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Evaluation of regional water security in China based on dualistic water cycle theory

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Abstract

Water security is the basis of sustainable human development. A new evaluation system of water security was established based on the natural–social dualistic water cycle theory, and then applied to characterize water security issues in China. At the national scale, the current state of water security was moderate, which was attributed to the improvement of water resource management level. However, it is still seriously inadequate in coordination of water use between ecological protection and socio-economic development, and wastewater treatment and reuse. Consequently, a resilient and integrated water management with adaptive capacity is needed. Moreover, the water security state in southern China was better than that in northern China, which was mainly attributed to the abundance of water resources in the south. Although the critical factors hindering water security were significantly different among China's 31 administrative regions, the low urban sewage reuse rate was a common factor, and irrigation efficiency was low in most parts of southern China. While in northern China, water resource overexploitation, polluted water quality and degraded aquatic ecosystems were common challenges. The results are consistent with the actual situations of China, and the related analysis can provide a reference for increasing regional water security.

Keywords: China; Critical factors; Dualistic water cycle theory; Water security

Introduction

As the source of life, water binds all living beings on this planet. Additionally, water is a main material basis and a principal guarantee for socio-economic growth and sustainable development. Consequently, water security is an important component of national security, and provides pivotal support for other securities related to food, economy and ecology security. With the increasingly intense human activities and

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climate change, a water security crisis, mainly including water scarcity, water pollution, flooding disaster, and overall water environment deterioration, has been widespread and become a bottleneck hampering sustainable development around the world. Vörösmarty *et al*. (2010) revealed that nearly 80% of the world's population was under serious threat from water scarcity. According to the data released by the World Water Week in Stockholm, 26–31 August 2012, 60% of the world's ecosystem services were deteriorating (Du *et al.,* 2014). In the European Union (EU), 40% of the surface water bodies and 30% of groundwater ones were identified as being at risk of failing the objectives of the Water Framework Directive 2000/60/EC (WFD) regarding protection of water resources by 2015. As many as 47% of EU citizens (in some countries figures reached 71%) identified that water pollution is the most worrying environmental issue (Kanakoudis & Tsitsifli, 2010). Currently, water security has assumed an increasingly prominent position in the international water and development community (Lautze & Manthrithilake, 2012).

As the most populous country in the world, China is endowed with only low water availability per capita at the national scale, less than a quarter of the average value in the world. Furthermore, the limited water resources are unevenly distributed in both space and time, which are inconsistent with the rising socio-economic need for water. In pace with rapid socio-economic development, the inefficient use, wastage, and pollution of water resources have been common problems in recent decades. Owing to the water resources characteristics and poor management mode of China, the increasingly severe water security crisis has been faced and it is regarded as a considerable challenge among the numerous environmental problems in China (Zuo *et al*., 2016). It's worth mentioning that severe conflicts exist between water supply and demand. Two-thirds of China's 669 cities suffered water shortages, and many were in an extremely serious situation (Liu & Yang, 2012). Excessive water resource division reduced instream flows in many rivers and caused negative impacts on aquatic ecosystems. In the Yellow River basin, the length of the main channel with no flow was 700 km from the downstream, a distance accounting for 90% of the river course in the lower reach. The Yellow River Delta is becoming more fragile and susceptible to natural hazards (Jiang, 2009). According to *China's 2015 State of the Environment Report*, approximately 35.5% of the state-controlled river sections distributed in 10 large river basins across China contained water graded Class IV, V or worse and deemed unsafe for human consumption. Only 9.1% of groundwater monitoring sites distributed in 202 cities had good water quality, while 61.3% were deemed poor or worse (Ministry of Environmental Protection of China, 2015). Statistics showed that 31 provinces (cities, districts) suffered from floods of different levels in 2013, affecting 120 million people and killing 774 people, which caused direct economic losses of 314.6 billion (10^9) RMB. On the whole, these growing water security issues have become major threats that restrain the socio-economic development of China. 'Humanity stands at a defining moment in history', as Agenda 21 noted, and this is highly applicable to water security issues facing the Chinese government. Just as Xi Jinping, China's president, has said, the water-control ideas of China need to change, and innovation is absolutely necessary to ensure water security. Aiming to provide basic information for decision making to solve water security issues, it is necessary to conduct an in-depth evaluation of the state of regional water security in China.

Due to the complexity of the concept and connotation of water security itself, there is no unified evaluation method. Considering the impact of water scarcity on human development, the Water Poverty Index (WPI) (Fu *et al*., 2008), Water Scarcity Index (IWS) (Falkenmark & Widstrand, 1992), and Water Resources Vulnerability Index (WRVI) (Raskin *et al*., 1997) have often been used to evaluate regional water security. Additionally, water security was seen as a system, and large groups of indicators were selected to measure the degree of water security. As discussed in Scott *et al*. (2013), water security was considered a societal-ecosystem-hydroclimatic (SEH) coupling system. Grigg (2016) proposed that water security meant having a secure water system, being safe from floods and droughts, and being protected from disruptions and sabotage. Moreover, several scholars identified evaluation indicators based on some other consideration, such as Pressure-State-Response framework, and the carbon and water footprint (Kanakoudis *et al.*, 2012; Sun *et al.*, 2016; Veettil & Mishra, 2016).

In China, the theory of 'dualistic water cycle' was proposed and received extensive attention and development (Lu *et al.*, 2016). In recent years, global climate change and the intensification of human activity have resulted in profound changes in water cycle processes and water resources, and have produced serious water problems. According to this theory, the main reason is that the driving force, structure, and parameters of the water cycle have dualistically evolved under the influence of human activities and consequently resulted in run-off reduction, water pollution, and degradation of natural ecosystems. The evolutionary mechanism of the water cycle and the accompanying water environment and eco-hydrology processes form the scientific basis underlying water problems. Therefore, the dualistic water cycle theory can be used to support effective solutions of these problems. Based on the dualistic water cycle theory, a number of studies have been carried out towards the assessment and management of water resources, water environment, and water ecology, as well as the development and application of relevant models (Jia *et al.*, 2006; Zhang *et al.*, 2015). The new Scientific Decade 2013-2022 of IAHS, entitled 'Panta Rhei – Everything Flows', is dedicated to research activities on change in hydrology and society (Montanari *et al.*, 2013). During this research stage, it is of great significance for a profound understanding of China's water security based on the dynamic change of the dualistic water cycle.

In addition, previous studies on water security evaluation in China mainly focused on municipal, regional and river-basin scales (Xia & Zhang, 2008; Yang *et al.*, 2012; Liu *et al.*, 2014). Few studies have conducted a comprehensive evaluation of regional water security in China, which has resulted in limited guidance on understanding and solving water security issues at country level. Because of the different characteristics of socio-economic development, water resources conditions, and water resources utilization patterns in different regions in China, the current states, issues, and causes of water security are significantly different.

In this paper, the relationship between water security and the dualistic water cycle theory was explored, and then the dualistic water cycle theory introduced to guide the establishment on a new evaluation system of regional water security. Based on the evaluation system, water security issues in China and its 31 provinces, autonomous regions, and municipalities (hereafter 'administrative regions') were evaluated, and the temporal and spatial variation, and critical factors of water security were analyzed. The results showed that water security issues and their critical factors vary in the 31 administrative regions and can reflect regional water resources characteristics, water management level and socio-economic conditions. The related analyses are helpful for a more scientific management and regulation of water resources towards improving water security in China.

