Heilongjiang	0.6373	0.5673	0.3549	0.5050
Shanghai	0.2041	0.8885	0.0022	0.2603
Jiangsu	0.4157	0.6121	0.0219	0.3051
Zhejiang	0.6721	0.6215	0.4005	0.5490
Anhui	0.5612	0.4551	0.2649	0.4141
Fujian	0.7374	0.6237	0.2529	0.4938
Jiangxi	0.7847	0.5178	0.3356	0.5100
Shandong	0.1185	0.5785	0.1037	0.2345
Henan	0.2341	0.4623	0.2264	0.2990
Hubei	0.5916	0.5692	0.9986	0.6572
Hunan	0.6946	0.5069	0.3699	0.5056
Guangdong	0.6066	0.6307	0.2099	0.4476
Guangxi	0.8142	0.4814	0.6873	0.6343
Hainan	0.6451	0.5645	0.4140	0.5313
Chongqing	0.5656	0.6057	0.1991	0.4268
Sichuan	0.6843	0.4768	0.2387	0.4364
Guizhou	0.7236	0.4272	0.4199	0.5030
Yunnan	0.7638	0.4638	0.7863	0.6399
Tibet	1.0000	0.2796	0.4480	1.0000
Shaanxi	0.4558	0.4824	0.1298	0.3364
Gansu	0.3851	0.3781	0.1976	0.3148
Qinghai	0.9571	0.4614	0.9819	0.6879
Ningxia	0.0542	0.5006	0.2218	0.2363
Xinjiang	0.7689	0.4353	0.4179	0.5131

Table 4 | Average values of ecological security index in the study area from 2007 to 2016

Region	RW	RE	ES
Beijing	0.8155	1.0000	0.9124
Tianjin	0.0916	0.0000	0.0648
Hebei	0.4353	0.4219	0.4286
Shanxi	0.2689	0.0000	0.1901
Inner Mongolia	0.7445	0.0000	0.5264
Liaoning	0.4391	1.0000	0.7723
Jilin	0.6747	0.4290	0.5654
Heilongjiang	0.6690	0.4026	0.5521
Shanghai	0.4786	0.0000	0.3384
Jiangsu	0.3497	0.1389	0.2661
Zhejiang	0.7189	0.9088	0.8194
Anhui	0.6167	0.5489	0.5838
Fujian	0.7980	0.7488	0.7738
Jiangxi	0.9369	1.0000	0.9690
Shandong	0.4693	0.4599	0.4646
Henan	0.5095	0.6689	0.5946
Hubei	0.8050	0.7883	0.7967
Hunan	0.9821	0.0000	0.6945
Guangdong	0.7891	0.7387	0.7643
Guangxi	0.9585	1.0000	0.9795
Hainan	0.9370	0.6689	0.8141
Chongqing	0.9928	0.0000	0.7020
Sichuan	0.8846	0.6645	0.7823
Guizhou	0.8142	1.0000	0.9118
Yunnan	0.8693	0.6594	0.7716
Tibet	0.9948	1.0000	0.9974
Shaanxi	0.6797	1.0000	0.8550
Gansu	0.7485	1.0000	0.8832
Qinghai	0.9749	1.0000	0.9875
Ningxia	0.3671	0.0090	0.2597
Xinjiang	0.9969	1.0000	0.9984

from 2007 to 2016, which is obtained from flood control security evaluation factors (R_a, R_c, R_e). Based on Table 2, the spatial distribution of the average flood control security index in the study area from 2007 to 2016 was obtained (Figure 2). The flood control security index for Heilongjiang, Shanghai, Jiangsu, Zhejiang, Henan and Shandong exceeds 0.6, which indicates that the flood control security level of these areas is higher. This is mainly due to the fact that these areas are prone to more rainfall and flood events, are more developed in society and economy, have more investment in infrastructure, and are more advanced in technology, so they have better performance in this regard (Liu *et al.* 2018b). On the contrary, the flood control security index of other provincial administrative areas is lower than 0.6, which indicates that the flood control security level in these areas is lower. In particular, the flood control security level of Xinjiang and Qinghai in the west of the study area is the lowest at 0.4088. This low level is due to the rare rainfall,

