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Research on the safe utilization of agricultural water resources in the Yellow River Basin

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ABSTRACT

Considering the current problems related to the utilization of agricultural water resources in the Yellow River Basin, we propose the definition of the safe utilization of agricultural water resources based on the summary and analysis of recent studies on water resources security. Through the analysis of water resources development and utilization in the basin over the years, an evaluation index system for agricultural water resources security in the basin was constructed, and a weighted cooperative game method combination was used to evaluate the agricultural water resources security in the basin using the weighted TOPSIS model. The evaluation results show that the utilization of agricultural water resources in the areas under the jurisdiction of Sichuan and Shandong Provinces in the basin was in a secure or a relatively higher state, whereas Ningxia was in a relatively unsecure state, and the remaining provinces were in a basic secure state. Based on the evaluation results, we have provided the corresponding countermeasures for the safe utilization of agricultural water resources in terms of water-saving irrigation technology, water resources monitoring system, and water resources management system to support the effective implementation of efficient water-saving irrigation of agricultural water resources in the Yellow River Basin.

Key words: cooperative game theory, CRITIC method, safe utilization of agricultural water, weighted TOPSIS model, Yellow River Basin

HIGHLIGHTS

- The definition of safe water utilization in agriculture is proposed.
- An index system suitable for the safe utilization of agricultural water resources in the Yellow River Basin is constructed.
- The corresponding countermeasures for the safe utilization of agricultural water resources are put forward from the aspects of agricultural water use mode and water-saving irrigation technology.

1. INTRODUCTION

As an essential ecological protection barrier and food production base in China, the Yellow River Basin has suffered from frequent water-related disasters induced by activities affecting climate change, sedimentation, and river changes. Since the 21st century, the increasing urbanization of the river basin, the rapid socio-economic development, and the enhanced living standards of the natives have been driving the water demand for domestic use and industrial and agricultural production purposes. Thus, water shortages, water quality degradation, deterioration of the water ecosystem, and the funnel expansion of groundwater caused by the overexploitation of water resources have emerged as severe threats to the safety of both the ecosystem and water supply, which can potentially restrict sustainable economic and social progress in the basin. The problem of water resource security in the Yellow River Basin, which is the largest water resource consuming department, caused by agricultural water use cannot be ignored.

Numerous studies worldwide have attempted to address the problem of water resource security; however, most of them have focused on the urban areas, and only a few of them have focused on the safe utilization of agricultural water resources in river basins. To solve the problem of agricultural water resources security currently faced by the Yellow River Basin and improve the efficiency of agricultural irrigation water and the comprehensive grain production capacity, this study clarifies the definition and connotation of agricultural water resources security utilization by summarising and analysing the findings of studies on water resources security at home and abroad. The evaluation results obtained by analysing the current situation of water resources in the Yellow River Basin, constructing an evaluation index system for the safe utilization of agricultural

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water resources in the basin, and introducing cooperative game theory to optimize the index weights are highly scientific. By combining the evaluation results with the national '14th Five-Year Plan', the present study proposes countermeasures for the safe utilization of agricultural water resources in the Yellow River Basin, which is of great significance to ensure food security in the valley, promote high-quality development of the valley, and save agricultural water resources in the next section of the valley, thereby providing a reference for intensive utilization and optimal allocation of water resources.

2. DEFINITION AND CONNOTATION OF SAFE UTILIZATION OF AGRICULTURAL WATER RESOURCES

The research on water resources security began in the late 20th century, and its content is diverse and involves complex factors. Foreign scholars interpret water-resource security based on the natural attributes of water and particular water resources that contribute to the economic, societal, and environmental and human development. They have defined water resource security as the adequate water supply that supports economic and social development at a reasonable water price, which guarantees human survival and health, and maintains a virtuous ecological environment and sustainable development (Partnership 2000; Grey & Sadoff 2007; Falkenmark 2013). Domestic researchers have evaluated water resources security in their research fields. For instance, Xia (Xia 2002) emphasized the importance of ecological water use for water resource security, suggesting that water resource security ensures the water supply for routine life and industries at a reasonable price under the premise of meeting safe and ecological water use. Jia *et al.* (Jia *et al.* 2002) asserted that water resource security should be based on freshwater security and that safe water, which meets the supply and demand of water resources, can be obtained at a reasonable cost. Zheng (Zheng 2003) defined water resource security from both broad and narrow perspectives. Some experts have researched agricultural water resource security specifically. For example, Ye (Ye 2003) stated that agricultural water resource security should include sufficient water volume, stable supply, and reasonable price. Liu *et al.* (Liu *et al.* 2006) indicated that agricultural development should not be threatened by water supply. In summary, earlier studies on water resources security by experts and scholars were conducted from the perspective of water security and suggested that water resources can support and ensure human survival and sustainable economic and social development. However, research on agricultural water resources security is limited, and has been conducted from the perspectives of water quantity and irrigation water supply, but the problems caused by the utilization efficiency and water use structure of water resources remain to be solved. Therefore, based on the research on water resources security and existing agricultural water resources security, this study summarizes and further improves the definition of safe utilization of agricultural water resources.

2.1. Definition

The safe utilization of agricultural water resources refers to the efficiency of advanced water-saving irrigation technologies aimed at optimizing the pattern and efficiency of agricultural water use in a virtuous cycle of the ecological environment. Consequently, the development of river basins or regions is no longer threatened by the water quantity and quality. The temporal and spatial distribution of water resources can effectively guarantee the stability of the crop growth environment. Moreover, the management system of regional water resources can ensure that people are entitled to receive equal agricultural water.

2.2. Connotation

The safe utilization of agricultural water resources includes three aspects: safety of agricultural water quantity, safety of water quality, and safety of use efficiency:

(1) The quantity of agricultural water resources is affected by the geographical location, climate, soil characteristics, and temporal and spatial distribution. The supply of water resources should be slightly greater than or equal to the agricultural demand for irrigation. To ensure adequate water supply for irrigation and conservation of natural water resources, sustainable methods for utilising water should be practised. (2) The quality of both surface water and, groundwater affects agriculture. Though water quality requirements of agriculture are lower than those of other industries, securing good-quality water is a prerequisite for agriculture. The quality of water affects all stages of crop growth. Therefore, sustainable use of groundwater and arable land is necessary. When surface water and groundwater are used as water sources for irrigation, the water quality must meet the standards required for farmland irrigation. Agricultural water quality should be stringently monitored to ensure the safety of groundwater, arable land, and crops; (3) the security of agricultural water use lies in reasonable and efficient use of water and employing cost-effective processes for irrigation. To improve the efficiency of agricultural water use, saving water through minimal use is the primary approach. To control the scale of irrigation in a basin (region), the structure of agricultural

water use should be adjusted, and the planting of high water-consuming crops should be reduced. Other measures include popularizing water-saving irrigation technologies and improving the efficiency of water delivery and distribution. In this manner, water use can be minimized, and the economic, social, and ecological benefits can be maximized.