Materials and methods

Study area and data

A nation-scale evaluation of the current state and change of water security facing China from 2006 to 2015 was conducted. The 31 administrative regions in mainland China (Figure 1) were defined as regional study units to further analyze the spatial allocation of water security throughout the country. Besides, the critical factors hindering the improvement of water security in China and its 31

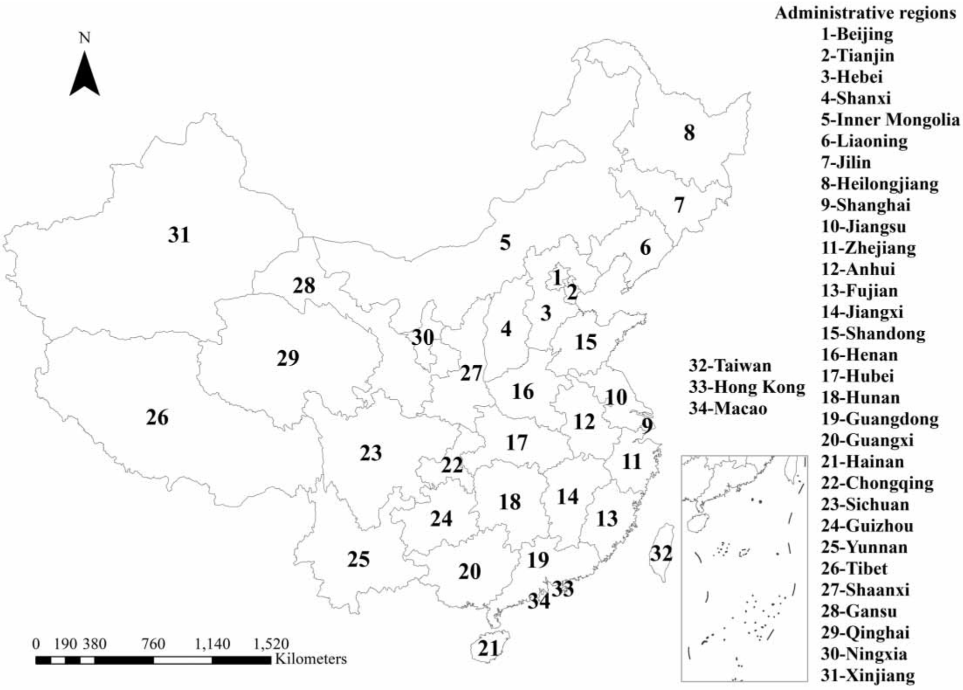

Fig. 1. Location of the 31 administrative regions of China.

administrative regions were identified. Taiwan, Hong Kong and Macao were not included in the study due to lack of related data. The dataset in this analysis related to the natural and social water cycle conditions and was obtained from China Water Resources Bulletin (MWR, 2006–2015), China Statistical Yearbook (NBS, 2006–2015), China Environmental Statistical Yearbook (MEP, 2006–2015), and Bulletin of Flood and Drought Disasters in China (State Flood Control and Drought Relief Headquarters, 2006–2015) during the period 2006–2015.

Evaluation indicator system based on dualistic water cycle theory

Dualistic water cycle theory. The socio-economic development process can be viewed as a gradual intervention of human beings on the natural water cycle. As the intervention increased in depth and breadth, the natural characteristics and processes of the water cycle have changed significantly, and the water cycle has evolved gradually from the dominant 'natural' unitary mode into the 'natural–social' dualistic coupled mode, known as the dualistic water cycle. Under the combined action of social system and water system, the driving force, cycle structures and cycle parameters of the water cycle have undergone a dualistic evolution effect (Qin *et al*., 2014).

On the one hand, unlike most other natural resources, water circulates naturally affected by solar radiation, gravity and other natural driving forces. When water evaporates, it changes from liquid to gas and eventually re-condenses as a liquid. This circulation allows water to be constantly recharged, and enables water and heat to be continuously redistributed over the world. Consequently, the natural water cycle supports and maintains water service functionality in resource, ecology, and environment. Unfortunately, water resources are limited and unevenly distributed in time and space, and the carrying capacity of a water environment and restoration ability of a water ecology are limited within a certain period of time. These properties are the internal causes of water insecurity. On the other hand, humans take water from nature, use it for their survival and production, and return it to the natural water system via drainage. Especially, the social water cycle mainly includes water taking, utilization, sewage treatment, reclamation and draining (Lu *et al.*, 2016). Due to the intense human activities, the cyclic processes are likely to be present in every aspect of the natural water cycle, and then greatly affect the quantity, quality and distribution pattern of water resources, the carrying capacity of water environment, and the restoration ability of water ecology. Finally, water service functionality in resource, ecology, and environment is significantly changed. If the change is negative, the risk of water insecurity will increase. Consequently, an unhealthy social water cycle is the external cause of water insecurity. Overall, the dualistic effect caused by the interaction between the natural water cycle and social water cycle is considered as the primary cause of water insecurity.

Evaluation indicator system for water security. According to the dualistic water cycle theory, water security can be understood as a healthy water cycle, including the natural water cycle and social water cycle, which harnesses the productive potential of water and limits its destructive impact. The natural water cycle determines the natural state of water security when there is no human activity or when human intervention is negligible. The social water cycle determines the intensity, depth and breadth of the transformation of the natural state of water security. This transformation may be positive or negative. In the case of water scarcity in arid regions, on the one hand, because of low precipitation, high temperature and evaporation, these regions are more prone to drought, even though the natural water cycle is dominant and not impeded by human activities. On the other hand, when the social water cycle is intense and unhealthy, water resources are excessively exploited and wasted, and then a water scarcity crisis becomes much more serious. In contrast, if a series of measures, such as reinforcing unified regulation of water resources, improving water use efficiencies, and intensifying inspection and supervision, are carried out to achieve a healthy social water cycle, the risk of water scarcity crisis will be greatly reduced. We can take the Haihe River basin as an example. The basin has a semi-arid and semi-humid climate with an average rainfall of 527 mm (1956–2007). The wet months (June–September) account for 75%–85% of the annual precipitation. Although human activity was much less intense previously than it is now in the agricultural economy stage, there have been many occasions of consecutive drought. Unfortunately, an unhealthy social water cycle has become dominant in recent decades. Currently, 4,000 km of the lower reaches of the Haihe River, which occupies 40% of the total length of the river, has experienced no flow, the area of wetland within the basin has decreased from 10,000 km^2 at the beginning of the 1950s to 1,000 km^2 at present, and over-extraction of groundwater has been estimated at about 90 billion m^3 (Xia *et al.*, 2007). As is evident, the imbalance between water demand and water supply is greatly aggravated as a result of an unhealthy social water cycle.