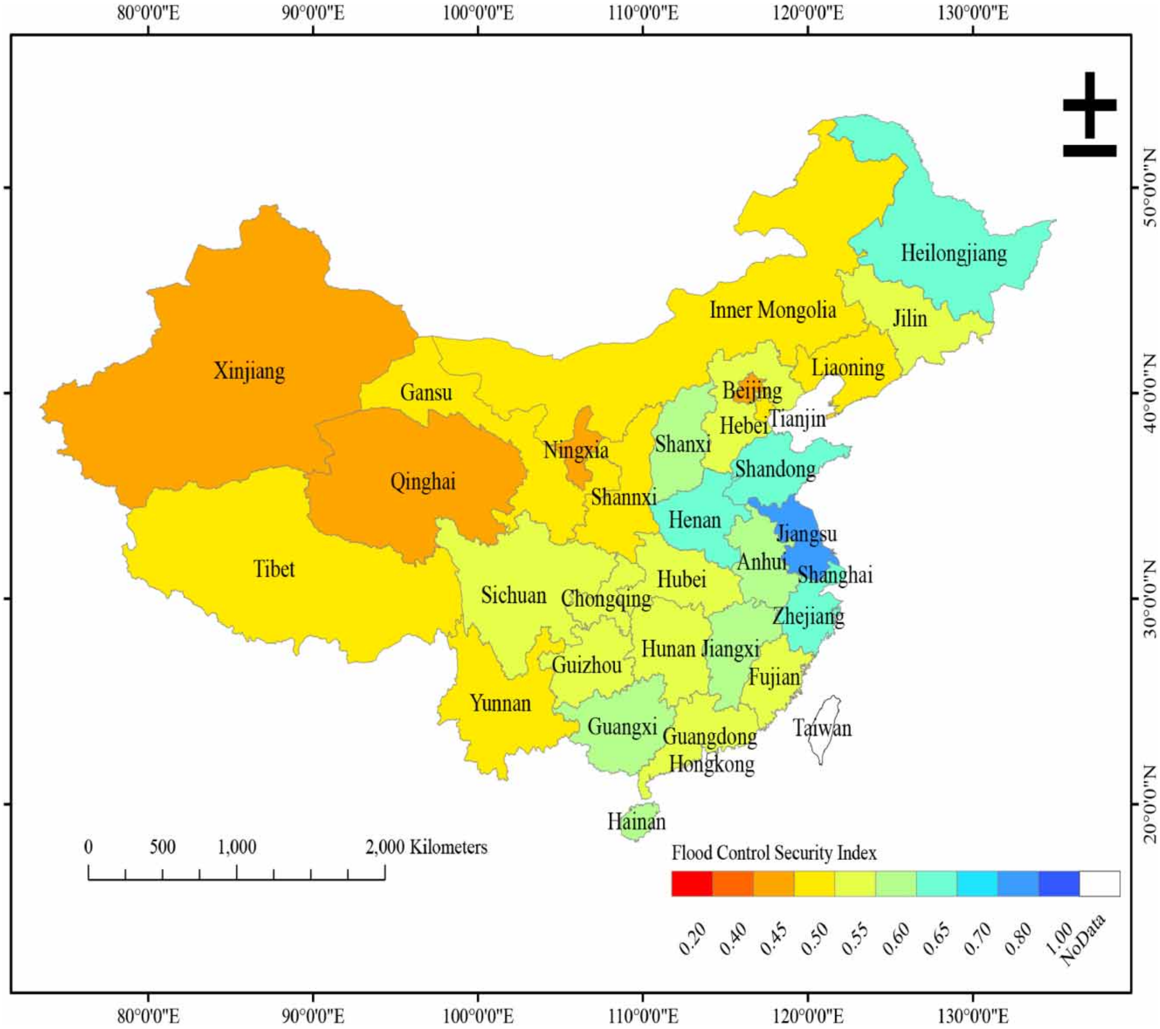

Figure 2 | Spatial distribution of annual average flood control security index in the study area from 2007 to 2016.

rare flood and insufficient flood control infrastructure in western China (especially the northwest) (Zhang *et al.* 2019). In this case, people are more vulnerable to floods and suffer more losses. These areas require a higher level of flood control alarms. Relevant government departments of the study area need to strengthen the unified management of water resources and flood control, and speed up the preparation or revision of emergency operation plans for flood control operation of important rivers. In addition, relevant departments need to speed up the formulation of water distribution plans and water conservancy renovation plans for major rivers, improve the unified dispatching management scheme, clarify the dispatching project and authority, and strengthen the flood risk management.

Characteristics of resources security in the study area

Resource security reflects the coordination of regional basic resources, economic development and water supply capacity. Table 3 shows the average value of the resource security index (*RS*) for each administrative region in the study area from 2007 to 2016, which was obtained from resource security evaluation factors (W, U, C). Based on Table 3, the spatial distribution of the annual average resource security index in the study area from 2007 to 2016 was obtained (Figure 3). In all administrative regions of the study area, the resource security index (*RS*) of Tibet is equal to 1, which indicates that the level of resource security in the region is very high. This is mainly due to the

