Evaluation of water security based on capacity for socio-economic regulation

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ABSTRACT

From the perspective of social and economic regulation, the development trend of regional water security in different periods and under different regulation strengths is evaluated by using the fuzzy set pair analysis method. The results show: the degree of regional water resources security changes from insecurity in the pilot period of water-saving society construction to basic security, and then to security in the planning period, with the enhancement of economic and social regulation. The order of importance of each index is C19 > C1 = C5 > C18 > C14 > C10 > C13 > C3 = C4 > C8 > C7 > C15 > C16 > C12 > C2 > C11 > C17 > C6 > C9, the long-term shortage of water resources is the most important factor, the contribution rate is 60%, but the index weight of economic and social coordination ability is large, and its rapid change causes the improvement of water resources security; the contradiction between the regulation intensity of social and economic indicators in the planning year and the demand for water resources is not matched, and the degree of water security is mainly restricted by the shortage of regional water resources.

Key words | comprehensive evaluation, fuzzy set pair analysis, social and economic regulation, water resources security

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HIGHLIGHTS

- The important role of social and economic regulation and control measures in water shortage was discussed.
- The influencing factors on water resource shortage were discussed.
- The evaluation of water resource safety can be judged by comprehensive connection degree.
- The contribution of factors in different years to regional water resources security was analyzed.
- Strengthening economic and social control measures is conducive to solving the problems of regional water resource shortage.

INTRODUCTION

Population growth, socio-economic development and urbanization have aggravated climatic effects in arid areas, resulting in a series of water resources problems, such as water pollution, fragile aquatic ecosystems and frequent drought and flood disasters. At the same time, the implementation of water-saving interventions, stringent water resources management, sustainable development and other adaptive measures (Zhengwei *et al.* 2016; Xia & Bing 2018) have to a certain extent improved and enhanced the robustness of water resources systems in China. Adapting to changing social and environmental factors to improve the security of water resources has become a research focus.

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Different studies have considered different definitions of water security. Some scholars have applied a relatively narrow definition, considering security of supply, balancing supply and demand, water resources carrying capacity and environmental carrying capacity (Page 2001; Yiping *et al.* 2013; Wen *et al.* 2014). The assessment of water security has in recent years become more important with increasing social changes. With clear objectives for the quantity and quality of water resources, and under pressure of limited water resources, regulation is vital for consolidating environmental objectives with economic and social adaptation measures (Handmer *et al.* 1986).

Water security is a complex social issue, and includes aspects of economic production and human lifestyle (Zhifei 2017). In addition to the quantity and quality of water resources, water security should also consider (Jun & Wei 2016) the utilization and management of water resources. Water security is impacted by social changes (Jun *et al.* 2011) such as developments in science and technology and level of social development. It is emphasized (Yirong & Jiancang 2014; Jun *et al.* 2016) that coordination between the water resources system as a complex socio-economic and environmental system and an evaluation index system should reflect the binary nature of the natural and socio-economic system. Water security based on the most stringent water management system (Junyuan *et al.* 2016) is the embodiment of regulating water security through social management.

Water security should in addition to the water resources themselves include social and economic changes, scientific and technological development and management and control of water resources. The negative impacts of climate change in arid areas may lead to increasing frequency of floods and droughts, water shortages and increasing risk of deterioration of the aquatic environment, thereby resulting in a serious water security crisis (Jun *et al.* 2011). These factors could result in water constraints persisting for a long time. When water shortages and resulting environmental problems cannot entirely be overcome by fully using the inherent potential of water resources, adaptation to more efficient use of water resources is required (Ohlsson 1998; Qiting 2017). Socio-economic regulation and control of capacity can be used to enhance water security (Ohlsson 2000) through the mobilization of secondary resources (social resources), enhancing socio-economic adaptability (Huaiwen *et al.* 2011), alleviating pressure on water resources and restoring system function processes (Huaiwen *et al.* 2011; Liping & Deshan 2014).

The limited water resources of arid areas have a great impact on water security and this is difficult to change in the short term. Through the enhancement of active coordination between society, economy and environment, limitations of the water resource can be compensated for and the water needs of social development can be met.

The evaluation of water security should include social and economic regulation. Water security should encompass the degree to which the water quantity and quality needs of society can be met and the probability of guaranteeing sustainable development of the economy, society and ecology. 'Control efficiency' is based on the degree and effect of social and economic regulation and adjustment, such as (Yirong & Jiancang 2014) implementation of water-saving interventions, stringent water resources management policies, social investment in environmental management and protection, comprehensive consideration of changes in social factors such as urbanization and population growth and consideration of comprehensive water resources control measures. This paper selects the water-saving society pilot construction period of 2006–2013 for research historical data, and compares the planning data from 2018 to 2020 to explore the impact of different regulation intensities on water security and its change trend.

MATERIALS AND METHODS

Definition of the water security evaluation index

Ningxia in northwest China encompasses arid and semi-arid areas, and often suffers serious water shortages. Water security is the key factor required for sustainable development. In the case of long-term and serious shortage of water resources, the proportion of agricultural water consumption is very large. The agricultural water is rich but its utilization rate is very low. The water utilization coefficient of agricultural irrigation is far lower than the average level of China (Table 1).