Based on the aforementioned analysis, regional water security is suggested to be reflective of two criteria: healthy natural water cycle and healthy social water cycle. A healthy natural water cycle can provide good water service functions in resource, ecology and environment, and a healthy social water cycle can harness the productive potential of water and limit its destructive impact. Consequently, the conditions of water resources, water environment, and water ecology were selected to characterize the natural water cycle. The water supply capacity, water utilization level, sewage treatment level, and flood control capacity were used to measure the healthiness of the social water cycle. Accordingly, some evaluation indicators that can effectively reflect these aspects were identified to quantitatively analyze the state of regional water security. To comparatively analyze water security issues of 31 administrative regions in China, these indicators were also selected according to some criteria, such as measurable, comparable, and acquirable. Finally, 26 basic indicators at the fourth layer in this study were obtained and further formed an evaluation indicator system for water security. The evaluation indicator system was divided into four layers comprising an object layer, a criterion layer, a classification layer, and an indicator layer (Table 1). Moreover, an explanation of all indicators is shown in Table 2.

It should be noted that although some indicators are only part of the natural water cycle or social water cycle, their security states are affected by both natural water cycle elements and social water cycle elements due to the interaction between the natural water cycle and social water cycle. For example, the river water quality satisfaction rate (X1201) reflects the water environment state in the

Table 1. Evaluation indicator system for water security.

Object layer	Criterion layer	Subsystem layer	Indicator layer	Unit
Regional water security	Healthy natural water cycle	Water resources	Water resources per capita (X1101)	m^3
			Precipitation (X1102)	mm
			Water production modulus (X1103)	10^4 m^3 km^{-2}
			Water resources utilization rate (X1104)	%
		Water environment	River water quality satisfaction rate (X1201)	%
			Fertilizer use per unit irrigated farmland area (X1202)	Kg hm^{-2}
			Chemical oxygen demand (COD) level in water (X1203)	g m^{-3}
			Ammonia-nitrogen level in water (X1204)	g m^{-3}
		Water ecology	Run-off depth (X1301)	%
			Ecological water requirement satisfaction rate (X1302)	%
			Wetland area proportion (X1303)	%
			Forest coverage (X1304)	%
	Healthy social water cycle	Water supply capacity	Water supply pipe length per capita (X2101)	m
			Water access rate (X2102)	%
			Area proportion of crop affected by drought (X2103)	%
			Population affected by drought (X2104)	%
			Effective irrigation area proportion (X2105)	%
		Water utilization level	Total water use per capita (X2201)	m^3
			Water use per 10,000 yuan of GDP (X2202)	m^3
			Effective utilization coefficient of irrigated water use (X2203)	–
			Water use per 10,000 yuan of added industrial output (X2204)	m^3
		Sewage treatment level	Sewage treatment proportion of GDP (X2301)	‰
			Urban sewage treatment rate (X2302)	%
			Urban sewage reuse rate (X2303)	%
		Flood control capacity	Economic loss caused by floods (X2401)	‰
			Population affected by floods (X2402)	%

Table 2. Explanation of evaluation indicators for water security.

Evaluation indicators	Calculation methods	Indicator direction
Water resources per capita (X1101)	Total water resources/total population	Positive
Precipitation (X1102)	Obtained from the water resources bulletin	Positive
Water production modulus (X1103)	Total water resources/total land area	Positive
Water resources utilization rate (X1104)	Total water use/total water resources	Negative
River water quality satisfaction rate (X1201)	Percentage of monitoring river sections with water quality better than Class III (including Class III)[a]	Positive
Fertilizer use per unit irrigated farmland area (X1202)	Fertilizer use/total irrigated farmland area	Negative
Chemical oxygen demand (COD) level in water (X1203)	COD discharge amount/total water resources	Negative
Ammonia-nitrogen level in water (X1204)	Ammonia-nitrogen discharge amount/total water resources	Negative
Run-off depth (X1301)	The depth of the water obtained by spreading the total run-off evenly over the whole basin area within a certain period	Positive
Ecological water requirement satisfaction rate (X1302)	Ecological water usage/total water resources	Positive
Wetland area proportion (X1303)	Wetland area/total land area	Positive
Forest coverage (X1304)	Forested land area/total land area	Positive
Water supply pipe length per capita (X2101)	Urban water supply pipe length/total urban population	Positive
Water access rate (X2102)	Population with access to tap water/total population	Positive
Area proportion of crop affected by drought (X2103)	Crop area affected by drought/total farmland area	Negative
Population affected by drought (X2104)	Population affected by drought/total population	Negative
Effective irrigation area proportion (X2105)	Effective irrigated farmland area/total farmland area	Positive
Total water use per capita (X2201)	Total water use/total population	Negative
Water use per 10,000 yuan of GDP (X2202)	Total water use/gross domestic product	Negative
Effective utilization coefficient of irrigated water use (X2203)	Obtained from the water resources bulletin	Positive
Water use per 10,000 yuan of added industrial output (X2204)	Industrial water use/added industrial output value	Negative
Sewage treatment proportion of GDP (X2301)	Sewage treatment investment/gross domestic product	Positive
Urban sewage treatment rate (X2302)	Urban sewage treated/sewage discharged	Positive
Urban sewage reuse rate (X2303)	Urban sewage reused/sewage discharged	Positive
Economic loss caused by floods (X2401)	Direct economic losses caused by floods/gross domestic product	Negative
Population affected by floods (X2402)	Population affected by floods/total population	Negative

[a]Class III in the national water quality standard of China. Water quality better than Class III (including Class III) mainly requires: dissolved oxygen ≥ 5 mg L^{-1}, COD ≤ 20 mg L^{-1}, $BOD_5 \leq 4$ mg L^{-1}, ammonia nitrogen ≤ 1.0 mg L^{-1}.

natural water cycle, but it is also affected by the sewage treatment rate in the social water cycle. Moreover, population affected by drought (X2104) reflects the water supply capacity in the social water cycle, but it is also affected by precipitation in the natural water cycle.

Quantitative methods of regional water security

Security degree calculation of indicators. Each indicator has its security degree (*ISD*) with a range [0,1]. *ISD* of the positive indicator increases with increasing indicator value, while *ISD* of the negative indicator decreases with increasing indicator value (Figure 2). The analytical method of piecewise linear membership functions was used to quantitatively describe the security degree of a single indicator. According to Zuo *et al.* (2014), five representative values for each indicator, consisting of worst value (*a*), poor value (*b*), passing value (*c*), better value (*d*), and optimal value (*e*), should be determined. In this paper, these values were initially determined based on the maximum, mean and minimum value of each indicator during the evaluation period, and then revised by consulting seven water-related experts and using the existing research results. The results are shown in Table 3. Then, Equations (1) and (2) were used to calculate *ISD* of the positive indicator and negative indicator, respectively,

$$ISDk = \begin{cases} 0 & xk \leq ak \\ 0.3\left(\dfrac{xk - ak}{bk - ak}\right) & ak < xk \leq bk \\ 0.3 + 0.3\left(\dfrac{xk - bk}{ck - bk}\right) & bk < xk \leq ck \\ 0.6 + 0.2\left(\dfrac{xk - ck}{dk - ck}\right) & ck < xk \leq dk \\ 0.8 + 0.2\left(\dfrac{xk - dk}{ek - dk}\right) & dk < xk \leq ek \\ 1 & ek < xk \end{cases} \quad (1)$$