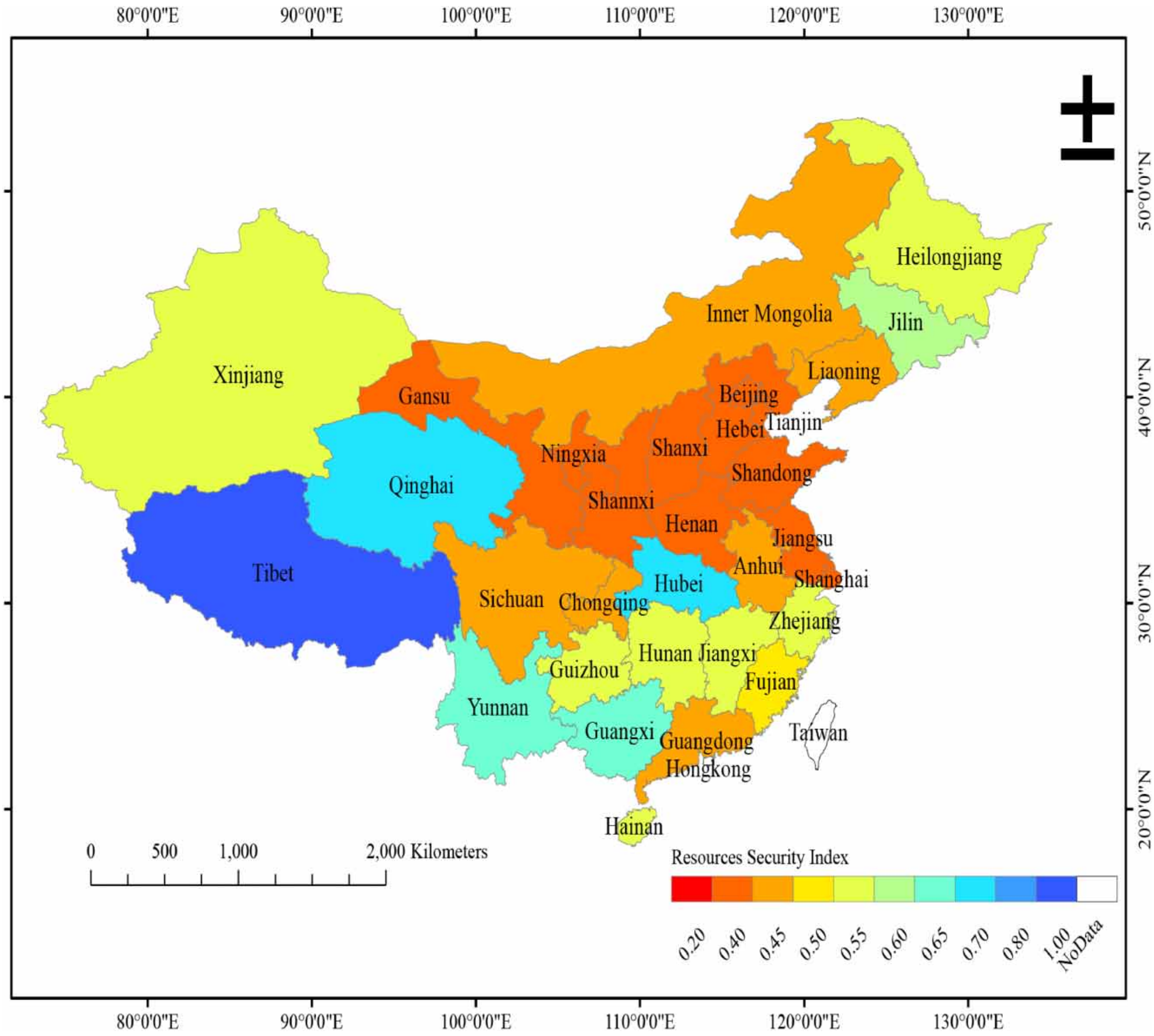

Figure 3 | Spatial distribution of annual average resource security index in the study area from 2007 to 2016.

relatively high per capita water resources in Tibet, which is twice as large as that in the rest of the world. In addition, the low urbanization rate, sparse population and relatively high per capita water resources in this area make Tibet have a superior resource security effect (Liu *et al.* 2018b). The resource security index (*RS*) of Qinghai, Hubei, Guangxi and Yunnan is higher than 0.6, which indicates that the resource security water in these areas is higher. The resource security indexes of Beijing, Tianjin, Hebei, Shanxi, Shanghai, Jiangsu, Shandong, Henan, Shaanxi and Gansu are lower than 0.4, which indicates that the resource security level of these areas is relatively low. This is mainly because the urbanization rate of Beijing and Tianjin is very high ($U > 0.8$), and the per capita water resources are scarce ($W < 0.12$), which leads to the lack of per capita water resources. Especially, the per capita water resources of Tianjin are lower than that of the world minimum standard of water resources per capita (97 m^3). Additionally, the water supply capacity of Hebei, Shanxi, Shanghai, Jiangsu, Shandong, Shaanxi and Gansu is very low ($C < 0.14$). This indicates that the above-mentioned administrative regions are facing great challenges in resource security, these regions need to reasonably adjust the industrial structure, optimize the industrial layout, and improve the efficiency of water resource allocation according to the natural conditions and relevant development plans of water resources in each region.