To improve the efficiency of agricultural water consumption is to improve the safety and security of the region. The fairness and interests of regional water use are

Table 1 | The basic conditions of the water resource in the studied area

Annual average precipitation	Annual potential evaporation	Per capita annual water availability	The proportion of agricultural water consumption (2013)	The water utilization coefficient of agricultural irrigation (2013)	Urban sewage recycling rate C4 (2013)
305 mm	1,800 mm	634 m^3	87%	0.48	14.6%

greatly affected by agricultural water-saving. Therefore, when selecting indicators, this paper focuses on the agricultural water-saving situation, and does not consider the ecological, industrial and living aspects in detail. By referring to domestic and foreign literature (Min *et al.* 2006; Huaiwen *et al.* 2011; Li & Songhong 2014; Liping & Deshan 2014), 19 indices were selected to establish a water safety evaluation index for Ningxia (Table 2).

(1) The basic characteristics of water security are reflected by water resources condition indices C1–C5.
(2) The water security assessment not only includes basic functions of water resources, but also economic, social and environmental service functions, particularly the increases to water security provided by economic, social and environmental regulation. Therefore, indices that reflect coordination between society, economy and the aquatic environment reflect 'the efficiency of active economic and social regulation'. The selection of indicators focused on the implementation of social progress and adjustment capacity C6–C10 and capacity for economic coordination to enhance implementation C11–C14. Finally, indices considering the impacts of coordination with the aquatic environment were selected, namely C15–C19. Because the indicators of coordination ability should not be quantified and compared, the present study selected efficiency and benefit indicators to express the effect of coordination, focusing on the support of urban water-saving technologies and the growth of the city economy.

Determination of security criteria for indicators

According to the meaning of the indicators, relevant literature and the water availability within the study region, water security criteria were categorized into five levels.

(1) Very safe (Level I): The socio-economic factors, aquatic environment and social coordination capabilities are compatible with regional water resources conditions and are very secure.
(2) Moderately safe (Level II): The socio-economic factors, aquatic environment, social coordination capacity and regional water resources conditions are moderately adaptive and safe.
(3) Basic safety (Level III): The socio-economic factors, aquatic environment and social coordination capabilities are in general adapted to regional water resources conditions; however, the system is vulnerable to exceedance of a critical point of safety and security which may result in water insecurity.
(4) Insecure (Level IV): The socio-economic factors, aquatic environment, social control capacity and regional water resources are not coordinated, and water resources cannot support regional economic and social development.
(5) Extremely unsafe (Level V): The water resources and aquatic environment are seriously polluted, and the social economy, aquatic environment and capacity for social control are inadequate. The fundamental problems resulting from water shortages cannot be overcome, resulting in lowered economic and social development.

The specific basic data and evaluation level standards are shown in Table 3.

Water security evaluation model based on entropy weight fuzzy set

The fundamentals of water security assessment include socio-economic factors, water resources and aquatic environment composite system aspects, which are associated with large degrees of uncertainty (Min *et al.* 2006; Li & Songhong 2014). Fuzzy set pair analysis (Jun *et al.* 2016) is a multi-objective decision-making method that introduces the concept of the degree of fuzzy connection to deal with uncertainty based on the theory of set pair analysis.

Table 2 | Water resources safety rating indicator system

Target layer	Criteria layer	Indicator layer	Indicator calculation	Characterization	Unit	Nature
Water security assessment	Urban water resources condition B1	Per capita water resources C1	Total water resources/total population	Measuring the extent of urban water shortages	m^3/person	↑
		Current rainfall C2	The sum of precipitation in the year	Reflecting the precipitation in the urban area	mm	↑
		Water resources development utilization rate C3	Regional water consumption/water resource availability × 100%	Local water resources development and utilization	%	↓
		Urban sewage recycling rate C4	Sewage recycling capacity/total sewage treatment × 100%	Reflecting the ability of sewage resources	%	↑
		Unit per hm^2 water resources C5	Total water resources/total area	Reflecting the amount of urban water resources	m^3/hm^2	↑
	Social coordination ability B2	Urbanization rate C6	Urban population/total population × 100%	Measuring urbanization levels	%	↑
		Natural population growth rate C7	Annual population increase/total population × 100%	Reflecting the speed of population development	%	↓
		Urban water supply network loss rate C8	(Total water supply – total effective water supply)/total water supply × 100%	Measuring the water supply efficiency of urban water supply systems	%	↓
		Urban life water-saving equipment penetration rate C9	The number of water-saving appliances used again/the number of reused water appliances × 100%	Reflecting people's understanding of resource crisis	%	↑
		Agricultural water-saving irrigation area proportion C10	Water-saving irrigation area/total area of irrigation area × 100%	Characterizing the optimal allocation of agricultural water	%	↑
	Economic coordination ability B3	Per capita GDP C11	Gross GDP/total population	Measuring regional economic development	Yuan/person	↑
		10,000 yuan GDP water consumption C12	Total water consumption/total GDP	Economic benefit	m^3	↓
		Agricultural 10,000 yuan increase in water consumption C13	Total water withdrawal/total agricultural output increased	Reflecting agricultural water efficiency	m^3	↓
		Agricultural water use proportion C14	Agricultural water consumption/total water consumption × 100%	Reflecting the urban industrial water structure	%	↓
	Ecosystem coordination ability B4	Urban green coverage rate C15	Total area of urban green space/total urban area × 100%	Reflecting urban greening levels	%	↑
		Environmental protection investment proportion C16	Environmental protection investment/total investment × 100%	Reflecting the importance of cities to environmental governance	%	↑
		Urban sewage treatment rate C17	Concentrated sewage treatment volume/total sewage volume × 100%	Reflecting industrial water recycling levels	%	↑
		Industrial wastewater discharge compliance rate C18	Industrial wastewater discharge scalar/industrial wastewater discharge total × 100%	Responsibility to reflect environmental responsibility	%	↑
		Urban drinking water quality compliance rate C19	Drinking water scalar/total reference water × 100%	Measuring water safety	%	↑