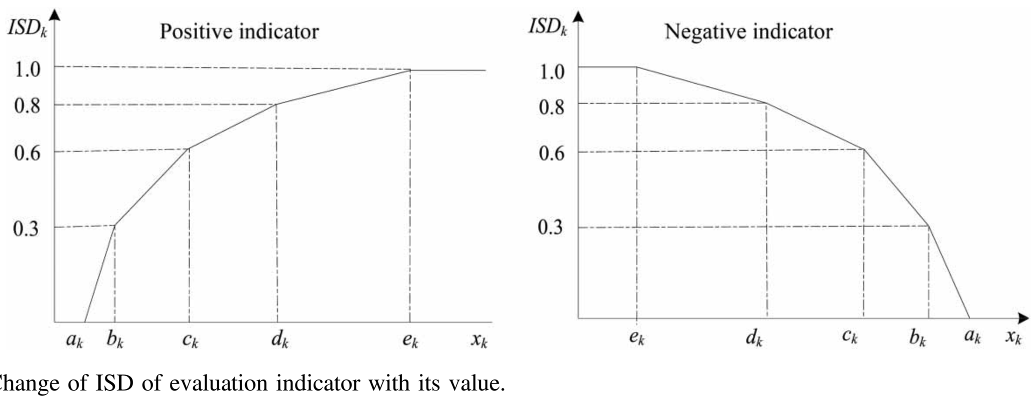

Fig. 2. Change of ISD of evaluation indicator with its value.

Table 3. Representative values and weights of evaluation indicator for water security in China.

Evaluation indicators	*a*	*b*	*c*	*d*	*e*	$w_{i,k}$[a]
X1101	300	700	1,700	2,500	3,000	0.25
X1102	100	500	1,000	1,500	2,000	0.25
X1103	0	30	60	100	140	0.25
X1104	100	70	40	20	0	0.25
X1201	0	30	60	80	100	0.3
X1202	2,000	1,500	900	500	200	0.3
X1203	50	20	6	3	0	0.2
X1204	10	3	0.8	0.3	0	0.2
X1301	0	200	400	800	1,200	0.2
X1302	0	2	4	10	16	0.3
X1303	0	4	8	11	15	0.3
X1304	0	15	25	40	50	0.2
X2101	0	0.4	0.9	1.4	1.8	0.25
X2102	70	80	90	95	100	0.25
X2103	10	7	4	2	0	0.15
X2104	50	30	15	7	0	0.15
X2105	15	30	50	80	100	0.2
X2201	1,800	1,200	600	400	160	0.25
X2202	600	350	120	60	15	0.25
X2203	0.30	0.40	0.50	0.65	0.80	0.25
X2204	400	250	90	40	6	0.25
X2301	0	0.3	0.6	1.5	2	0.3
X2302	0	30	60	80	100	0.4
X2303	0	5	30	45	60	0.3
X2401	20	10	4	2	0	0.5
X2402	25	15	5	3	0	0.5

[a]Subscript *i* represents the *i*-th subsystem, and $w_{i,k}$ represents the weight of the *k*-th indicator in the *i*-th subsystem. In each of subsystem layers, the sum of the weights of indicators is equal to 1.

$$ISDk = \begin{cases} 1 & xk \leq ek \\ 0.8 + 0.2\left(\dfrac{dk - xk}{dk - ek}\right) & ek < xk \leq dk \\ 0.6 + 0.2\left(\dfrac{ck - xk}{ck - dk}\right) & dk < xk \leq ck \\ 0.3 + 0.3\left(\dfrac{bk - xk}{bk - ck}\right) & ck < xk \leq bk \\ 0.3\left(\dfrac{ak - xk}{ak - bk}\right) & bk < xk \leq ak \\ 0 & ak < xk \end{cases} \quad (2)$$

where x_k is the actual value of the *k*-th indicator, and ISD_k is the security degree of the *k*-th indicator.

Calculation of regional water security degree. The weighted sum of *ISD* of the various evaluation indicators was used to calculate regional water security degree (*WSD*). First, in each of seven subsystem layers, the weight of the indicators was determined (Table 3) based on the importance of each indicator. Then, the security degrees of seven subsystems including water resources, water environment, water ecology, water supply capacity, water utilization level, sewage treatment level, and flood control capacity were expressed as *WRSD*, *WESD*, *WYSD*, *WSSD*, *WUSD*, *STSD*, and *FCSD*, respectively and calculated using the following equations:

$$SD_i = \sum_{k=1}^{n_i} w_{k,i} ISD_{k,i} \tag{3}$$

where for $i = 1,2\ldots,7$, SD_i represents *WRSD*, *WESD*, *WYSD*, *WSSD*, *WUSD*, *STSD*, and *FCSD*, respectively, and n_i are the number of indicators in the i-th subsystem layer.

Based on the security degree of the seven subsystems, the health degrees of the natural water cycle and social water cycle were calculated as follows:

$$NHD = \alpha_1 WYSD + \alpha_2 WESD + \alpha_3 WYSD \tag{4}$$

$$SHD = \beta_1 WSSD + \beta_2 WUSD + \beta_3 STSD + \beta_4 FCSD \tag{5}$$

where *NHD* and *SHD* represent the health degree of the natural water cycle and social water cycle, respectively. Reflecting the equal importance of each subsystem for regional water security, the weights were defined as $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$, $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 1/4$.

Finally, regional water security degree, which contained both health natural water cycle and health social water cycle, was calculated as follows:

$$WSD = \sqrt{NHD \bullet SHD} \tag{6}$$

where *WSD* is the regional water security degree with a range [0,1], and water security level increases with the increasing *WSD* values.

According to the values of *WSD*, the degree of regional water security was divided into seven grades by an equal interval of 0.143: very low, low, general low, moderate, general high, high, and very high.

Results and discussion

Current state analysis of regional water security in China

Considering the effect of dramatic inter-annual variability of some evaluation indicators, it is unsatisfactory to analyze the current state of regional water security in China based only on the evaluation results of 2015. Accordingly, the average of the 2013–2015 evaluation results of water security was used to comparatively analyze current states of water security in China and its 31 administrative regions in this paper, as shown in Figures 3–5.

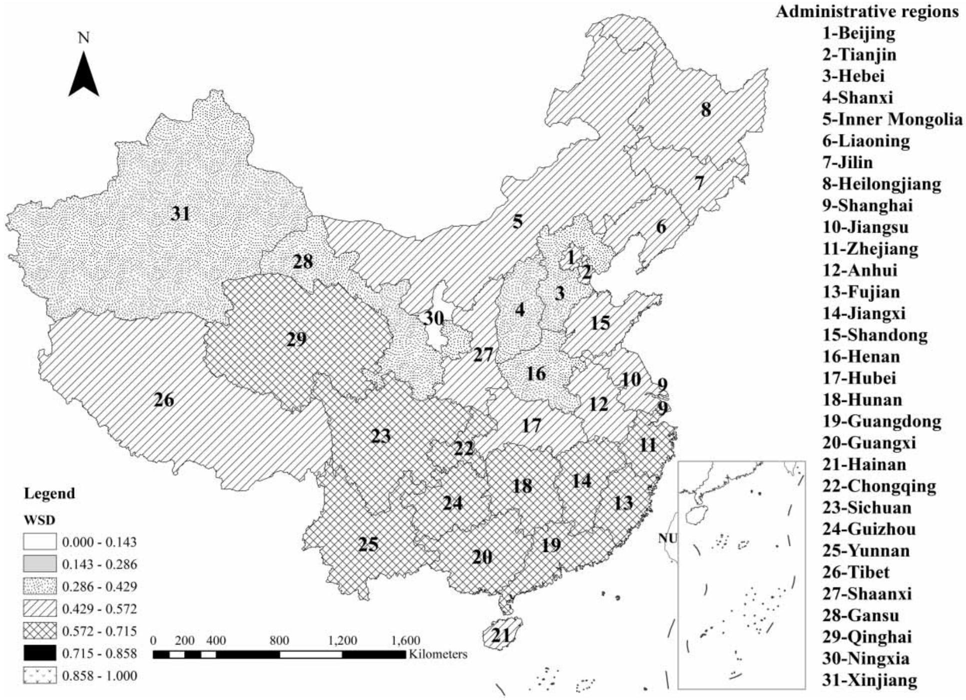

Fig. 3. Average water security degrees in the 31 administrative regions from 2013 to 2015.