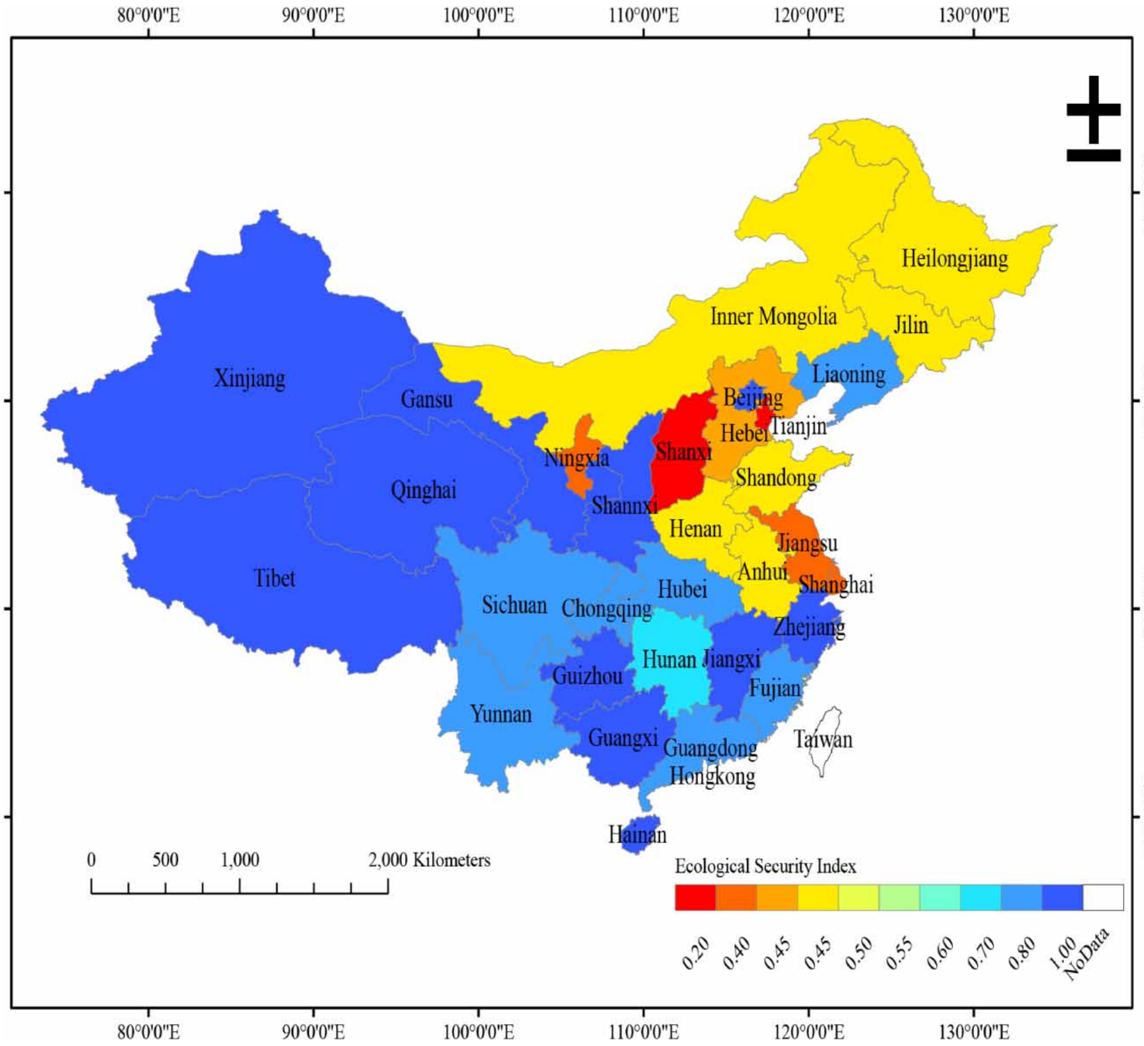

Figure 4 | Spatial distribution of annual average ecological security index in the study area from 2007 to 2016.

Characteristics of ecological security in the study area

Ecological security fully reflects the water quality and ecological characteristics of rivers, lakes and reservoirs. Table 4 shows the average value of the ecological security index (*ES*) for each administrative region in the study area from 2007 to 2016, which was obtained from ecological security evaluation factors (*RW*, *RE*). Based on Table 4, the spatial distribution of the annual average ecological security index in the study area from 2007 to 2016 was obtained (Figure 4). The results show that the ecological security indexes of Beijing, Zhejiang, Jiangxi, Guangxi, Hainan, Guizhou, Shaanxi, Tibet, Gansu, Qinghai and Xinjiang all exceed 0.8, which indicates that the ecological security of these areas is at a high level. According to the data in the China Water Development Statistical Yearbook and China Water Resources Bulletin, the results of regional ecological security assessment during the period of 2007–2016 show that the above-mentioned areas have better environmental governance, and the proportion of rivers above class III and non-eutrophication lakes and reservoirs that meet the requirements of *RW* and *RE* is relatively large. However, the ecological security index related to water quality of rivers, lakes and reservoirs in Tianjin and Shanxi is lower than 0.2. This indicates that the ecological security of Tianjin and Shanxi is at a low level, which may be