Table 3 | The water security assessment set for Ningxia in 2006–2020

Index	2006	2007	2008	2009	2010	2011	2012	2013	2018	2019	2020	Level I Very safe	Level II Moderately safe	Level III Basic safety	Level IV Insecure	Level V Extremely unsafe	Single indicator Weights	Criterion layer weight
C1	175.66	170.19	149.02	134.71	147.09	136.87	166.95	172.21	159.6	160.1	163.5	$\geq$ 3,000	1,700–3,000	1,000–1,700	500–1,000	$\leq$ 500	0.093	0.3136
C2	249	299	250	235	293	284	339	321	389	346	311	$\geq$ 1,000	800–1,000	600–800	400–600	$\leq$ 400	0.028	
C3	95.72	97.15	93.00	90.55	97.53	94.07	98.41	96.12	96.2	96.5	96.6	$\leq$ 30	30–50	50–70	70–90	$\geq$ 90	0.049	
C4	8.01	8.99	10.56	12	13.7	13.98	14.25	14.6	20.2	23	25	$\geq$ 50	30–50	15–30	5–15	$\leq$ 5	0.049	
C5	20,473	20,050	17,770	16,259	17,996	16,896	20,859	21,749	20,923	20,861	20,142	$\geq$ 60,000	30,000–60,000	15,000–30,000	6,000–15,000	$\leq$ 6,000	0.093	
C6	43.10	44.02	44.98	46.10	48.12	49.82	50.67	52.02	58	59.9	61	$\geq$ 80	60–80	40–60	20–40	$\leq$ 20	0.023	0.1864
C7	6.41	9.76	9.69	9.68	9.04	8.97	8.93	8.62	7.78	8.03	8.12	$\leq$ 2	2–4	4–6	6–10	$\geq$ 10	0.046	
C8	19	12	11.9	11.7	8.5	9	8.3	7	7	7	6	$\leq$ 8	8–10	10–15	15–18	18–20	0.032	
C9	38	45	55	70	75	80	83	87	96	97	100	$\geq$ 90	70–90	50–70	30–50	$\leq$ 30	0.015	
C10	1.45	3.20	5.01	5.85	7.20	11.60	16.40	20.17	41.4	47.7	55.2	$\geq$ 50	35–50	20–35	5–20	$\leq$ 5	0.07	
C11	11,710	13,669	17,784	21,346	25,931	32,228	35,950	39,210	50,659	54,500	59,000	$\geq$ 50,000	25,000–50,000	10,000–25,000	4,000–10,000	$\leq$ 4,000	0.027	0.1864
C12	1,098	851	675	541	440	357	298	281	178.6	162	150	$\leq$ 500	500–1,000	1,000–1,500	1,500–2,000	$\geq$ 2,000	0.032	
C13	913	670	576	274	217	189	162	147	115	92	80	$\leq$ 500	500–1,000	1,000–1,500	1,500–2,000	$\geq$ 2,000	0.05	
C14	93.13	92.44	93.19	92.37	91.71	91.02	90.08	87.52	87.2	86.9	86.8	$\leq$ 60	60–70	70–80	80–90	$\geq$ 90	0.078	
C15	16.5	17.4	20.3	25.1	27.6	29.6	30.5	37.9	42.2	43.6	44	$\geq$ 30	20–30	15–20	10–15	$\leq$ 10	0.042	0.3136
C16	4.95	5.14	5.17	5.22	5.23	5.51	6.25	7.82	9.52	9.88	10	$\geq$ 10	7–10	5–7	3–5	$\leq$ 3	0.036	
C17	53.4	54	55.26	71.2	76	84.5	88.2	89	92.2	93.2	95	$\geq$ 90	70–90	50–70	30–50	$\leq$ 30	0.024	
C18	78.2	83.6	91.7	97	97.8	98	98.5	99	97.6	99.1	100	$\geq$ 85	75–85	60–75	45–60	$\leq$ 45	0.081	
C19	94.07	95.48	96.29	99.5	99.9	100	100	100	100	100	100	$\geq$ 99	96–99	93–96	90–93	$\leq$ 90	0.13	

(1) Set pair analysis is based on the system pairing principle and is used to analyze a system consisting of one definite and one uncertain data set, which may be identical, different or contradictory to each other, to deal with and describe the problem of synthesis integration. Fuzzy set pair analysis is based on set pair analysis. Fuzzy logic theory is applied to set pair analysis and is better able to consider the fuzziness of the standard boundary of the grade. Fuzzy logic theory is more objective and allows simpler solutions to uncertain problems. The principles are as follows (Li & Songhong 2014; Yongan & Wensheng 2018).