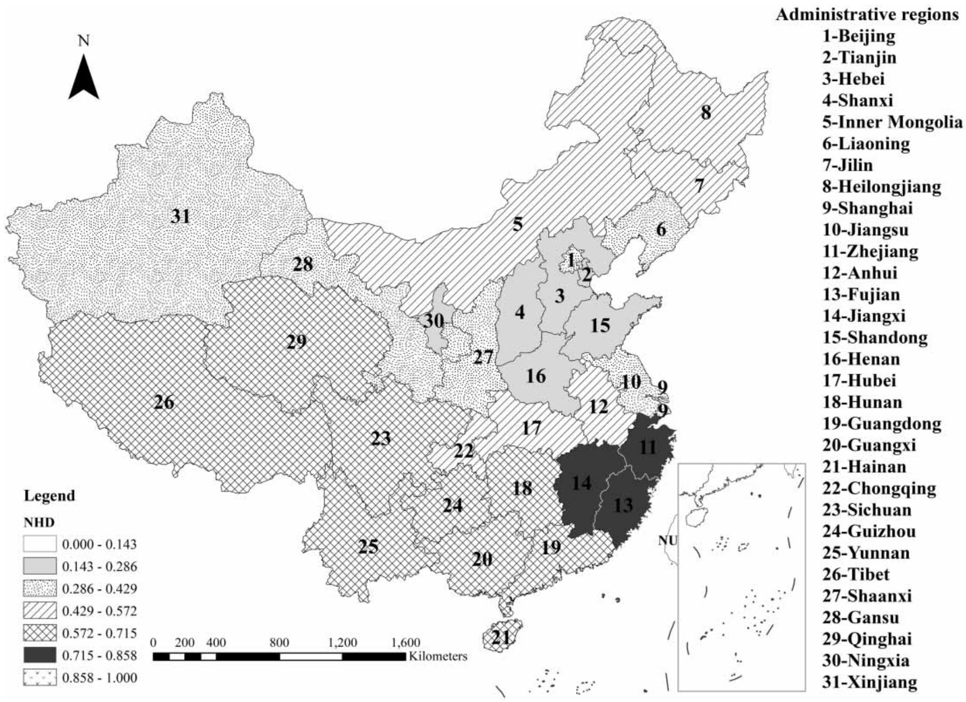

Fig. 4. Average health conditions of natural water cycle in the 31 administrative regions from 2013 to 2015.

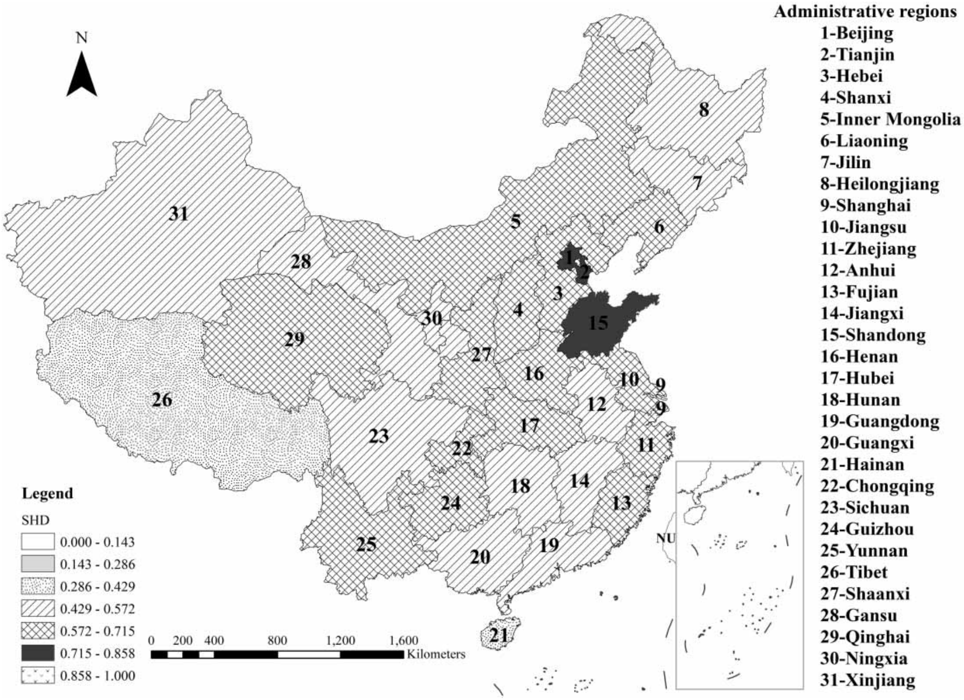

Fig. 5. Average health conditions of social water cycle in the 31 administrative regions from 2013 to 2015.

At the national scale, the water security degree was 0.558, which indicated that the current state of water security in China was moderate. However, considering China's rapid urbanization and population growth, the current water security was fragile, and more efforts need to be made to achieve a higher level of water security. The health condition of the social water cycle (0.625) in China was better than that of the natural water cycle (0.499). The health condition of the social water cycle was relatively acceptable and made a more positive contribution to water security. The security degree of the water supply capacity and water utilization level reached a value of 0.7, and the security degree of flood control capacity was nearly 0.6. The good water supply capacity, water utilization level, and flood control capacity contributed to the healthy social water cycle. However, the security degree of sewage treatment level was low, which was the main aspect that hindered the health of the social water cycle, and that threatened water security. In contrast to the relatively healthy social water cycle, the natural water cycle was in an inadequate health condition, which was mainly due to poor water ecology (0.350).

Furthermore, the current states of water security in the 31 administrative regions were comprehensively analyzed. It may be seen that the current state of water security in southern China was generally better than that in northern China. The health condition of the natural water cycle was best in southern China, moderate in northeastern China, and worst in central and northwestern China. This phenomenon is consistent with the distribution characteristics of water resources in China. Generally, the regions in northern China had the best social water cycle, followed by southern China, and the condition was worst in northwestern China and Tibet. The result reflects the efforts made for the efficient management of water resources in different regions. Compared to northern China, southern China had lower water utilization level and sewage treatment level, and faced more serious flood disasters. The water resources management level was poor in northwestern China and Tibet.

From the point of view of the administrative regions, a better understanding can be obtained about the spatial differences in the current states of water security.