3. ANALYSIS OF THE CURRENT SITUATION AND SAFE UTILIZATION OF WATER RESOURCES IN THE YELLOW RIVER BASIN

3.1. The current situation of water resources

The Yellow River Basin is a semi-arid and semi-humid region located in China. The annual average river runoff in this basin accounts for 2% of the national total, with per capita water resources being less than 30% of the national level, which is far lower than the world-recognized 'standard of extreme water shortage'. The average water volume per mu (1 hectare = 15 mu) of arable land is only 17% of the national level, whereas the basin arable land accounts for 15% of the total (Hu *et al.* 2012). To research the safe utilization of agricultural water resources in this region, we analysed the distribution of water resources, the structure of water use, and the extent of development during 2010–2019. The present research data were mainly sourced from the *Bulletin of Yellow River Water Resources*, the *Statistical Yearbook of the Yellow River*, the *Bulletin of China Ecological Environment*, bulletins of provincial water resources, and planning reports of water resources. The missing data were obtained through interpolation.

(1) Total water resources and trends

The information on the total water resources in the basin was sourced from the Huayuankou hydrological station. As shown in Figure 1, the total water resources in 2018 was the highest at 77.417 billion m^3, representing a wet year in the basin, while 2002 was a dry year, with the total water resources hitting the lowest at 40.304 billion m^3. The number of water resources varied dramatically over the years, with the highest to the smallest ratio being 1.92. The average amount of water resources from 2001 to 2019 was 56.851 billion m^3, which is 1.11% here than the average amount during 1987–2019 and 6.09% lower that the average amount during 1956–2019. The total water resources in the basin increased from 41.646 billion m^3 in 2001 to 75.415 billion m^3 in 2019, depicting an upward fluctuation trend. Surface water resources accounted for >80% of the total value after 2003, increasing to 88% in 2019. This figure indicates that the amount of water resources in the Yellow River Basin has been increasing, indicating a tendency for a further increase (Dang 2020).

(2) Analysis of water use and water-use structure

According to the 'Bulletin of Yellow River Water Resources', the analysis of the amount of water intake, water use, and water consumed was performed in the nine provinces along the Yellow River during 2010–2019 (Figure 2). The analysis was based on the water distribution plan proposed by the State Council in 1987. The analysis results indicated that the

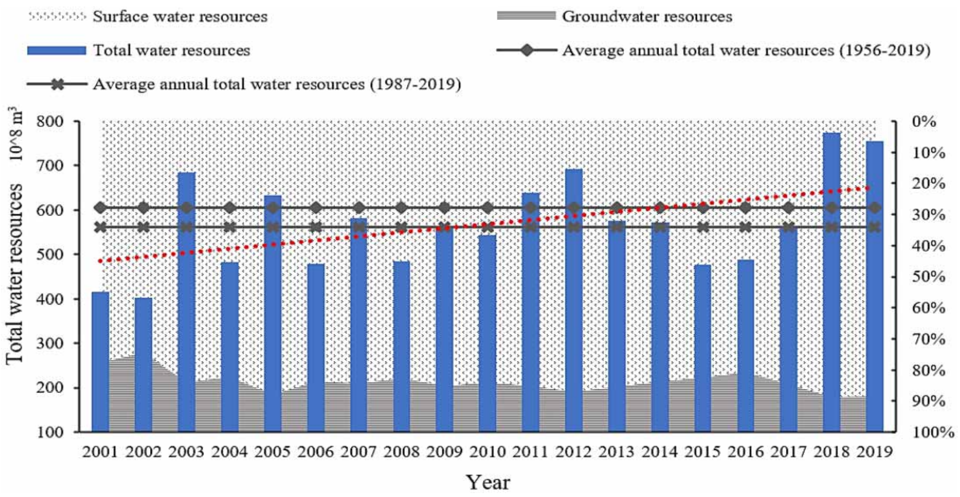

Figure 1 | Water resources and change trend of the Yellow River Basin from 2001 to 2019.

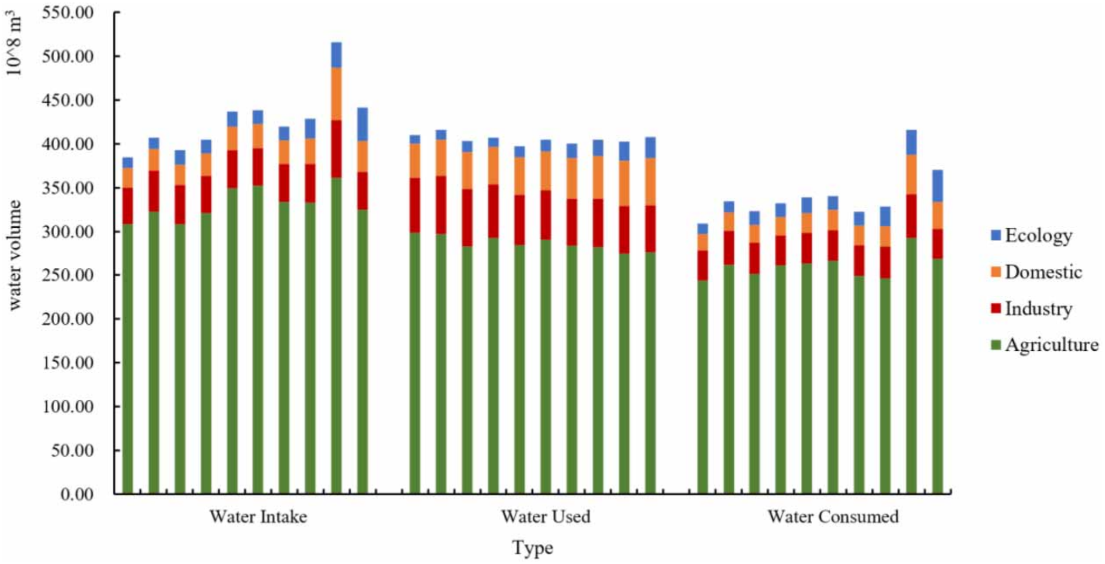

Figure 2 | Water resources utilization of various industries in the Yellow River Basin from 2010 to 2019.