Using water security as the evaluation target, fuzzy logic theory constitutes a set of water security assessment indicators and safety level standards $H(A\_t,B\_k)$. The evaluation index value consists of $t = 1, 2,\ldots t$, where t is the total number of evaluation indicators, equal to 19. The evaluation index is regarded as a set A_t, with the evaluation level standard set expressed as B_k; $k = 1, 2,\ldots k$, where k is the number of evaluation level standards, equal to 5. According to the basic principle of set pair analysis, the symbol quantization process is performed on H, and when the evaluation index value is compared with the corresponding evaluation level standard, if it happens to be in the kth standard, the quantized symbol 'k', and so on.

(2) According to the set pair principle, the total number of water security evaluation choices is T, where S is the number of indicators that meet the same evaluation level as the evaluation index, called the collection A_t. B_k is common, and is called 'the same'. The number of indicators with different levels of evaluation K-1 is P, called the set A_t, whereas B_k is the opposite, and is called 'the opposite'. The evaluation level differs by level I, level II, and the level of K-2 is recorded as F_1, F_2, $F_{K\text{-}2}$. F is different from the set A_t. B_k is neither shared nor shared, F is for 'the difference'; from this, the K-member relationship of the water security set to H is obtained (Wenjuan et al. 2018):

$$\mu_{A_t - B_k} = \frac{S}{T} + \frac{F}{T} I + \frac{P}{T} J = a + \sum_{1}^{K-2} b_K I_K + cJ \tag{1}$$

In Equation (1), a, b and c represent the identity, difference and opposite components of the sets A_t and B_k, respectively, and meet the conditions $a + b + c \neq 1$; I_1, I_2, $I_3 \ldots I_{k\text{-}2}$ represent the coefficient of the uncertainty component, which has a value of -1 to 1, with a value closer to 1 representing the level to be evaluated; J is the opposite coefficient with a value of $-p$.

The difference uncertainty component coefficient I_k in Equation (1) can be determined by the uniform value method (Wenjuan et al. 2018; Yongan & Wensheng 2018):

$$I_k = \frac{1 - 2k}{(K - 1)} \tag{2}$$

In Equation (1), the closer a is to 1, the more similar are the two sets, whereas the opposite is true for c. The greater the connection value of the two sets, the more likely the indicator value belongs to the level standard.

(3) Calculation of the degree of connection of a single indicator

In the evaluation, B_k is defined as the set B_k of a specific index t-level rating standard; that is, the degree of connection of a single indicator is calculated first. The specific formula reference (Wenjuan et al. 2018) is as follows:

$$\mu_{A_t \sim B_k} = \begin{cases} 1 + 0I_1 + \cdots 0I_{k-2} + 0J & (x_1 \geq s_1) \\ \dfrac{2x_t - s_1 - s_2}{s_1 - s_2} + \dfrac{2s_1 - 2x_t}{s_1 - s_2} I_1 + 0I_2 + \cdots + 0I_{K-2} + 0J & \left(\dfrac{s_1 + s_2}{2} \leq x_t < s_1\right) \\ 0 + \dfrac{2x_t - s_2 - s_3}{s_1 - s_3} I_1 + \dfrac{s_1 + s_2 - 2x_t}{s_1 - s_3} I_2 + \cdots + 0I_{K-2} + 0J & \left(\dfrac{s_2 + s_3}{2} \leq x_t < \dfrac{s_1 + s_2}{2}\right) \\ \cdots & \\ 0 + 0I_1 + \cdots + \dfrac{2x_t - 2s_{K-1}}{s_{K-2} - s_{K-1}} I_{K-2} + \dfrac{s_{K-1} + s_{K-2} - 2x_t}{s_{K-2} - s_{K-1}} J & \left(s_{K-1} \leq x_t < \dfrac{s_{K-2} + s_{K-1}}{2}\right) \\ 0 + 0I_1 + 0I_2 + \cdots + 0I_{K-2} + 1J & (x_t < s_{K-1}) \end{cases} \tag{3}$$

$$\mu_{A_t\sim B_k}=\begin{cases}1+0I_1+\cdots 0I_{k-2}+0J & (x_1\le s_1)\\ \dfrac{s_1+s_2-2x_t}{s_2-s_1}+\dfrac{2x_t-2s_1}{s_2-s_1}I_1+0I_2+\cdots+0I_{K-2}+0J & \left(s_1<x_t\le\dfrac{s_1+s_2}{2}\right)\\ 0+\dfrac{s_2+s_3-2x_t}{s_3-s_1}I_1+\dfrac{2x_t-s_1-s_2}{s_3-s_1}I_2+\cdots+0I_{K-2}+0J & \left(\dfrac{s_1+s_2}{2}<x_t\le\dfrac{s_2+s_3}{2}\right)\\ \cdots & \\ 0+0I_1+\cdots+\dfrac{2s_{K-1}-2x_t}{s_{K-1}-s_{K-2}}I_{K-2}+\dfrac{2x_t-s_{K-1}-s_{K-2}}{s_{K-1}-s_{K-2}}J & \left(\dfrac{s_{K-2}+s_{K-1}}{2}<x_t\le s_{K-1}\right)\\ 0+0I_1+0I_2+\cdots+0I_{K-2}+1J & (x_t<s_{K-1})\end{cases}\quad(4)$$

Equation (3) applies to the attribute where $K>2$ is a positive indicator, where $s_1 \geq s_2 \geq \ldots \geq s_{K\sim 1}$. Equation (4) is applied to the index where the attribute of $K>2$ is negative, and $s_1 \leq s_2 \leq \cdots \leq s_{K\sim 1}$.