The water security degrees of Zhejiang, Fujian, Jiangxi, Guangdong, Yunnan, Guizhou, and Qinghai were larger than 0.6, and Zhejiang had the best value (0.681). Qinghai is known by reputation as an 'ecological source' and a 'Chinese water tower', so its environmental protection has always been given full attention. Consequently, its natural water cycle and social water cycle were relatively healthy. The remaining regions are located in southern China, and characterized by a well-developed social economy and good natural environment. The health degrees of the natural water cycle and social water cycle in these regions were larger than 0.6 and 0.5, respectively.

Ningxia, Gansu, Xinjiang, Shanxi, Henan, and Hebei, in central and northwestern China, had a general low water security state. Rainfall is low and unevenly distributed, the natural environment is fragile, and human actives are intense. Thus, the natural water cycle has been severely damaged.

The water security degree of the remaining 18 regions was in the range of 0.45 to 0.60, which indicated that the water security state in these regions was moderate. Taking into account the health conditions of the natural water cycle and social water cycle, water security in these regions could be further analyzed from three aspects. First, for Beijing, Tianjin, Inner Mongolia, Liaoning, Jilin, Shanghai, Jiangsu, Shandong, and Shaanxi, the health condition of the social water cycle was much better than that of the natural water cycle. Second, for Hainan, Tibet, Guangxi, and Hunan, the health condition of the natural water cycle was much better than that of the social water cycle. Third, for Heilongjiang, Anhui, Hubei, Chongqing, and Sichuan, the health condition of the natural water cycle was nearly equal to that of the social water cycle.

Change analysis of regional water security in China

At the national scale, the evaluation results of water security in China from 2006 to 2015 are shown in Figures 6 and 7. The water security degree increased from 0.516 to 0.581 during the evaluation period. It can be seen that the water security state in China was slowly improving, but is still at a moderate level.

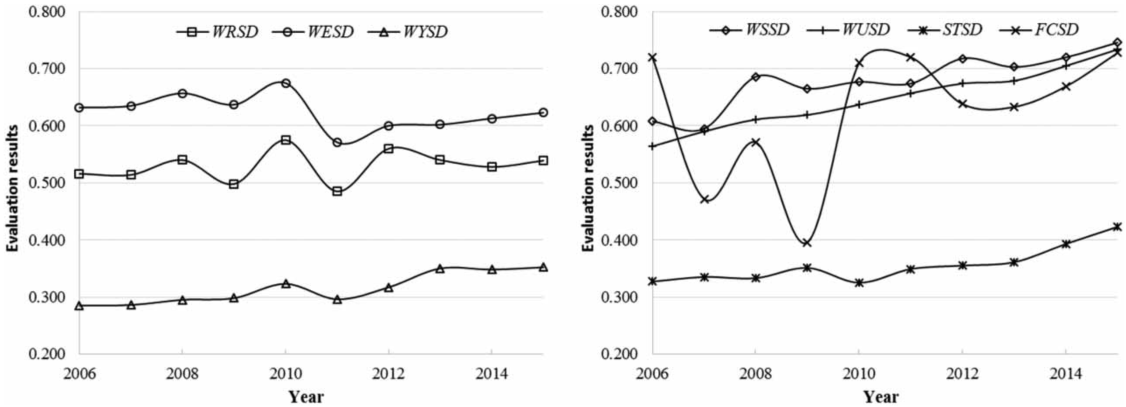

Fig. 6. Change of security degree of the seven subsystems in China from 2006 to 2015.

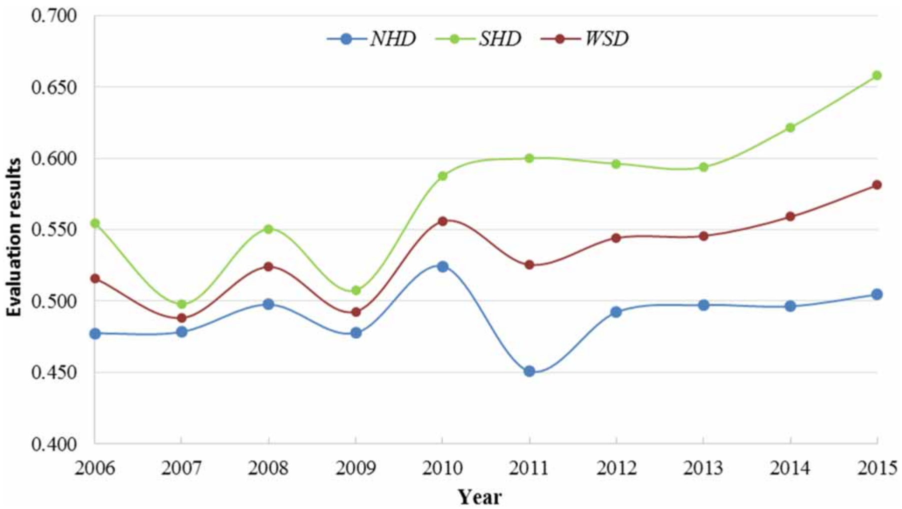

Fig. 7. Change of *NHD, SHD,* and *WSD* in China from 2006 to 2015.

Furthermore, the health degree of the natural water cycle had been staying at a low level, mainly due to the poor natural characteristics of water resources in China. The health condition of the natural water cycle was worst in 2011. The reason may be that southern China suffered a severe drought in 2011, and precipitation, run-off depth, and water resources per capita in China were the lowest during the evaluation period. The poor health condition of the natural water cycle in these years hindered the improvement of the water security state in China. In contrast, the health degree of the social water cycle experienced a significant increase. From 2006 to 2015, water use per 10,000 yuan of GDP was reduced from 270 to 90 m^3, irrigation efficiency was raised from 0.38 to 0.54, water use per 10,000 yuan of added industrial output was reduced from 147 to 58 m^3, and industrial wastewater and COD discharges have been steadily declining. There was a steady improvement in water supply capacity, water utilization level, and sewage treatment level, but not in flood control capacity. This indicated that the water resource planning and regulation measures implemented by the Chinese government had made a positive impact. As flood control capacity decreased sharply in 2007 and 2009, the health condition of the social water cycle deteriorated, and eventually caused the decreased water security state. In general, owing to poor water resources characteristics, improving China's water security relies heavily on a healthy social water cycle. Moreover, due to the interaction between the social water cycle and natural water cycle, the improvement of the social water cycle has a positive effect on the natural water cycle. There is a strong possibility that China's economic expansion and corresponding high rates of urbanization will continue for a period of time, during which improving the water supply capacity, water utilization level, sewage treatment level, and flood control capacity, especially the sewage treatment level, should be a priority.