upper reaches of Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, the middle reaches of Shaanxi and Shanxi in some years (2015 onward), and the lower reaches of Shandong and Henan all exceeded their quotas. The water intake increased slowly from 2010 to 2019, with a peak of 36.160 billion m^3 in 2018. The amount of agricultural water intake accounted for 70.05% of the total water intake. The water consumption decreased year by year, albeit this difference was not significant. In addition, the use of water resources in the middle reaches of the Yellow River remained relatively stable. Inner Mongolia recorded the largest water intake and water use of 19% and 22%, respectively Shandong Province had a slow increase in water use from 2010 to 2019, with the peak in 2015 accounting for 23% of the total amount consumed that year. The water use structure thus indicates that agricultural water consumes a large share of water resource use, followed by industrial and domestic water use, and the water consumed in the ecological environment has increased significantly over time. To improve and refine water resource management, China has gradually shifted from extensive water use to a more economical and intensive approach toward water use. In 2019, the agricultural water use was 276.2 billion m^3 in this region, which is 7% lower than that in 2010, indicating a continually declining trend.

(3) The extent of water resources development and water utilization

The water resource development and utilization rates were determined to assess the extent of water resource development and utilization in the Yellow River Basin. From 2010 to 2019, the water resource development and utilization rates were relatively high, being 73.72% in 2019, far exceeding the internationally recognized ecological warning line for water resource development of 40%. The water resource utilization rates of Qinghai, Sichuan, and Gansu were 4.51%, 0.39%, and 27.4%, respectively, which are lower than the internationally recognized level of rational development and utilization of surface water of 30%. The development and utilization rates of water resources in Shaanxi, Shanxi, and Shandong were 63.9%, 86.46%, and 97.39%, respectively, which far exceeded the standard of 40%. These provinces have faced water shortages and deterioration of the ecological environment. The utilization rate of Ningxia, Inner Mongolia and Henan provinces has exceeded 100%, and the local water demand needs to be alleviated through overexploitation of groundwater and diversion (Figure 3).

3.2. The situation of safe utilization of agricultural water resources

(1) Analysis of agricultural water resource utilization

Several irrigation areas in the Yellow River Basin are mainly distributed on both banks of the Huangshui River, Ganning and Ningxia Plateaus, Ningmeng River Tao Plain, Fenwei Basin, Lower Yellow River Plains of Henan Yiluoqin River, and Shandong Dawen River Valley. Among these, the Ningmeng Hetao Irrigation Area, the Fenwei Irrigation Area, and the Yinhuang

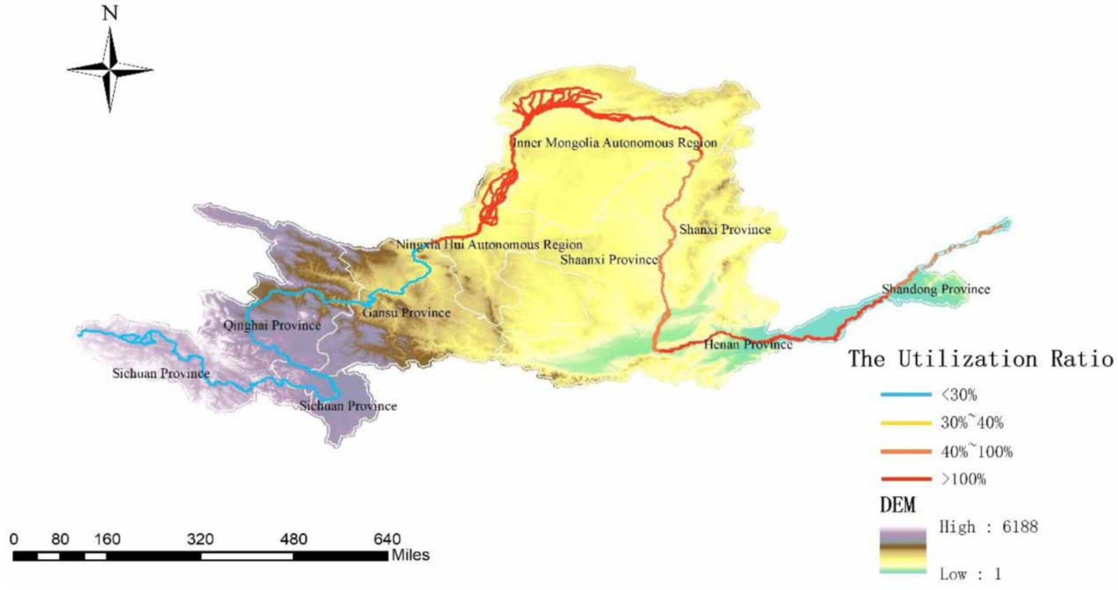

Figure 3 | The extent of water resources development and utilization.

Irrigation Area accounted for >70% of the entire irrigation area and 80% of the total water use. As the critical area driving China's agricultural economy, the Yellow River Basin directly bears the economic and social development of this region and ensures the country's food security. According to the statistics, the total arable land area of the basin is 166.3 million hm^2, with an effective irrigated area of 83.64 million mu. In 2019, the grain output of nine provinces along the Yellow River stood at 233.3834 million tonnes, accounting for 35.16% of the total national grain output. The Yinhuang Irrigation Area in the basin and outside its lower reaches constitute 16.6% of the country's total area, with an adequate irrigation area of 13.2%. The whole grain output in the lower reaches alone accounts for 13.4% of the national total.

The difference in the amount of agricultural irrigation water used in the upper and lower reaches of the basin is large. The effective utilization coefficients of irrigation water provinces, except for Gansu, Shaanxi, Henan, and Shandong, were lower than 0.559. The low overall level of agricultural water efficiency indicated a large scope for improvement (Zhang *et al.* 2015, Zhang & Xiao 2020). The long-term average agricultural water use was 28.6 billion m^3, representing 70.60% of the total water utilization of this basin, which is much higher than that of 40% in developed countries and 60–65% in developing countries.

(2) The quality of agricultural water

Several factors such as climate change, topography, soil environment, water resources, and irrigation methods affect the quality of crops. Earlier studies on agricultural water use were based on water resources. However, water quality contributes to the quality of crops and the sustainable development of soil, groundwater, and agricultural land (Hou *et al.* 2017). Water quality changes in the Yellow River Basin from 2001 to 2019 are shown in Figure 4.