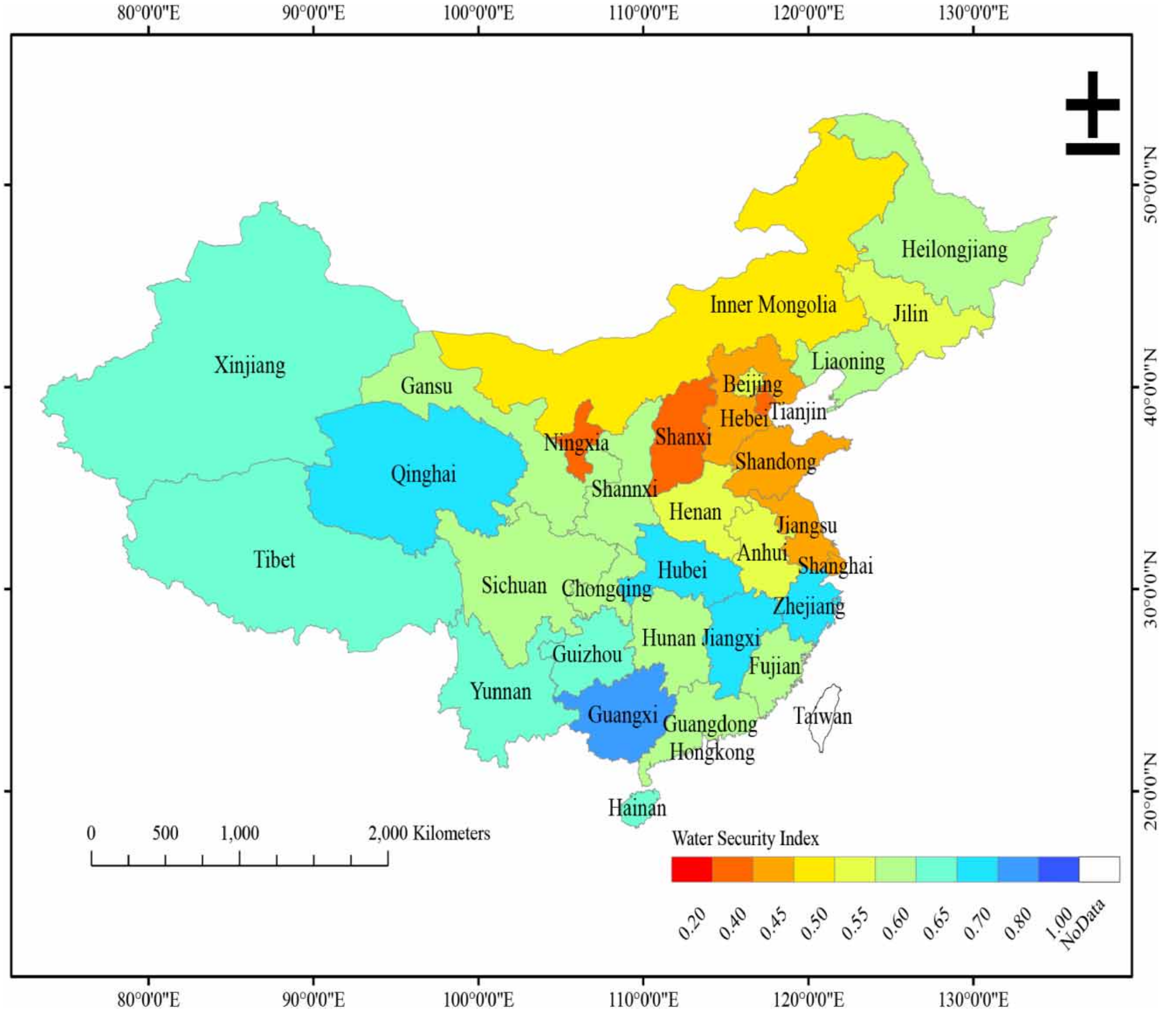

Figure 5 | Spatial distribution of annual average water security index in the study area from 2007 to 2016.

caused by the serious water pollution and eutrophication of lakes and reservoirs in these two areas. The ecological security index of Shanghai, Jiangsu and Ningxia varies between 0.2 and 0.4 and this indicates that the ecological security of these areas is at the general level. In addition, the ecological security index of the remaining areas is more than 0.5, which indicates that the ecological security of these areas is at a relatively high level. In general, since the release of the Water Pollution Control Action Plan by the State Council in April 2015, the water ecological security situation in the study area has been improved, and the water ecological environment protection has been strengthened (Liu *et al.* 2018b). In order to ensure the sustainable and healthy development of ecological security in the study area, the relevant departments of environmental protection need to formulate effective measures to reduce the total amount of pollutants, control the movement rate of pollutants, improve the efficiency of sewage treatment, realize the comprehensive treatment of major rivers, and improve the ecological security early warning system.

Characteristics of water security in the study area

Table 5 shows the average value of the water security index (*WSI*) for each administrative region in the study area from 2007 to 2016, which was obtained from *FS*, *RS* and *ES*. Based on Table 5, the spatial distribution of the annual average water security index in the study area from 2007 to 2016

Table 5 | Average values of water security index in the study area from 2007 to 2016