In addition, the changes in water security states in the 31 administrative regions from 2006 to 2015 were determined (Figure 8). Except for Hainan and Xinjiang, the water security states in other regions increased but at different rates. The average annual rate of increase was in the range of 0.1% to 4.5%, of which the largest was in Ningxia. Generally, the growth rate in southern China was higher than that in northern China. Moreover, for some regions in northern China, such as Ningxia, Gansu, and Xinjiang,

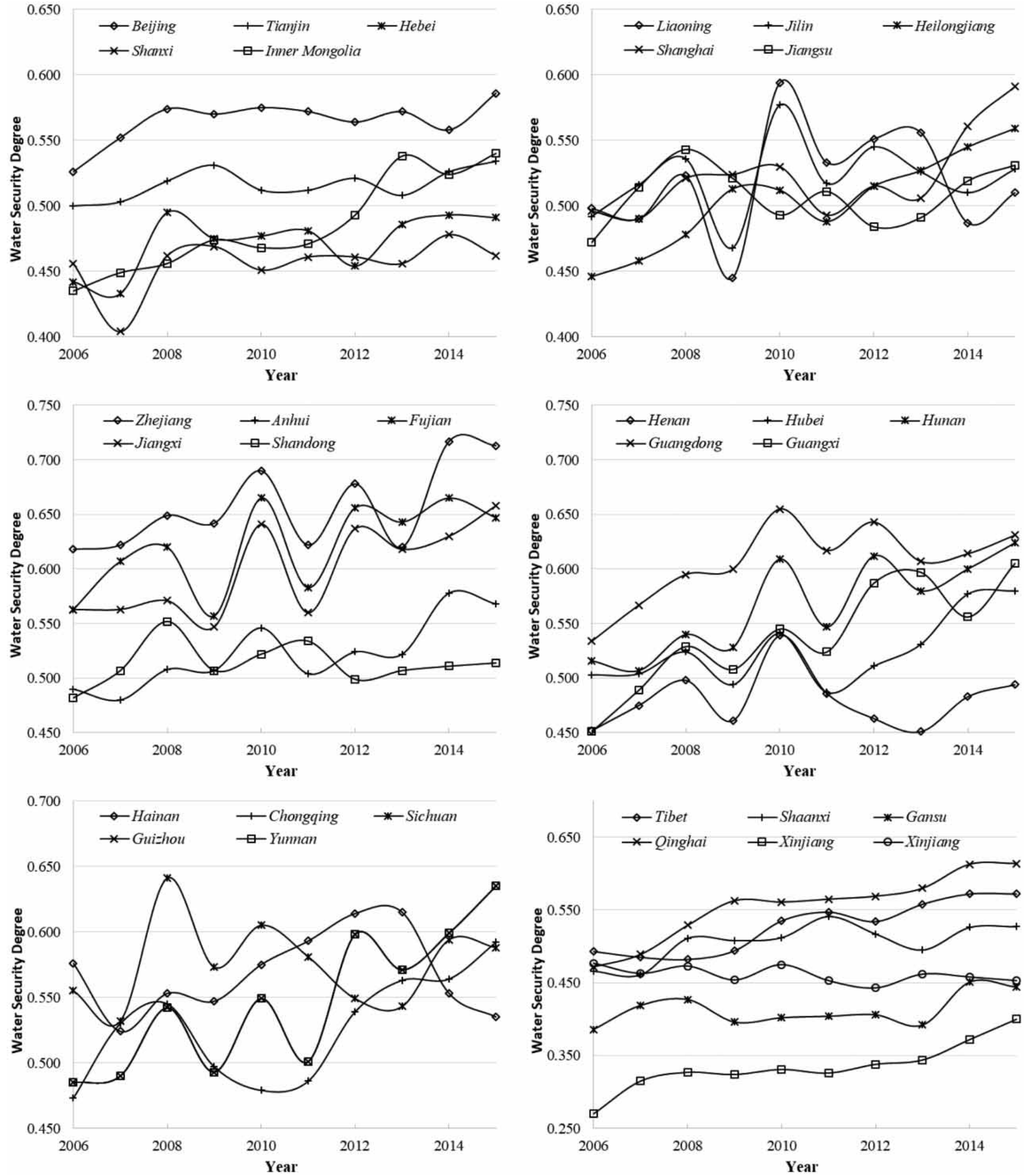

Fig. 8. Change of *WSD* in 31 administrative regions from 2006 to 2015.

the water security had remained in a poor situation during the evaluation period. In contrast, Zhejiang, Fujian, Jiangxi, Guangdong, Sichuan, and Yunnan, located in southern China, had a good water security state.

Critical factors hindering regional water security in China

The evaluation indicator of an *ISD* less than 0.4 throughout the evaluation period was considered as the critical factor that hindered regional water security. Consequently, based on the evaluation results of water security in China and its 31 administrative regions, the critical factors were selected and are listed in Table 4.

At the national scale, precipitation (X1102), water production modulus (X1103), ecological water requirement satisfaction rate (X1302), wetland area proportion (X1303), and urban sewage reuse rate (X2303) were critical factors hindering water security in China. As precipitation and water production modulus are determined by China's poor water resources characteristics, these factors are difficult to improve through people's efforts. Therefore, the focus of improving water security in China should be on increasing ecological water usage and urban sewage reuse, and protecting and remediating wetlands.

It can be seen that the critical factors hindering water security among the 31 administrative regions were significantly different. It should be noted that low urban sewage reuse rate was a common factor in most regions, except for Beijing, Hebei, Jiangsu, Sichuan, Guizhou, and Yunnan. Specifically, the factors concentrating on water resources, water environment, and water ecology restricted the improvement of water security in Beijing, Tianjin, Hebei, Shanxi, Shandong, and Henan. Water resources management level is relatively high in these regions, so inter-basin water transfer and sewage reuse should be effective ways to alleviate water insecurity. In Shaanxi, Gansu, Xinjiang, and especially in Ningxia, the critical factors reflected the poor natural characteristics and management level of water resources that imposed more pressure on water security. Effective water resources management is urgently needed in these regions. Inner Mongolia, Liaoning, Jilin, and Heilongjiang are located in northeastern China, where water quality was acceptable, but precipitation was low and the ecological water requirement failed to be satisfied. Although Shanghai and Jiangsu are located in southern China and have high precipitation, water resources were scarce, and water pollution was serious due to the rapid economic development and urbanization of a large and growing population. Not only in Henan, Shaanxi, and Gansu, located in central and western China, but also in many southern regions of China, there was a low effective irrigation area proportion. Hence, regional agricultural infrastructure needs to be improved. Hunan and Hainan faced a serious risk of flooding, while Yunnan had a limited urban water supply capacity. In Tibet, the scale of human activity is small, and the economy is backward, so the critical factors mainly reflected on poor water resources management.

Conclusions

Water security is represented by good water service functionality in resource, ecology, and environment, which is dominated by the 'natural–social' dualistic water cycle. As a complex system involving both water system and social system, water security reflects on two aspects: healthy natural water cycle and healthy social water cycle. Based on the dualistic water cycle theory, a new evaluation system of regional water security was established, and water security issues and their critical factors in China and its 31 administrative regions during the period of 2006–2015 were analyzed.

At the national scale, the water security state in China slowly improved from 2006 to 2015, and the current state was moderate. On the one hand, the health condition of the social water cycle experienced a

Table 4. Critical factors hindering regional water security from 2006 to 2015.