The figure indicates that the proportion of Grades I–III water in the Yellow River Basin increased from 2001 to 2019, while the proportion of water with an inferior Grade V reduced significantly. Before 2005, the pollution level of water resources was extremely high, and the proportion of Grade V water was high. In 2001, Grade V water accounted for 56%, while Grades I–III water accounted for only 12%. The primary pollutants included dissolved oxygen, permanganate index, 5-day biochemical oxygen demand, volatile phenols, and petroleum. After several years of improvement in the river basin management and ecological protection status, water pollution in 2011 decreased. The water quality of the mainstream was better than that of the tributaries, and these tributaries were mainly distributed between Toudaoguai and Longmen in the middle reaches. Moreover, the Fen River on the left bank of the Yellow River and the Wei River on the right bank were heavily polluted.

In 2019, the water resources in this area were lightly polluted, while the mainstream of the Yellow River exhibited excellent water quality, albeit the tributaries were moderately polluted. Water resources above Grade III accounted for 72.9%, indicating a trend of gradual improvement. Polluted tributaries (lower than Grade V) were mainly distributed in the Shaanxi and Shanxi Provinces. For example, Fen River, the second-largest tributary of the Yellow River, was heavily polluted. The leading

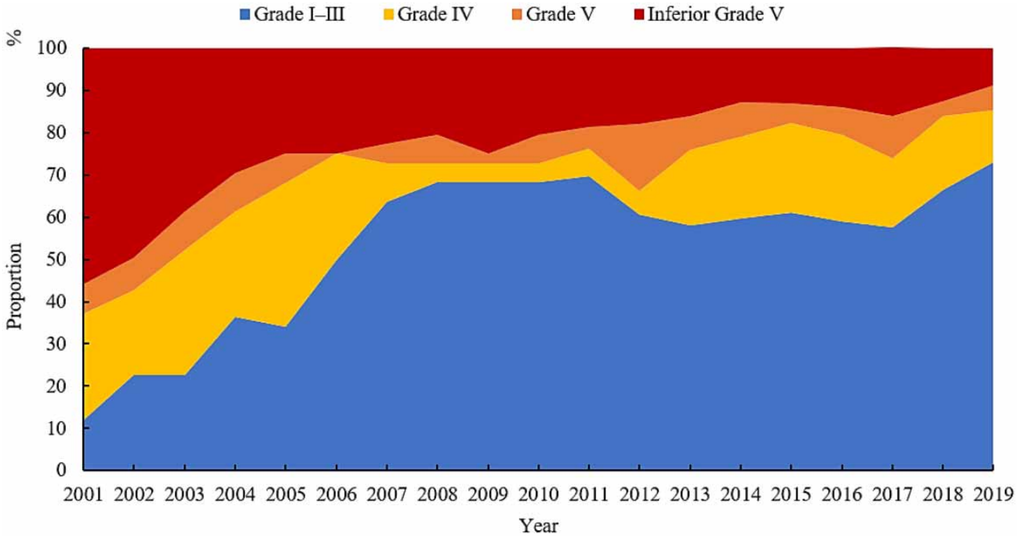

Figure 4 | Trends in water quality changes in the Yellow River Basin.

cause of Fen River pollution was the unsatisfactory treatment of industrial wastewater and domestic sewage, with the level of pollutants, such as chemical oxygen demand, ammonia nitrogen, total phosphorus exceeding the standard limits. If left uncontained, the water body of the river can be destroyed, thereby affecting the irrigation of the farmland and the growth of crops on either side of the bank. Owing to the low water quality requirements for agricultural water use, the present overall water quality of the Yellow River Basin can meet the requirements.

4. EVALUATION OF SAFE UTILIZATION OF AGRICULTURAL WATER RESOURCES

Based on the aforementioned analysis of water resource amount and the status quo of agricultural water resources in the Yellow River Basin, we evaluated the safe utilization of agricultural water resources. Presently, the evaluation methods employed for water resource security are both qualitative and quantitative in nature. Qualitative evaluation involves systematic analyses of the development status and the influencing factors of the regional economy, society, water resources, and ecological environment through observation, analysis, empirical judgement, and determination of the major influencing factors. The evaluation results of this method are highly subjective in nature. The quantitative evaluation involved quantification of the evaluation index using a comprehensive evaluation method such as fuzzy mathematical evaluation method, grey system theory evaluation method, and other evaluation models (Wu *et al.* 2008; Shu *et al.* 2013). When compared with qualitative evaluation, it is a more objective, standardized, and simple approach. In this study, we adopted a comprehensive evaluation model combining the cooperative game combined weights and the TOPSIS model to evaluate the agricultural water resource security in this region.

4.1. Establishment of the index system

Objective and reasonable evaluation can reflect the benefits generated by the safe utilization of agricultural water resources, thereby providing a scientific decision-making basis for the sustainable development of agriculture (Jia *et al.* 2002). Based on the basic principles of index selection and the connotation of the safe utilization of agricultural water resources, we established an evaluation index system to evaluate agricultural water resources, including water resources system, social system, economic system, and ecological system (Table 1).

4.2. Determination of the evaluation criteria

We evaluated the safe utilization of agricultural water resources in the Yellow River Basin. The data on the indicators were sourced from *the Bulletin of Yellow River Water Resources*, *Bulletins of Provincial Water Resources*, *the Yearbook of Statistics*, *the Ecological Environment Bulletin*, and *Regional Survey Reports*. Based on the evaluation research on relevant watershed (regional) water resources security and in the light of expert opinions, we categorized the evaluation indicators

Table 1 | Evaluation index system for the safe utilization of agricultural water resources

Objective	Systems	Evaluation index	Unit	The meaning of indicators
Safe utilization of agricultural water resources in the Yellow River Basin	Water resource system	Water production modulus (A1)	10,000 m^3/km^2	The number of water resources stored per unit area of the basin
		Irrigation water consumption per mu (A2)	m^3	The amount of per-unit water resources used to support farmland irrigation
		Rate of agricultural water consumption (A3)	%	The amount of water level for agriculture
		The rates of water resource development and utilization (A4)	%	The extent of development and use of water resources
	Social system	Per capita water resources (A5)	m^3	The distribution of water resources based on population
		Urbanization rate (A6)	%	The level of social and economic development
		Water quota for rural population (A7)	L/person·d	Per capita water consumption in rural areas
		Per capita food production (A8)	kg	Per capita share of food production
	Economic system	The effective utilization coefficient of irrigation water (A9)	–	The extent to which irrigation water is effectively used for crops
		Water use per 10,000 yuan of GDP (A10)	m^3	Water consumption for socio-economic development
		Water use per 10,000 yuan of agricultural output value (A11)	m^3	The burden of agricultural water on water resources
		Per capita GDP (A12)	10,000 yuan	Economic and social development level
	Ecological system	Ecological water replenishment ratio (A13)	–	Degree of regional attention to ecological civilization construction
		High-quality river length ratio (A14)	%	The proportion of the length of the Grade I~III river section
		The amount of chemical fertilizer used per unit of arable land (A15)	kg/km^2	The impact of agriculture on the quality of water resources
		Sewage treatment rate (A16)	%	Regional river water quality and sewage treatment system

into five grades: Grade I (Very Secure), Grade II (Secure), Grade III (Basic Secure), Grade IV (Relatively Insecure), and Grade V (Insecure). These grading results are summarized in Table 2.