Region	FS	RS	ES	WSI	Security level
Beijing	0.4258	0.2630	0.9124	0.5337	Generally safe
Tianjin	0.4737	0.2303	0.0648	0.2563	Relatively unsafe
Hebei	0.5344	0.2496	0.4286	0.4042	Generally safe
Shanxi	0.5636	0.2602	0.1901	0.3380	Relatively unsafe
Inner Mongolia	0.4797	0.4434	0.5264	0.4832	Generally safe
Liaoning	0.4629	0.4273	0.7723	0.5541	Generally safe
Jilin	0.5137	0.5531	0.5654	0.5441	Generally safe
Heilongjiang	0.6020	0.5050	0.5521	0.5530	Generally safe
Shanghai	0.6145	0.2603	0.3384	0.4044	Generally safe
Jiangsu	0.7709	0.3051	0.2661	0.4474	Generally safe
Zhejiang	0.6285	0.5490	0.8194	0.6656	Relatively safe
Anhui	0.5813	0.4141	0.5838	0.5264	Generally safe
Fujian	0.5303	0.4938	0.7738	0.5993	Relatively safe
Jiangxi	0.5549	0.5100	0.9690	0.6780	Relatively safe
Shandong	0.6385	0.2345	0.4646	0.4459	Generally safe
Henan	0.6406	0.2990	0.5946	0.5114	Generally safe
Hubei	0.5494	0.6572	0.7967	0.6678	Relatively safe
Hunan	0.5369	0.5056	0.6945	0.5790	Generally safe
Guangdong	0.5410	0.4476	0.7643	0.5843	Generally safe
Guangxi	0.5634	0.6343	0.9795	0.7257	Relatively safe
Hainan	0.5750	0.5313	0.8141	0.6402	Relatively safe
Chongqing	0.5246	0.4268	0.7020	0.5511	Generally safe
Sichuan	0.5253	0.4364	0.7823	0.5813	Generally safe
Guizhou	0.5197	0.5030	0.9118	0.6448	Relatively safe
Yunnan	0.4712	0.6399	0.7716	0.6276	Relatively safe
Tibet	0.4661	0.4622	0.9974	0.6419	Relatively safe
Shaanxi	0.4707	0.3364	0.8550	0.5540	Generally safe
Gansu	0.4929	0.3148	0.8832	0.5636	Generally safe
Qinghai	0.4088	0.6879	0.9875	0.6947	Relatively safe
Ningxia	0.4464	0.2363	0.2597	0.3141	Relatively unsafe
Xinjiang	0.4088	0.5131	0.9984	0.6401	Relatively safe

was obtained (Figure 5). The results show that the water security index of Guangxi is the highest among all administrative regions in the study area ($WSI = 0.7257$), which indicates that the water security in this area is in a safe state. The water security indexes of Zhejiang, Jiangxi, Hubei, Hainan, Guizhou, Yunnan, Tibet, Qinghai and Xinjiang vary from 0.6 to 0.8, which indicates that these areas are in a relatively safe state, while the water security indexes of Tianjin, Hebei, Shanxi and Ningxia are less than 0.4, which indicates that the water security of these regions is in an unsafe state. This is mainly due to the low level of resource security and ecological security in Tianjin, Hebei, Shanxi and Ningxia, which may be caused by the serious water shortage and low control rate of ecological water functional areas in these areas.

To sum up, the northern part of the study area (Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia) suffers from serious water shortage, and the water quality of lakes and reservoirs is poor, which is reflected by the lower resource security index and ecological security index in these areas. The above problems are the main reasons for the unsafe water security in these areas. The northeast of the study area (Heilongjiang, Jilin and Liaoning) is relatively balanced in flood control security, resource security and ecological security, which leads to the overall high-water security index in these areas, and the water security is in a general state of security. The east part of the study area (Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Shanxi and Shandong) has strong flood control capacity and a high-water security index. However, the resource security level and ecological security level of Shanghai and Jiangsu are relatively low. The water security indexes of the central regions (Henan, Hubei and Hunan) in the study area are similar to that of the eastern regions. Henan is the most populous area in the study area, which leads to the most serious problem of resource shortage. The south (Guangdong, Guangxi, Hainan) and southwest (Chongqing, Sichuan, Guizhou, Yunnan, Tibet) of the study area have a high water security index, and the lakes, rivers and reservoirs in these areas have good water quality. The water security situation in the northwest of the study area (Shaanxi, Ningxia, Gansu, Qinghai, Xinjiang) is generally good. However, Ningxia is facing relatively unsafe water resources and environmental conditions, which need more attention. The above conclusions are consistent with the published articles (Liu *et al.* 2018b; Wang *et al.* 2019c; Zhao *et al.* 2019), which indicates that the water security evaluation model proposed in this paper has scientific and reliable application value.