(1) The weight of the water safety evaluation index can be determined (Wenjuan *et al.* 2018) by the entropy method. The weight of each indicator is expressed by ω_t. The theory behind the approach is as follows.

1. The initial data of the t indicators of m samples of n different periods constitute a judgment matrix:

$$R=(x_{ij})(i=1,2,\cdots m;\ j=1,2,\cdots T)\quad(5)$$

x_{ij} is the characteristic value of sample j and index i.

2. The normalized judgment matrix.

The larger the value, the better the indicator:

$$\mu_{ij}=X_{ij}/\max X_{ij}\quad(6)$$

The smaller the value, the better the indicator:

$$\mu_{ij}=\min X_{ij}/X_{ij}\quad(7)$$

3. Determine the entropy of the evaluation index:

$$f_{ij}=\mu_{ij}/\sum_{j=1}^{T}\mu_{ij}\qquad H_i=-\frac{1}{\ln T}\left(\sum_{j=1}^{T}f_{ij}\ln f_{ij}\right)\quad(8)$$

4. Calculate the entropy weight of the evaluation index:

$$W=(\omega_i)_{1\times m}\qquad \omega_i=\frac{1-H_i}{m-\sum_{i=1}^{m}H_i}\quad(9)$$

(2) Calculation of degree of contact

The index corresponding to the set A of the evaluation index system is the evaluation level standard set B of a certain level, and the k-yuan connection degree of $H(A\_t, B\_k)$ of the set pair can be calculated according to the following formula:

$$\mu_{A\tilde{B}}=\sum_{t=1}^{T}\omega_t\mu_{A_t-B_1}$$

$$=\sum_{t=1}^{T}\omega_t a_t+\sum_{t=1}^{T}\omega_t b_{t,1}I_1+\sum_{t=1}^{T}\omega_t b_{t,2}I_2+\cdots+\sum_{t=1}^{T}\omega_t b_{t,K-2}I_{K-2}+\sum_{t=1}^{T}\omega_t c_t J$$

$$=f_1+f_2I_1+\ldots+f_{k-1}I_{k-2}+f_kJ,\quad(10)$$

where f_1 represents the probability that the evaluation target belongs to the I-level standard, f_2 is the probability that the evaluation target belongs to the II-level standard, f_k is the probability that the evaluation target belongs to the K-level standard.

(3) Determine the rating

Calculate the confidence to determine the level of water security, as follows:

$$h_k=(f_1+f_2+f_3+\cdots+f_k)>\lambda,\quad k=1,2,3\ldots K,\quad(11)$$

where h_k is the attribute measure and λ represents the confidence.

In Equation (11), the value of confidence λ should neither be too large nor too small as these would lead to the evaluation results being too conservative or too uncertain, respectively. Therefore, λ should generally fall within [0.5, 0.7], and the current study uses a value of 0.5. The level in which the evaluation sample falls is determined by Equation (11), i.e., the sample belongs to the k level corresponding to h_k.

Data sources

The evaluation system began in 2006 during the comprehensive implementation of water-saving interventions within society and ended in 2013. The basic data of all indicators were obtained from the Ningxia Water Resources Bulletin and Water Resources Survey Bureau 2006–2013 and the Statistical Communiqué of the National Economic and Social Development of Ningxia Hui Autonomous Region 2006–2013. The planning year basic data (2018–2020) were from the Ningxia Water Resources Allocation Planning Report 2016–2020. In 2018, the actual data will be used for statistics, and the planning data will be used for those not available, and the planning forecast data will be used for all the years from 2019 to 2020.

EXAMPLE ANALYSIS AND DISCUSSION

The model combining the entropy method and set pair analysis was used to evaluate water security within Ningxia. The former method provided the weight of each indicator whereas the latter determined the level of safety. The method considered the fuzziness of the equal-level boundary and the differences between the weights of each evaluation index. The results of the method avoided subjective randomness.

To construct a set of water security indices $H_{2006\sim2013,2018\sim2020}(A_{19},B_5)$ for water resources in Ningxia, the single degree $\mu_{A_t\sim B_1}$ of contact for all indicators was first calculated, thereby providing the weight of each indicator. The final total was the calculated degree of contact $\mu_{2006\sim2013,2018\sim2020}(A_{19},B_5)$, within the interval $[-1, 1]$ which was further divided into five intervals (Huawei *et al.* 2015; Wenjuan *et al.* 2018; Yongan & Wensheng 2018), and the tenth to 15th columns of Table 3 correspond to the five levels of the water security evaluation from high to low and from left to right. First, the set results were compared with the corresponding values of each level to obtain the classification of water security status for eight consecutive years. Water security status μ had a positive relationship with the connection value and water security status. Finally, the water security status was evaluated and analyzed and development trends were identified. At the same time, the confidence criterion was calculated, and the confidence attribute h_k of each year was determined to obtain the level of water security.

Determination and analysis of entropy weight

The weights of the indicator layer and criterion layers were determined based on the entropy weight method, the results of which are shown in Table 3.