4.3. Determination of combined weight

To make the index weight more objective and accurate, we applied both subjective and objective weighting methods to calculate the weight of the index and used the cooperative game to determine the combined weight of each indicator as follows:

(1) The Analytic Hierarchy Process (AHP) is a subjective weighting method. This clear, flexible, and widely used method can simplify complex issues. However, the weighting results are primarily affected by its subjectivity. The specific weight $w_j^{(1)}$ calculation process was introduced previously (Deng *et al.* 2012; Zhang *et al.* 2020).

(2) The entropy weight method (EWM) is an objective weighting method. Certain sample data are required for this method, which is then applied by using the variability between the sample information. The entropy weighting method is more objective than the AHP and the Delphi method. The calculation process of weight $w_j^{(2)}$ is given elsewhere (Lu *et al.* 2010).

(3) Based on the contrast strength and the conflict of evaluation indicators, the CRITIC method comprehensively measured the objective weight of the indicators. According to the variability of and the correlation between the indicators, the

Table 2 | The grading standard of evaluation index

	Grade					
Index	**Grade I Very Secure**	**Grade II Secure**	**Grade III Basic Secure**	**Grade IV Relative Insecure**	**Grade V Insecure**	**Indicator attributes**
A1	≥ 50	[35, 50)	[20, 35)	[10, 20)	<10	+
A2	<350	[350, 450)	[450, 550)	[550, 650)	≥ 650	−
A3	<30	[30, 45)	[45, 60)	[60, 75)	≥ 75	−
A4	<20	[20, 30)	[30, 40)	[40, 55)	≥ 55	−
A5	$\geq 5{,}000$	[3,000, 5,000)	[2,100, 3,000)	[1,000, 2,100)	$<1{,}000$	+
A6	<30	[30, 45)	[45, 60)	[60, 75)	≥ 75	−
A7	≥ 140	[120, 140)	[100, 120)	[80, 100)	<80	+
A8	≥ 500	[450, 500)	[400, 450)	[300, 400)	<300	+
A9	≥ 0.7	[0.6, 0.7)	[0.5, 0.6)	[0.4, 0.5)	<0.4	+
A10	<30	[30, 90)	[90, 150)	[150, 210)	≥ 210	−
A11	<450	[450, 900)	[900, 1,500)	[1,500, 2,000)	$\geq 2{,}000$	−
A12	$\geq 75{,}000$	[50,000, 75,000)	[35,000, 50,000)	[20,000, 35,000)	$<20{,}000$	+
A13	≥ 5.5	[3, 5.5)	[1, 3)	[0.5, 1)	<0.5	+
A14	≥ 100	[90, 100)	[80, 90)	[70, 80)	<70	+
A15	<2	[2, 3)	[3, 4)	[4, 5)	≥ 5	−
A16	≥ 100	[90, 100)	[70, 80)	[60, 70)	<60	+

Note: '+' is a positive indicator, meaning that the indicator promotes the targets; the '−' is a negative indicator, which inhibits the targets.

greater the conflict is, when the contrast between indicators is constant, it is positively correlated with the weight. The correlation of the indicators is negative with the conflict but positive with the corresponding weight (Diakoulaki *et al.* 1995; Guan *et al.* 2017). The main calculation process used herein is as follows:

1) Calculation of the contrast strength of the indicators after nondimensional processing of the indicators in the forward/reverse direction:

$$\begin{cases} \bar{x}_j = \dfrac{1}{n}\sum\limits_{i=1}^{n} x_{ij} \\ S_j = \left(\sum\limits_{i=1}^{n} (x_{ij} - \bar{x}_j)^2/(n-1)\right)^{0.5} \end{cases} \tag{1}$$

where $\bar{x}_j$ is the mean value of n evaluation samples, and S_j is the standard deviation of the jth index.

2) Calculation of the conflict of indicator R_j and the amount of information C_j:

$$R_j = \sum_{i=1}^{p} (1 - r_{ij}) \tag{2}$$

$$C_j = S_j \times R_j = S_j \sum_{i=1}^{p} (1 - r_{ij}) \tag{3}$$

where r_{ij} was the correlation coefficient between the evaluation indexes i and j. The greater conflict of indicator R_j indicated a weak correlation among indicators; the greater the amount of information C_j, greater was the weight value.

3) CRTTIC for weight calculation:

$$w_j^{(3)} = C_j / \sum_{j=1}^{p} C_j \tag{4}$$

(4) The cooperative game method consisted of various methods and weighed the interests of multiple parties, thus delivering more accurate results. The process of determining the combined weights is as follows (Chen & Yang 2013):

1) Calculation of the consistency correlation coefficient of $L_j^{(l)}$ between $w_j^{(l)}$ and $w_j^{(y\_l)}$:

$$L_j^{(l)} = \frac{\sum_{j=1}^{n}[w_j^{(l)} - \bar{w}_j^{(l)}][w_j^{(y-l)} - \bar{w}_j^{(y-l)}]}{\left\{\sum_{j=1}^{n}[w_j^{l} - \bar{w}_j^{l}]^2\right\}^{1/2}\left\{\sum_{j=1}^{n}[w_j^{(y-l)} - \bar{w}_j^{(y-l)}]^2\right\}^{1/2}} \tag{5}$$

where $w_j^{(l)}$ represent the l^{th} weight ; $\bar{w}_j^{(l)}$ represents the mean of the l^{th} weight; $w_j^{(y\_l)}$ is the combined weight of y-l weights, except $w_j^{(l)}$; $\bar{w}_j^{(y-l)}$ is the combined $y - l$ weights of except $w_j^{(l)}$.