CONCLUSIONS

Based on flood control security, resource security and ecological security, which can comprehensively reflect the water security situation, this paper establishes the corresponding security indexes, and uses the coupling coordination model and state space model to organically combine these security indexes, and constructs a water security comprehensive evaluation model. The proposed model is used to study the flood control security, resource security and ecological security of each administrative region in 2007–2016 in China. The water security level of each administrative region in the study area is characterized according to the above-mentioned security and the water security issues between each region are analyzed and compared by using the water security level. The results show that, in terms of flood control security, except for the relative security of Heilongjiang, Shandong, Henan, Jiangsu, Shanghai, Zhejiang, the flood control security capacity of other administrative regions needs to be further improved. In terms of resource security, Beijing, Tianjin, Hebei, Shanxi, Shaanxi, Gansu and Ningxia have a relatively low level of resource security due to their low resource base conditions, these areas need to improve the efficiency of resource utilization and establish a sound resource security system. In addition, the uncoordinated level of resources, population and economic development in Shanghai, Jiangsu, Shandong and Henan also leads to the relatively low level of resource security, these areas need to establish appropriate resource optimization allocation programs to improve the coordination between social and economic development and resource utilization. In terms of ecological security, the level of ecological security in Tianjin, Shanxi, Shanghai, Jiangsu and Ningxia is relatively low, so it is urgent to strengthen the restoration and protection of ecological water environment in these areas. Compared with the traditional water security evaluation system, which needs multi-layer design, a complex calculation method and different evaluation indexes, the water safety evaluation model proposed in this paper has clear theory, simple structure, easy interpretation, strong robustness, and good promotion and application.

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REFERENCES

Awan, U. K., Liaqat, U. W., Choi, M. & Ismaeel, A. 2016 A SWAT modeling approach to assess the impact of climate change on consumptive water use in Lower Chenab Canal area of Indus basin. *Hydrol. Res.* **47**, 1025–1037.

Biswas, A. K. 1999 Water crisis – current perceptions and future realities. *Water Int.* **24**, 363–367.

Cheng, K., Yao, J. & Ren, Y. 2019 Evaluation of the coordinated development of regional water resource systems based on a dynamic coupling coordination model. *Water Sci. Technol. Water Supply* **19**, 565–573.

Dong, Q. & Xia, L. 2014 Risk assessment of water security in Haihe River Basin during drought periods based on D-S evidence theory. *Water Sci. Eng.* **7**, 119–132.

Emam, A. R., Kappas, M. & Hosseini, S. Z. 2015 Assessing the impact of climate change on water resources, crop production and land degradation in a semi-arid river basin. *Hydrol. Res.* **46**, 854–870.

Falkenmark, M. 2002 Water security for the 21st century – Building bridges through dialogue. In: Proceedings of the 11th Stockholm Water Symposium, Stockholm, Sweden, 13–16 August 2001. *Water Sci. Technol.* **45**, VII–VIII.

Falkenmark, M. & Lundqvist, J. 2009 Towards water security: political determination and human adaptation crucial. *Econ. Water Resour.* **2**, 489–503.

Fang, Q., Wang, G., Liu, T., Xue, B.-L. & Yinglan, A. 2018a Controls of carbon flux in a semi-arid grassland ecosystem experiencing wetland loss: vegetation patterns and environmental variables. *Agric. For. Meteorol.* **259**, 196–210.

Fang, Q., Wang, G., Xue, B., Liu, T. & Kiem, A. 2018b How and to what extent does precipitation on multi-temporal scales and soil moisture at different depths determine carbon flux responses in a water-limited grassland ecosystem? *Sci. Total Environ.* **635**, 1255–1266.

Gain, A. K., Giupponi, C. & Wada, Y. 2016 Measuring global water security towards sustainable development goals. *Environ. Res. Lett.* **11**, 124015.

Han, D., Wang, G., Liu, T., Xue, B.-L., Kuczera, G. & Xu, X. 2018 Hydroclimatic response of evapotranspiration partitioning to prolonged droughts in semiarid grassland. *J. Hydrol.* **563**, 766–777.

Harris, J. M. & Kennedy, S. 1999 Carrying capacity in agriculture: global and regional issues. *Ecol. Econ.* **29**, 443–461.

Jiang, Y. 2015 China's water security: current status, emerging challenges and future prospects. *Environ. Sci. Policy* **54**, 106–125.

Kawada, Y., Nakamura, Y. & Otani, S. 2019 An axiomatic foundation of the multiplicative human development index. *Rev. Income Wealth* **65**, 771–784.

Kumar, P. 2015 Hydrocomplexity: addressing water security and emergent environmental risks. *Water Resour. Res.* **51**, 5827–5838.

Larson, R. B. 2017 Water security. *Northwest. Univ. Law Rev.* **112**, 139–200.

Ledingham, J., Archer, D., Lewis, E., Fowler, H. & Kilsby, C. 2019 Contrasting seasonality of storm rainfall and flood runoff in the UK and some implications for rainfall-runoff methods of flood estimation. *Hydrol. Res.* **50**, 1309–1323.

Li, J., Guan, X., Wang, G. & Jiang, H. 2016 Assessment on agricultural non-point source pollution in a drinking water source using remote sensing images. *Chin. J. Ecol.* **35**, 3382–3392.

Li, W., Yao, Y. & Shekhar, D. K. 2019 State-space model for transient behavior of membrane-based liquid desiccant dehumidifier. *Int. J. Heat Mass Transfer* **144**, 118711.

Liu, F., Song, X., Yang, L., Han, D., Zhang, Y., Ma, Y. & Bu, H. 2018a Predicting the impact of heavy groundwater pumping on groundwater and ecological environment in the Subei Lake basin, Ordos energy base, Northwestern China. *Hydrol. Res.* **49**, 1156–1171.