Evaluation of index layer

According to the evaluation results of the index layer (Table 3), the influence of the 19 indicators in the index layer on the security of water resources in Ningxia from largest to smallest was: C19 > C1 = C5 > C18 > C14 > C10 > C13 > C3 = C4 > C8 > C7 > C15 > C16 > C12 > C2 > C11 > C17 > C6 > C9.

The top three indicators represent the basic quantity and quality conditions to ensure water security, thereby indicating that the conditions of water resources in this region are an important constraint on water security. Excluding the top three indicators, water security constraints, water resources development and utilization rate and other water resource conditions, the ranks of indices 4–10 were in the following order: C18 > C14 > C10 > C14 > C5 > C8 > C7, where one index falls into the category of coordination with the aquatic environment, three indices fall within coordination capabilities, two fall within economic coordination capabilities and one falls within water resources conditions. Five of the seven indicators account for the coordination between socio-economic factors and the environment, which fully demonstrates the important position and role of coordination between society, economy and aquatic environment under the basic condition of 'water quantity and quality'. The effects of indices 6 and 4 within economic and social coordination and the consequent impacts on water resources security are far greater than those of indices 7, 9 and rate of uptake of urban water-saving appliances, which indicates that for areas such as Ningxia where agricultural water consumption is extremely high, the weights of indices 6 and 4 on water security are much greater than that of 7. Compared with urban water resources, the regulation of agricultural water resources utilization provides a greater benefit to water security, and is therefore a key point on which to focus in Ningxia.

Evaluation of criteria layer

According to the calculation result of Equations (5)–(9), the water resources condition criteria layer has a weight of 0.313, a social coordination capacity of 0.186, an economic coordination capacity of 0.187 and a water environment coordination capacity of 0.313. Since water resources are scarce and the water environment is poor, this indicates that the basic conditions of water resources and water environment coordination capacity remain important in restricting water security in Ningxia. Both contribute >60% of the binding force, and the influence of social coordination capacity and economic coordination capacity accounts for approximately 37%. However, as shown by changes in the basic data (Figure 1), the relative change of the basic conditions of water resources during 2006–2013 was very small, except for a change in the rate of C4 to 45%. For example, the rate of change of C5 was the largest, but only 5.8%. C1 was not affected by the various factors, but the five indicators of social coordination capacity, C6–C10, showed rates of change of 17.2%, 25.7%, 63.2%, 56.3% and 92.8%, respectively. The rates of change for

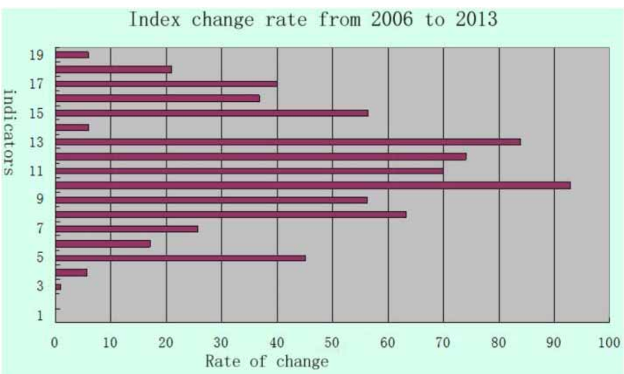

Figure 1 | Rates of change of each indicator during 2006–2013.

C11–C14 were 70%, 74%, 83.9% and 6.0%, respectively. The rates of change of water environment coordination capacity of C15–C19 were 56.5%, 36.7%, 40%, 21% and 5.93%, respectively. The rate of change of each indicator is shown in Figure 1. From the perspective of relative change rate, under the condition of basic conditions of water resources remaining mostly unchanged, the obvious changes in social, economic and aquatic environment coordination ability are an important factor driving improved regional water resources security, particularly related to water-saving measures. Important indices include the efficiency indices C8–C10, benefit indices C12–C13 and environmental protection investment and efficiency indicators C11 and C15–C18, while reclaimed water reuse is also an important driving factor. After 2006, investments in the social, economic and aquatic environment of Ningxia greatly improved. Soon after, the water-saving level, water consumption level, management level, and economic input level of Ningxia improved rapidly. The changes in regulation efficiency indicators reflect the significant contribution of socio-economic factors, input of resources to the aquatic environment and regulation of the impact of regional water resources security over the past eight years. Under unfavorable conditions of natural endowment of water resources, it is necessary and effective to strengthen and improve the water security status of the region through social and economic regulation and management in line with the shortage of water resources.

Evaluation of the contribution degree in different years

To further clarify the evaluation results, the contribution of the indicators of the eight different levels of the year to water security was obtained and the rankings of the top six are shown in Table 4. It is evident that the impact of different indicators on regional water security differs for different levels.