2) Calculation of $w_j^{(y\_l)}$, when $y = 3$:

$$\begin{cases} w_j^{(3\_1)} = \dfrac{w_j^{(2)} + w_j^{(3)}}{2}, l = 1 \\ w_j^{(3\_2)} = \dfrac{w_j^{(1)} + w_j^{(3)}}{2}, l = 2 \\ w_j^{(3\_3)} = \dfrac{w_j^{(1)} + w_j^{(2)}}{2}, l = 3 \end{cases} \tag{6}$$

3) Calculation of the combined weight:

$$W_j = \sum_{j=1}^{n} w_j^{(l)} L_j^{(l)} \tag{7}$$

4.4. Weighted TOPSIS model

TOPSIS model, also known as the approximate ideal solution ranking method, is usually applied for multi-objective decision evaluation. This method is universal compared with the single-objective assessment. However, the conventional TOPSIS model is influenced by subjective factors for determining the evaluation index weights, and there may be some differences between the obtained evaluation results and the actual values (Lei *et al.* 2016). Therefore, we applied the cooperative game method to determine the combined weights to improve the positive and negative ideal solutions of the evaluation objects and establish a weighted TOPSIS model to evaluate the agricultural water security in the Yellow River Basin.

The main calculation steps of the model are as follows:

1) Establishment of a weighted decision matrix:

The cooperative game method was adopted to determine the combined weight set W_j, and $Z = W_j \times X_{ij}$ was applied to establish a weighted normalized decision matrix $Z = (\mathrm{z_{ij}})_{\mathrm{m \times n}}$, where $\mathrm{z_{ij}} = w_j \times x_{ij}$.

2) Determination of the positive and negative ideal solutions Z_j^{+}和Z_j^{-}:

$$Z_j^{+} = \{maxz_{ij}|j = 1, 2, \cdots, n\} = \{Z_1^{+}, Z_2^{+}, \cdots, Z_n^{+}\} \tag{8}$$
$$Z_j^{-} = \{minz_{ij}|j = 1, 2, \cdots, n\} = \{Z_1^{-}, Z_2^{-}, \cdots, Z_n^{-}\} \tag{9}$$

3) Calculation of the distance between the sample object and the positive and negative ideal solutions $\mathrm{D_i^{+}}$ and $\mathrm{D_i^{-}}$:

$$D_i^{+} = \sqrt{\sum_{j=1}^{n}(Z_j^{+} - Z_{ij})^2} \tag{10}$$

$$D_i^{-} = \sqrt{\sum_{j=1}^{n}(Z_j^{-} - Z_{ij})^2} \tag{11}$$

4) Calculation of closeness T_i (safe water utilization index):

The closeness value of T_i ranges from 0 to 1. The closer the value of T_i is to 1, the closer is the sample to the positive ideal point, which hints at better evaluation result and vice versa.

$$T_i = \frac{D^-}{D_i^+ + D_i^-} \tag{12}$$

4.5. Evaluation results and analysis

(1) Determination of the indicator weights

Based on the present situation of agricultural water resources in the Yellow River Basin, we established a comprehensive evaluation index system for the safe utilization of agricultural water resources and determined the combined weights by using the cooperative game method. As shown in Table 3, the water resource system and the social system had large weights, indicating that their influence on the use of agricultural water resources was strong. According to the combined weight results of the evaluation indexes, the irrigation water consumption per mu (0.1081), per capita water resources (0.1587), effective utilization coefficient of irrigation water (0.0684), and ecological water recharge ratio (0.0563) indicated greater weights in each system, suggesting that the safe utilization of agricultural water resources in the basin was influenced by agricultural irrigation water and human activities. Simultaneously, improving the agricultural water utilization efficiency and increasing the ecological water recharge ratio are critical approaches to ensure the safe utilization of agricultural water resources.

(2) Results and analysis of agricultural water security evaluation

To evaluate the results objectively and reasonably, we established a standardized decision matrix with evaluation indexes and critical values for grading criteria to calculate the closeness of each grade index using the weighted TOPSIS model. The closeness value T_i corresponded to the grade interval of Grade I (0.3615,1.0000), Grade II (0.2731,0.3615), Grade III (0.1838, 0.2731), Grade IV (0.1280, 0.1838), and Grade V (0.0000, 0.1280). The calculation results show the gradation of safe water utilization for each province (district) in the Yellow River Basin (Figure 5).

As evident from Figure 5, the utilization of agricultural water resources in the Sichuan Province basin was in a very secure state; that of Qinghai, Shaanxi, Henan, and Shandong Provinces was in a secure state; that of Gansu, Inner Mongolia, and

Table 3 | Weight calculation results

Systems	**Evaluation index**	**AHP**	**EWM**	**CRITIC**	**Combined weights**
Water resource system (0.2779)	Water production modulus (A1)	0.0515	0.0651	0.0619	0.0572
	Irrigation water consumption per mu (A2)	0.1629	0.0338	0.0523	0.1081
	Rate of agricultural water consumption (A3)	0.0361	0.0472	0.0679	0.0432
	The rates of water resource development and utilization (A4)	0.0967	0.0282	0.0550	0.0694
Social system (0.3410)	Per capita water resources (A5)	0.0750	0.3287	0.0688	0.1587
	Urbanization rate (A6)	0.0217	0.1584	0.0553	0.0708
	Water quota for rural population (A7)	0.0697	0.0138	0.0614	0.0502
	Per capita food production (A8)	0.0697	0.0462	0.0639	0.0613
Economic system (0.1865)	The effective utilization coefficient of irrigation water (A9)	0.1109	0.0008	0.0563	0.0684
	Water use per 10,000 yuan of GDP (A10)	0.0308	0.0288	0.0504	0.0322
	Water use per 10,000 yuan of agricultural output value (A11)	0.0786	0.0416	0.0603	0.0643
	Per capita GDP (A12)	0.0158	0.0179	0.0628	0.0215
Ecological system (0.1946)	Ecological water replenishment ratio (A13)	0.0776	0.0223	0.0504	0.0563
	High-quality river length ratio (A14)	0.0409	0.0147	0.0826	0.0367
	The amount of chemical fertilizer used per unit of arable land (A15)	0.0130	0.1074	0.0689	0.0504
	Sewage treatment rate (A16)	0.0491	0.0449	0.0818	0.0512