Regions	Critical factors
China	Precipitation, Water production modulus, Ecological water requirement satisfaction rate, Wetland area proportion, Urban sewage reuse rate
Beijing	Water resources per capita, Precipitation, Water production modulus, Water resources utilization rate, COD level in water, Ammonia-nitrogen level in water, Run-off depth, Wetland area proportion, Sewage treatment proportion of GDP
Tianjin	Water resources per capita, Precipitation, Water production modulus, Water resources utilization rate, River water quality satisfaction rate, COD level in water, Run-off depth, Forest coverage, Urban sewage reuse rate
Hebei	Water resources per capita, Precipitation, Water production modulus, Water resources utilization rate, COD level in water, Ammonia-nitrogen level in water, Run-off depth, Water supply pipe length per capita
Shanxi	Water resources per capita, Precipitation, Water production modulus, River water quality satisfaction rate, COD level in water, Ammonia-nitrogen level in water, Run-off depth, Wetland area proportion, Forest coverage, Water supply pipe length per capita, Urban sewage reuse rate
Inner Mongolia	Precipitation, Water production modulus, Run-off depth, Wetland area proportion, Urban sewage reuse rate
Liaoning	Water resources per capita, Water production modulus, COD level in water, Urban sewage reuse rate
Jilin	Precipitation, Water production modulus, Run-off depth, Ecological water requirement satisfaction rate, Effective irrigation area proportion, Urban sewage reuse rate
Heilongjiang	Precipitation, Water production modulus, Run-off depth, Ecological water requirement satisfaction rate, Urban sewage reuse rate
Shanghai	Water resources per capita, Water resources utilization rate, COD level in water, Ammonia-nitrogen level in water, Forest coverage, Sewage treatment proportion of GDP, Urban sewage reuse rate
Jiangsu	Water resources per capita, Water resources utilization rate, River water quality satisfaction rate, COD level in water, Forest coverage
Zhejiang	Urban sewage reuse rate
Anhui	Urban sewage reuse rate
Fujian	Urban sewage reuse rate
Jiangxi	Effective irrigation area proportion, Urban sewage reuse rate
Shandong	Water resources per capita, Water production modulus, Water resources utilization rate, COD level in water, Run-off depth, Forest coverage, Urban sewage reuse rate
Henan	Water resources per capita, Water production modulus, Water resources utilization rate, Run-off depth, Wetland area proportion, Water supply pipe length per capita, Effective irrigation area proportion, Urban sewage reuse rate
Hubei	Effective irrigation area proportion, Urban sewage reuse rate
Hunan	Effective irrigation area proportion, Urban sewage reuse rate, Population affected by floods
Guangdong	Fertilizer use per unit irrigated farmland area, Sewage treatment proportion of GDP, Urban sewage reuse rate
Guangxi	Fertilizer use per unit irrigated farmland area, Wetland area proportion, Effective irrigation area proportion, Urban sewage reuse rate
Hainan	Fertilizer use per unit irrigated farmland area, Effective irrigation area proportion, Urban sewage reuse rate, Population affected by floods
Chongqing	Fertilizer use per unit irrigated farmland area, Wetland area proportion, Effective irrigation area proportion, Urban sewage reuse rate
Sichuan	Wetland area proportion, Effective irrigation area proportion
Guizhou	Wetland area proportion, Effective irrigation area proportion
Yunnan	Wetland area proportion, Water supply pipe length per capita, Effective irrigation area proportion

(*Continued.*)

Table 4. (*Continued.*)

Regions	Critical factors
Tibet	Precipitation, Water production modulus, Ecological water requirement satisfaction rate, Forest coverage, Water use per 10,000 yuan of GDP, Effective utilization coefficient of irrigated water use, Water use per 10,000 yuan of added industrial output, Urban sewage treatment rate, Urban sewage reuse rate
Shaanxi	Water production modulus, Run-off depth, Ecological water requirement satisfaction rate, Wetland area proportion, Water supply pipe length per capita, Effective irrigation area proportion, Effective utilization coefficient of irrigated water use
Gansu	Precipitation, Water production modulus, Run-off depth, Ecological water requirement satisfaction rate, Wetland area proportion, Forest coverage, Water supply pipe length per capita, Effective irrigation area proportion, Urban sewage reuse rate
Qinghai	Precipitation, Water production modulus, Run-off depth, Urban sewage reuse rate
Ningxia	Water resources per capita, Precipitation, Water production modulus, Water resources utilization rate, River water quality satisfaction rate, COD level in water, Ammonia-nitrogen level in water, Run-off depth, Forest coverage, Total water use per capita, Water use per 10,000 yuan of GDP, Effective utilization coefficient of irrigated water use
Xinjiang	Precipitation, Water production modulus, Run-off depth, Ecological water requirement satisfaction rate, Wetland area proportion, Forest coverage, Total water use per capita, Water use per 10,000 yuan of GDP, Urban sewage reuse rate

significant increase, which showed that significant process has been made in effective water resource management across the country. The improvement can be attributed to many factors, such as change in both economic and industrial structure, technological advancement, and institutional and policy reforms. However, China's water institutions are yet complicated and fragmented, inhibiting effective water management and pollution control. The low ecological water requirement satisfaction rate and small wetland area proportion indicated that the management is inadequate in coordinating the allocation of water resources between ecological protection and socio-economic development. With limited water resources, the spatial and temporal characteristics of water availability require sufficient attention and being accounted for in socio-economic development. Furthermore, China is lagging behind in constructing and operating wastewater treatment and reuse facilities, which can be reflected by the low urban sewage reuse rate. Increasing the role of wastewater reuse may be more cost-effective than inter-basin water transfer. Associated with China's socio-economic development, the continuous growth of population and rapid urbanization will boost water demand, and further challenge China's water resources management; therefore, a resilient and integrated water management with adaptive capacity is needed. On the other hand, owing to the scarce and unevenly distributed water resources, the health condition of the natural water cycle in China maintained a low level. Moreover, climate change will introduce greater variability in the natural water cycle. The change will add to the challenges of water resources management, while the integrated hydrological socio-economic modeling based on reliable monitoring data needs to be developed.

In the 31 administrative regions, the water security state in southern China was better than in northern China, mainly attributed to the abundance of water resources in the south. Although the critical factors were significantly different among these regions, the low urban sewage reuse rate was a common factor, and most regions in southern China had low irrigation efficiency. It is worth noting that a more effective wastewater management needs to be established across the country, including enforcement of pollution treatment, increasing wastewater treatment and reuse facilities, and improving the removal efficiency of contaminants. For the regions in southern China, many strategies and measures need to be adopted for improving irrigation efficiency, such as agricultural infrastructure construction, irrigation innovation, and tillage practice and soil management. Moreover, compared with northern China, southern regions face more frequent and severe floods, especially Hainan. Therefore, the related information monitoring network and early warning and decision system need to be strengthened. For northern regions, water shortages, water resource overexploitation, and degraded water quality and aquatic ecosystems are common challenges; socio-economic development should be carefully examined with explicit consideration of water use in relation to water availability. Moreover, in some regions, such as Shaanxi, Gansu, Xinjiang, and Ningxia, water security was also severely threatened by the ineffective water resources management, so that the local governments' top priority is to change water use patterns, reform water prices, and promote effective implementation of Integrated Water Resource Management.

The evaluation results are in line with the actual situations of China and its 31 administrative regions, and reflect regional water security issues and their critical factors. Considering the evolutionary mechanism of the dualistic water cycle, a more comprehensive and intuitive understanding of the role of natural characteristics and management level of water resources on regional water security in China has been discussed. Some suggestions were proposed based on the characteristics of water insecurity in different regions, and the related analysis can be used as a reference in implementing regional water resources regulation for improving water security.

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