From 2006 to 2013, the impact of different indicators in different levels on water resources security differed, and with the gradual development of economic and social regulation and control, the constraints of water shortages on water security declined. (1) During the initial stage of water-saving interventions in 2006, the basic conditions of the water resources of the region remained the main

Table 4 | Sorting the contribution of indicators in different years to water resources security

Years	Top six indicators of contribution	Years	Top six indicators of contribution
2006	C7 > C4 > C1 > C2 > C5	2011	C18 > C13 > C15 > C14 > C12 > C3
2007	C5 > C18 > C7 > C9 > C15 > C1	2012	C18 > C13 > C15 > C12 > C8 > C3
2008	C18 > C5 > C7 > C13 > C15 > C8	2013	C18 > C5 > C13 > C15 > C14 > C12
2009	C18 > C15 > C13 > C7 > C8 > C12	2018	C1 > C18 > C10 > C14 > C15 > C4
2010	C18 > C15 > C13 > C8 > C3 > C12	2019	C1 > C18 > C10 > C14 > C15 > C4
		2020	C1 > C18 > C14 > C10 > C15 > C4

constraint. Water reuse had just started, which alleviated water shortages. (2) The implementation of water-saving interventions during 2007–2008 was fully implemented, which had a strong impact on overall water security, water management, wastewater reuse, urban water saving and reducing urban water losses. (3) On the basis of improved water quality and water loss reduction during 2009–2011, C13 and C12 became increasingly important for water security. (4) From 2012 to 2013, the rapid development in urban water-saving greatly improved water security; however, the large proportion of agricultural water use and the inefficient use of water became the constraints on the efficiency of alternative industrial regulation.

In general, in regards to water shortages, an increase in the regulation of the socio-economic environment improved water quality and the aquatic environment, water consumption efficiency increased and the degree of C4 and C14 had a large impact on water security during the study period. The enhancement of economic and social regulation and control weakened the impact of water shortages on water security. For the indicators with small annual contributions, such as C10 and C11, the contribution rate in each year was the lowest, indicating that this region with an underdeveloped economy has a large proportion of agricultural water and low degree of water-saving irrigation. It is also evident that all those indicators remain the important constraints affecting water security. Economic development determines the input of water security.

(5) Data for 2018–2020 were used for planning. The construction of a water-saving society is a whole society water-saving strategy to mobilize various economic and social resources and is carried out with high-intensity investment. Ningxia is one of the pilot projects. In this paper, the pilot construction period of the water-saving society with greater economic and social regulation intensity from 2006 to 2013 is selected as the research historical data, and the planning data of water-saving society construction from 2018 to 2020 are used for comparison, so as to explore the impact of different regulation intensities on water security and its change trend. It is evident that during the planning year, according to the current regulation and intensity, within the ranking of the degree of contribution to regional water security, the per capita water resources and water resources utilization rate reappear in the top six, and the discharge rate of industrial wastewater reaches the standard from the first place during 2008–2013 to the first place in the ranking. Secondly, C10 and C11 are included in the ranking, indicating that under the planning and control measures, the efficiency of industrial regulation and control is improved and is faster, the efficiency and ability for agricultural regulation and control does not match the level of social development, and the factors contributing to a greater degree to regional water insecurity gradually shift from industry to agriculture. The capacity of agricultural, economic and social regulation and control during the planning year cannot meet the social–economic demand for quantity and quality of water resources under resource constraints. The capacity of regulation and control has declined, and the binding force of water resources has increased. The basic conditions of water resources have once again become a constraint on water security.

(6) From the ranking of the indicators during 2006–2020, changes to the driving forces of regional water security are evident: during initial implementing of water-saving interventions, the population and basic conditions of water resources are the main factors (C7 > C4 > C1 > C2 > C5 in 2006), whereas during 2008–2013, the driving forces are concentrated in C18, C15, C13, C12, C3 and C14 and other ecological indicators. The indicators driving the capacity for environmental and economic coordination for the planning year for 2008–2013 are C18, C15 and C14. The per capita water resources amount C1 and water

resources development and utilization index C5 re-enter the main indicators, ranking first and sixth, respectively, and the rankings of the proportion of agricultural water-saving irrigation area C10 and the proportion of agricultural water use C14 have upward trends, indicating that for this region, along with the enhancement of regulation of socio-economic and ecological environment, congenital restraint of water resources has been improved to a certain extent, and water security has been enhanced. However, during the planning level year, shortages of water have once again become a major factor restricting water security. The contribution of the ability for socio-economic regulation on water security during the planning year cannot match the demand for water resources during the planning stage. According to current regulation intensity, the influence of water resources conditions on regional water resources security will again become the main constraining factor.

Evaluation of safety level

Table 3 shows the results of set-pair confidence analyses. The results of the two methods were consistent. The set-pair connection method showed the status of water resources in Ningxia during 2006 to be unsafe (4), of basic safety (4–3 during 2007–2013 and insecure during 2006–2008), and then of regional basic security. Water security within Ningxia is improving, although it remains at a basic security state; however, the degree of connection and confidence indicate that water security is moving towards a secure state. The grade of water resources security for Ningxia from 2006 to 2008 is 4 (insecurity and basic security), possibly because water resources remain insufficient, and C8, C10, C9 and C14 under the coordination ability of society, economy and the ecological environment. The standard is in an extremely unsafe state, which directly affects the water security of Ningxia in 2006, and the social, economic and ecological environment has not played a coordinating role in water resources, which impacts sustainable development. Since 2006, the effect of water-saving interventions in Ningxia has been reflected. With water resources remaining unchanged, other indicators have improved greatly; therefore, water security in Ningxia has gradually improved.