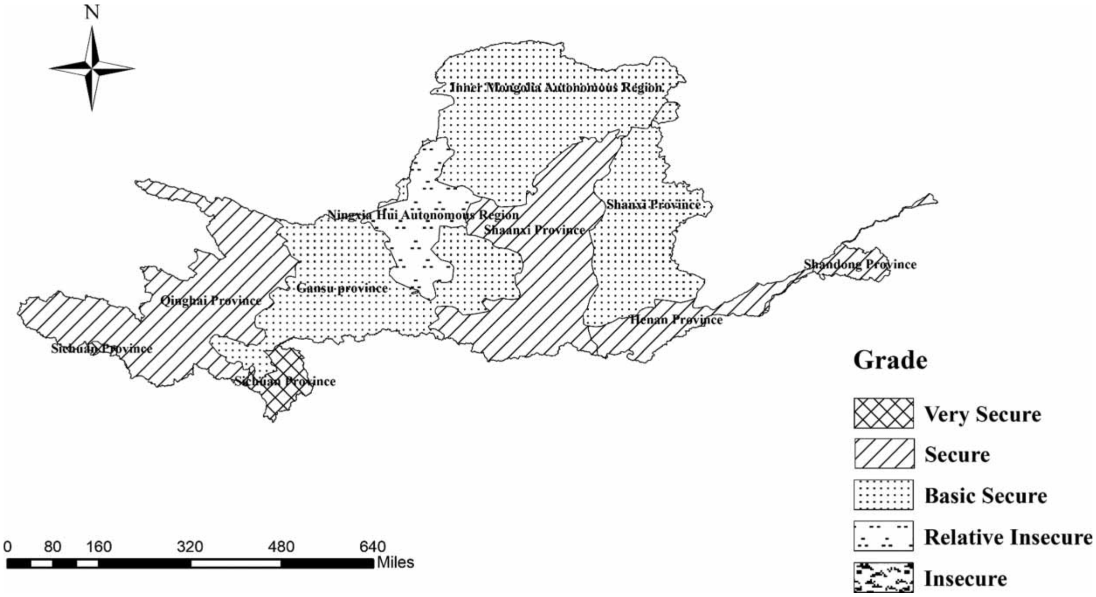

Figure 5 | Evaluation results of the safe utilization of agricultural water resources in the Yellow River Basin provinces (districts).

Shanxi Provinces was in a basic secure state; while that of Ningxia Province was in a less secure state. Overall, the agricultural water resource utilization in the Yellow River Basin was in the state of basic security or higher state. According to the evaluation results and the comprehensive analysis of the development status of the Yellow River Basin, the economic, social, industrial, and agricultural development in the upper, middle, and lower reaches of the basin varied. Except in Qinghai, Sichuan, and Gansu, the water resources utilization and development rates in other provinces were high (more than 40% of the ecological alert line). In terms of water content per unit area in the basin, the upstream areas of Qinghai (209,900 m^3/km^2) and Sichuan (360,000 m^3/km^2) are rich in water resources, while that in Ningxia (24,300 m^3/km^2) and Inner Mongolia (32,600 m^3/km^2) is lower than the water content per unit area in the Yellow River Basin. At the same time, there are many irrigated areas/farms in the Yellow River Basin, and the water demand for agricultural irrigation is high. During 2010–2019, Inner Mongolia had the largest, and Ningxia had the second-largest agricultural water consumption. The average irrigated water consumption per mu in the agricultural water use index was significantly higher in the upstream areas than in the downstream area. The average irrigation water consumption per mu in Ningxia, the largest province, was four times higher than that in Henan, the smallest province. However, the per capita grain production in the middle and downstream areas was higher than in the upstream areas. The aforementioned results indicated that the safe utilization of agricultural water resources in the basin was not only affected by natural geographical conditions but also closely related to the differences in crop types and irrigation systems between upstream and downstream areas and the construction of water-saving facilities.

5. COUNTERMEASURES FOR SAFE UTILIZATION OF AGRICULTURAL WATER RESOURCES IN THE YELLOW RIVER BASIN

(1) The reforms in agricultural water use structure in the basin should be guided through water rights allocation to improve the farm water use pattern. Theoretical research focusing on ensuring the security of water supply, food security, and ecological security in the basin should be conducted. Analysis of the current economic, social, and ecological development and the utilization of water resources in the basin can reveal the interrelationship between different systems and help improve the agricultural water use model. The development of agriculture in the basin can be integrated with the development of the water property rights system. Reforms can be introduced in the agricultural water use structure through water rights allocation with 'total control and quota management' as the guiding principle. Further improvements such as optimizing the agricultural planting structure, irrigation method, and irrigation system are required so that limited water resources can provide maximum benefits and improve water conservation in the basin, thereby promoting water use transformation from extensive to intensive.

(2) Upgradation and transformation of agricultural water-saving facilities in the basin should be vigorously promoted, application of water-saving irrigation technology should be promoted, and the utilization efficiency of agricultural water resources should be effectively improved. For example, in Hetao Plain, controlling plantations and planting low water-consuming plants can help optimize the planting structure and reduce water consumption in downstream areas. In the downstream areas, the use of groundwater for agricultural irrigation should be strictly controlled, the reduction and efficiency of chemical fertilizer, should be promoted, and the utilization efficiency of water and fertilizer should be improved. In Henan Province, the guidance on winter wheat spring moisture measurement irrigation technology has been formulated, which can significantly improve the water utilization efficiency of winter wheat and promote efficient utilization of agricultural water resources. Conducting research on soil moisture parameters in different spaces in the basin can provide better solutions for water-saving irrigation planning and flood prediction. Findings of this research may be valuable in the hydrological cycle, water-saving irrigation planning, groundwater recharge and water resources management (Angelaki *et al.* 2021).

(3) The construction of intelligent metering facilities should be accelerated, and automation in agriculture management and intelligent management of agricultural water in the basin should be established using information technology. During the '14th Five-Year Plan' implementation, application of information technology (IT) in managing agricultural water resources will be essential. Gradual improvement in the operational efficiency and risk control of irrigation projects in the basin through modern IT like real-time monitoring of water conditions and sound water dispatching plans are required. During the '13th Five-Year Plan', the Hetao irrigation district had created integrated water resources information projects and formed a unified information platform based on the experience of the past 10 years (Sun *et al.* 2021). For the development of agricultural information in the basin, the knowledge from the Hetao irrigation information platform accumulated over the years can be used to create a 'regional (point)-inter-regional(line)-basin-wide(surface)' water resources information platform. Such a platform can help monitor and forecast the climate, crop irrigation, drought, and water dispatching in large irrigation areas in the basin in real-time, strengthen coordination ability and efficiency of management units, and modernize irrigation area management.