Liu, H., Jia, Y., Niu, C., Gan, Y. & Xu, F. 2018b Evaluation of regional water security in China based on dualistic water cycle theory. *Water Policy* **20**, 510–529.

Masseroni, D., Ercolani, G., Chiaradia, E. A. & Gandolfi, C. 2019 A procedure for designing natural water retention measures in new development areas under hydraulic-hydrologic invariance constraints. *Hydrol. Res.* **50**, 1293–1308.

Norman, E. S., Dunn, G., Bakker, K., Allen, D. M. & de Albuquerque, R. C. 2013 Water security assessment: integrating governance and freshwater indicators. *Water Resour. Manage.* **27**, 535–551.

Ou, B., Fu, S., Wang, Y. & Wang, L. 2012 The comprehensive evaluation of rural drinking water security in Yunnan Province. In: *2012 International Conference on Structural Computation And Geotechnical Mechanics* (P. Yang & X. Jiang, eds). People's Republic of China, Kunming, pp. 155–158.

Parry, S., Hannaford, J., Lloyd-Hughes, B. & Prudhomme, C. 2012 Multi-year droughts in Europe: analysis of development and causes. *Hydrol. Res.* **43**, 689–706.

Ren, L., Li, Q. & Yuan, F. 2012 The hydrological cycle and water security in a changing environment in China. *Hydrol. Res.* **43**, 1–2.

Ren, Y., Yao, J., Xu, D. & Wang, J. 2017 A comprehensive evaluation of regional water safety systems based on a similarity cloud model. *Water Sci. Technol.* **76**, 594–604.

Rijsberman, M. A. & van de Ven, F. H. M. 2000 Different approaches to assessment of design and management of sustainable urban water systems. *Environ. Impact Assess. Rev.* **20**, 333–345.

Russo, T., Alfredo, K. & Fisher, J. 2014 Sustainable water management in urban, agricultural, and natural systems. *Water* **6**, 3934–3956.

Sullivan, C. 2002 Calculating a water poverty index. *World Dev.* **30**, 1195–1210.

Tian, J. & Gang, G. 2012 Research on regional ecological security assessment. In: *2012 International Conference on Future Energy, Environment And Materials* (G. Yang, ed.). Pt B. Hong Kong, People's Republic of China, pp. 1180–1186.

Wang, G., Hu, X., Zhu, Y., Jiang, H. & Wang, H. 2018 Historical accumulation and ecological risk assessment of heavy metals in sediments of a drinking water lake. *Environ. Sci. Pollut. Res.* **25**, 24,882–24,894.

Wang, G., Li, J., Sun, W., Xue, B., Yinglan, A. & Liu, T. 2019a Non-point source pollution risks in a drinking water protection zone based on remote sensing data embedded within a nutrient budget model. *Water Res.* **157**, 238–246.

Wang, P., Yao, J., Wang, G., Hao, F., Shrestha, S., Xue, B., Xie, G. & Peng, Y. 2019b Exploring the application of artificial intelligence technology for identification of water pollution characteristics and tracing the source of water quality pollutants. *Sci. Total Environ.* **693**, 133440.

Wang, Q., Liu, Y.-y., Zhang, Y.-z., Tong, L.-j., Li, X., Li, J.-l. & Sun, Z. 2019c Assessment of spatial agglomeration of agricultural drought disaster in China from 1978 to 2016. *Sci. Rep.* **9**, 14393.

Wilkinson, M. E. & Bathurst, J. C. 2018 A multi-scale nested experiment for understanding flood wave generation across four orders of magnitude of catchment area. *Hydrol. Res.* **49**, 597–615.

Yang, H., Wang, G., Wang, L. & Zheng, B. 2016 Impact of land use changes on water quality in headwaters of the Three Gorges Reservoir. *Environ. Sci. Pollut. Res.* **23**, 11,448–11,460.

Yao, J., Wang, G., Xue, B., Wang, P., Hao, F., Xie, G. & Peng, Y. 2019a Assessment of lake eutrophication using a novel multidimensional similarity cloud model. *J. Environ. Manage.* **248**, 109259.

Yao, J., Wang, G., Xue, W., Yao, Z. & Xue, B. 2019b Assessing the adaptability of water resources system in Shandong Province, China, using a novel comprehensive co-evolution model. *Water Resour. Manage.* **33**, 657–675.

Yao, J., Wang, P., Wang, G., Shrestha, S., Xue, B. & Sun, W. 2019c Establishing a time series trend structure model to mine potential hydrological information from hydrometeorological time series data. *Sci. Total Environ.* **698**, 134227.

Zhang, Y., Wang, Y., Chen, Y., Liang, F. & Liu, H. 2019 Assessment of future flash flood inundations in coastal regions under climate change scenarios – a case study of Hadahe River basin in northeastern China. *Sci. Total Environ.* **693**, 133550.

Zhao, L., Gong, D., Zhao, W., Lin, L., Yang, W., Guo, W., Tang, X. & Li, Q. 2019 Spatial-temporal distribution characteristics and health risk assessment of heavy metals in surface water of the Three Gorges Reservoir, China. *Sci. Total Environ.* **704**, 134883.

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