Table 5 shows the degree of connection, result of the confidence calculation and the corresponding rating of Ningxia's water security. According to the calculation results, the changes to water security of the water resources of Ningxia are drawn on the linkage line chart, as shown in Figure 2. From 2006 to 2013, water security (Figure 2) tended to move toward level 1. The probability of moving to levels 2 and level 3 decreased with time. The probability of moving toward level 4 increased slightly in 2011 compared with 2010. Water security was in a declining state for the remaining time, and the possibility of tending to level 5 decreased gradually. By examining the basic water resources data in 2011, it was found that rainfall and per

Table 5 | The calculated and rating results of the water security evaluation set of Ningxia in 2006–2013 and planning level year

years	f_1	f_2	f_3	f_4	f_5	μ Total contact	μ Determine security level	h_k	h_k Security level
2006	0	0.113	0.358	0.156	0.374	−0.3955	IV	0.627	IV
2007	0.074	0.129	0.311	0.116	0.370	−0.2895	IV	0.514	III
2008	0.125	0.137	0.259	0.122	0.358	−0.2255	IV	0.521	III
2009	0.288	0.080	0.158	0.124	0.350	−0.084	III	0.526	III
2010	0.331	0.078	0.140	0.129	0.322	−0.0165	III	0.549	III
2011	0.342	0.084	0.123	0.172	0.280	0.018	III	0.549	III
2012	0.382	0.054	0.172	0.122	0.270	0.078	III	0.608	III
2013	0.403	0.059	0.172	0.142	0.224	0.1375	III	0.625	III
2018	0.468	0.029	0.188	0.143	0.171	0.24	III	0.998	III
2019	0.469	0.038	0.186	0.136	0.171	0.249	II	0.999	II
2020	0.469	0.046	0.187	0.127	0.171	0.2575	II	0.999	II

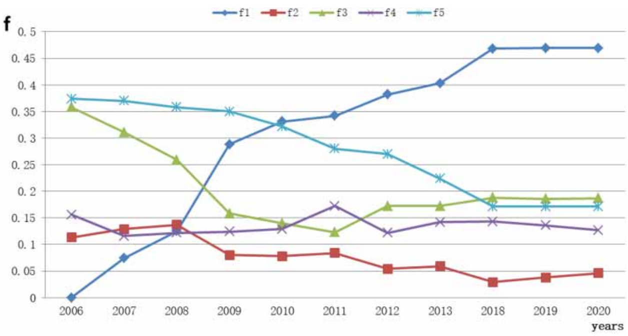

Figure 2 | Ningxia 2006–2020 water resources safety assessment set.

capita water resources in 2011 were lower than those in 2010 due to climate conditions, which may lead to fluctuations in the evaluation results. This illustrates that the possibility of extreme water insecurity in Ningxia is gradually decreasing and the possibility of regional security is increasing.

CONCLUSIONS AND RECOMMENDATIONS

The evaluation of water security based on social and economic regulation was discussed, and a water security evaluation system was established. Taking Ningxia as an example, we choose indicators reflecting the efficiencies of economic, social and aquatic environment regulation to represent the status of water security. The present study reflected the dynamic process of social economic regulation and control on water security using the entropy weight–set pair model. The data were evaluated for eight consecutive years. The results showed that under conditions of rigid constraints on water resources, economic and social control measures, such implementation of water-saving interventions, the most stringent water resources management system and investment within the aquatic environment can have obvious benefits for water security in the arid areas of Ningxia.

The assessment of water security based on the efficiency of social and economic regulation is suitable for arid regions and can reflect the main contradictions and directions for improving water security in arid regions.

(1) From 2006 to 2013 and 2018–2020, regional water resources security has gradually increased from insecurity to basic security, as well as security in the planning period, the impact of different indicators at different levels on water resources security differed, and with the gradual development of economic and social regulation and control, the constraints of water shortages on water security have declined.

(2) According to the evaluation results of the criteria layer, the basic conditions of water resources and the coordination ability of the water environment are still the important factors restricting water security in Ningxia. From the perspective of relative change rate, under the condition of basic conditions of water resources remaining mostly unchanged, the obvious changes in social, economic and aquatic environment coordination ability are an important factor driving improved regional water resources security, particularly related to water-saving measures.

(3) During the pilot construction of the water-saving society, at the initial stage of regulation, the contribution degree of water resources conservation and supplementary indicators and measures was higher, and the social and economic control measures in the middle and late stages of regulation gradually played a greater role; however, in the planning year, the factors affecting regional water resources security changed to some extent, and the shortage of water resources once again became a constraint factor, indicating the economic and social regulation power of the planning year. The degree of water resources and the contradiction between supply and demand of water resources do not match, which cannot effectively alleviate the regional water resources security situation.

(4) Among the factors affecting water resources security, the benefit index reflecting the coordinated development of society, economy and the water environment is an important index to promote regional water security. However, due to the slow development of regional regulation and control capacity, agricultural water use efficiency has not kept up. Strengthening social and economic coordination can improve water security and alleviate the impact of water shortage. However, if the capacity of water safety supervision cannot keep up with the needs of social and economic development,

the role of social and economic regulation in water security will be weakened.

In the future, the region should further strengthen the ability and means of social and economic regulation and control. The measures that can be taken are: continue to increase the area of agricultural water-saving irrigation, reduce the proportion of agricultural water use, improve the efficiency of agricultural water use, improve the rate of industrial sewage discharge reaching the standard, further reduce the water consumption of 10,000 yuan industrial added value, and improve the proportion of recycled water. Through these measures to further reduce agricultural water consumption, improve water efficiency, through agricultural water-saving to achieve ecological water, domestic water, and industrial water security support, and improve the overall security of regional water resources.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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