(4) A reliable water resources management system should be constructed to achieve safe utilization of agricultural water resources. On the basis of overall consideration of water resources conditions and food security in the basin (region), river basin management should involve strengthening system construction, establishing and perfecting water resources management system, and guiding the safe utilization of agricultural water resources in the basin by implementation of policies and regulations. Water resources should be considered as the largest constraint so that agricultural production can be standardized, and the carrying capacity of water resources in the basin should be regularly evaluated. Attention must be paid to the 'peaceful accumulation of problems', and water sustainability should be ensured. According to the statistics, the water resources per unit area in Ningxia Province and other basin regions is low. However, the average irrigation water consumption per mu is large, and the water resources development and utilization rates far exceed the internationally accepted standards. To guarantee the safe utilization of agricultural water resources, agricultural development in Ningxia Province and other areas should involve promoting the water-saving irrigation technology while adhering to the principle of setting land and production by water. In addition, constructing a comprehensive water property rights system, introducing reforms at agricultural water prices, improving the water price formation mechanism, establishing an agricultural water conservation incentive mechanism, and protecting the legitimate rights and interests of farmers in water use can eventually help achieve the objective.

6. CONCLUSIONS

Based on the basic characteristics of water resources in the Yellow River Basin and the connotation of safe utilization of agricultural water resources, the present study used the cooperative game weighted TOPSIS model to evaluate the safe utilization of agricultural water resources in 2019. The results show that the utilization of agricultural water resources in the basin, except in Ningxia, is basically secure and in a relatively higher level. According to the current situation of watershed development, the temporal and spatial distribution of water resources in the watershed is uneven, and there are great differences in economic and social development. The amount of water used for agricultural irrigation in the upper reaches is significantly higher than that in the middle and lower reaches; however, the grain output is lower than that in the lower reaches, indicating that the upper reaches need to speed up and improve the construction of agricultural water-saving projects and optimize the crop planting mode for agricultural development, while the lower reaches should pay attention to improving the utilization efficiency of water resources for the social and economic development to promote safe utilization of agricultural water resources in the basin. This study is of great significance to promote effective implementation of the national Yellow River strategy.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

REFERENCES

Angelaki, A., Sihag, P., Sakellariou-Makrantonaki, M. & Tzimopoulos, C. 2021 The effect of sorptivity on cumulative infiltration. *Water Supply* **21** (2), 606–614.

Chen, N. X. & Yang, Q. X. 2013 Set pair analysis of watershed water resources carrying capacity based on game theory combination weighting. *Journal of Irrigation and Drainage* **32** (2), 81–85.

Dang, L. J. 2020 Analysis and evaluation of water resources development and utilization in the Yellow river basin. *Water Resources Development and Management* **07**, 33–40.

Deng, X., Li, J. M., Zeng, H. J., Chen, J. Y. & Zhao, J. F. 2012 Research on computation methods of AHP weight vector and its applications. *Mathematics in Practice and Theory* **42** (7), 93–100.

Diakoulaki, D., Mavrotas, G. & Papayannakis, L. 1995 Determining objective weights in multiple criteria problems: the critic method. *Computers & Operations Research* **22** (7), 763–770.

Falkenmark, M. 2013 Adapting to climate change: towards societal water security in dry-climate countries. *International Journal of Water Resources Development* **29** (2), 123–136.

Grey, D. & Sadoff, C. W. 2007 Sink or swim? water security for growth and development. *Water Policy* **9** (6), 545–571.

Guan, X. J., Liu, W. K. & Hu, D. 2017 Application of pollution index method in water quality evaluation of Qingyihe river based on CRITIC weight. *Water Resources and Power* **35** (8), 49–52.

Hou, K., Li, Y. B., Qian, H. & Yang, M. 2017 Optimization of water quality monitoring cross-sections of the main stream of Yellow River in Ningxia. *South-to-North Water Transfers and Water Science & Technology* **15** (3), 100–107.

Hu, S. H., Chen, Q. H., Zhang, G. H. & Li, M. Z. 2012 Trend analysis of water resources utilization in the Yellow River Basin. *Journal of Water Resources and Water Engineering* **23** (2), 112–115.

Jia, S. F., Zhang, J. Y. & Zhang, S. F. 2002 Regional water resources stress and water resources security appraisement indicators. *Progress in Geography* **21** (6), 538–545.

Lei, X. P., Robin, Q. & Liu, Y. 2016 Evaluation of regional land use performance based on entropy TOPSIS model and diagnosis of its obstacle factors. *Transactions of the Chinese Society of Agricultural Engineering* **32** (13), 243–253.

Liu, B. C., Mei, X. R., Li, Y. Z. & You, Y. L. 2006 The connotation and extension of agricultural water resources security. *Scientia Agricultura Sinica* **05**, 947–951.

Lu, S. B., Huang, Q., Sun, X. Y. & Wu, C. G. 2010 The applied research of entropy proportion in the tendering procedures. *Journal of Hydroelectric Engineering* **3**, 221–224. + 176.

Partnership, G. W. 2000 Towards water security: a framework for action. *Seguridad Hidrica* **37** (1), 111–122.

Shu, R. Q., He, T. R. & Ban, R. P. 2013 Fuzzy comprehensive evaluation of water resources security of Shapingba District in Chongqing City. *Water Resources and Power* **31** (8), 31–33.

Sun, L., Yu, Y. T., Liu, S., Ao, Y. F. & Bian, H. M. 2021 Building a ‘smart irrigation area’ in the Yellow River Basin – a preliminary study on the current situation and development of Hetao irrigation area modernization. *Inner Mongolia Water Resources* **9**, 42–43.

Wu, K. Y., Jin, J. L., Zhou, Y. L. & Wang, W. S. 2008 Set pair analysis based variable fuzzy set assessment model for watershed water resources security. *Journal of Sichuan University (Engineering Science Edition)* **3**, 6–12.

Xia, J. 2002 A perspective on hydrological base of water security problem and its application study in North China. *Progress in Geography* **21** (6), 517–526.

Ye, Z. W. 2003 Discussion on agricultural water resources security and rural water conservancy adjustment strategy in China. *Rural Economy* **10**, 3–5.

Zhang, J. P. & Xiao, H. L. 2020 Past, current and future prospect for research on agricultural water use in Irrigation Districts in the Yellow River Basin. *Journal of Irrigation and Drainage* **39** (10), 9–17.

Zhang, H., Liu, Q. J. & Shi, S. J. 2015 Study of comprehensive evaluation of agricultural water resources utilization efficiency in the Yellow River Basin. *Meteorological and Environmental Sciences* **38** (2), 72–76.

Zhang, X. Y., Du, X. F. & Li, Y. B. 2020 Comprehensive evaluation of water resources carrying capacity in ecological irrigation districts based on fuzzy set pair analysis. *Desalination and Water Treatment* **187**, 63–69.

Zheng, H. T. 2003 Discussions on water resources safety and water resources safety warning. *China Water Resource* **11**, 19–22 + 5.

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