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Comprehensive evaluation of water resources security in the Yellow River basin based on a fuzzy multi-attribute decision analysis approach

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Abstract. In this paper, a fuzzy multi-attribute decision analysis approach (FMADAA) was developed for supporting the evaluation of water resources security in nine provinces within the Yellow River basin. A numerical approximation system and a modified left–right scoring approach were adopted to cope with the uncertainties in the acquired information. Also, four conventional multi-attribute decision analysis (MADA) methods were implemented in the evaluation model for impact evaluation, including simple weighted addition (SWA), weighted product (WP), cooperative game theory (CGT) and technique for order preference by similarity to ideal solution (TOPSIS). Moreover, several aggregation methods including average ranking procedure, Borda and Copeland methods were used to integrate the ranking results, helping rank the water resources security in those nine provinces as well as improving reliability of evaluation results. The ranking results showed that the water resources security of the entire basin was in critical condition, including the insecurity and absolute insecurity states, especially in Shanxi, Inner Mongolia and Ningxia provinces in which water resources were lower than the average quantity in China. Hence, the improvement of water eco-environment statuses in the above-mentioned provinces should be prioritized in the future planning of the Yellow River basin.

1 Introduction

Water is a fundamental resource for sustainable development of human society. Also, it is a critical factor for maintaining natural ecosystems. Water conflicts between human and ecosystems are posing great challenges for maintaining sustainability of water resources at the watershed scale. Along with the increasing consumptions of water resources by multiple users, water security crisis becomes an emerging issue that is facing decision-makers in many regions. How can the water resources be effectively allocated among the multiple water users without causing damages on local ecosystems? A balance between human beings and ecosystems needs to be maintained based on the introduction of water security not only for human society but also for local ecosystems. The development of an effective method is thus desired to help evaluate water security and facilitate the management of water resources scarcity (Brown and Hilweil, 1987; Loucks, 2000; WWAP, 2002; Chen, 2004; Zhang, 2010).

Water resources security is a concept that was proposed in the late 20th century (Jiang, 2001; Jia et al., 2002; Zheng, 2003; Xia and Zhang, 2007). It is generally believed that at a certain stage of social and economic development, water supply that can ensure both the quality and quantity is able to meet the needs of human survival, social progress, and economic development and is able to maintain a good ecological environment on the basis of not exceeding the carrying capacity of water resources and water eco-environment. This implies the desire to safeguard sustainable economic and social development based on sustainable water resources utilization. The evaluation and insurance of water security are the core issues of sustainable water resources management. Conventionally, water resources supporting capacity is considered as a basic water security measure which can be adopted for supporting the establishment of an evaluation–indicator system. At the same time, some scholars argue that water resources security's core point lies in the sustainability of water use. If water resources in a region can be used sustainably, then, its water can be considered safe. According to this theory, the indicator system can be established including targets, criteria and indicators. The evaluation can be carried on in accordance with the indicators in five aspects including water resources availabilities, water resources exploitation and utilization efficiencies, external eco-environment conditions, water resources deployment conditions, and ability in managing water resources (Jia and Zhang, 2003; Zhang and Jia, 2003; Jia et al., 2004; Zhang et al., 2005, 2008).

At the same time, many evaluation methods were developed for evaluating water resources sustainability, such as those based on statistic analysis, data envelopment analysis, principal components analysis, system dynamics method, "pressure–state–response" modeling, set pair analysis, vague set evaluation, fuzzy element model, water-poor exponential method, artificial neural networks, element analysis and so forth. Many scholars have applied these methods to many real-world cases (Han et al., 2001; Cong, 2007; Zhu et al., 2008). Because the uncertain factors in the indicator system have great influences on the scientificity of evaluation, in order to deal with non-linear optimization of the evaluation process, the expression of implicit functions, fuzzy and random problems, the uncertainty evaluation methods and intelligent methods of integrated assessment methods gradually emerged. Among those methods, fuzzy multi-attribute decision analysis approach (FMADAA) was one of the effective methods for multiple-criteria decision support. For example, it was adopted in a landfill selection problem in the city of Regina and was considered as a powerful tool for decision analysis. More recently, it has been rapidly developed in numerous fields such as management, engineering, and so on (Buede, 1996; Eom, 1999; Yu et al., 2004; Cai et al., 2009; Parviz and Saeed, 2010; George and Mike, 2011; Harrison et al., 2011; Ana et al., 2012).

In the last two decades, the amount of water resources has decreased significantly in the Yellow River basin of China. The problem of water shortage has become extremely serious (Li et al., 2004; Shen and Li, 2009; Li and Yang, 2004). Besides, water supply can not sufficiently meet the needs of industry, agriculture, residential and ecological sectors, which has made water security a particularly prominent problem affecting the economical and social development in the basin. In recent years, many scholars put their effort on the calculation of the supplied water quantity and requirement in order to analyze water utilization and water allocation (Xia et al., 2009) in order to provide support for water resources management in the Yellow River basin. However, a few researchers have carried out comprehensive water security evaluation in the Yellow River basin, especially in the analysis on the regional differences of the entire basin, which is important to the management in the basin. Therefore, the security evaluation in administrative regions of the basin is extremely necessary in order to promote the overall water resources security and to guarantee the coordinated development in the basin.

Since MADA aims to identify optimal alternatives for decision-makers, it is effective in supporting relevant decision-making processes. That is to say, various alternatives can be ranked according to certain criteria. Each region of the Yellow River basin can be considered as an alternative and each evaluation method can be considered as a criterion or an attribute. Also, in order to reflect uncertainties associated with the process, FMADAA needs to be adopted. It is suitable for evaluating water resources security in the Yellow River basin. Moreover, since the ranking results of different methods are inconsistent in practical application, the results will also be integrated, which could enhance applicability and accuracy of the results. In addition, fuzzy information usually encountered in practical evaluation processes can also be dealt with. Therefore, in the paper, we will adopt FMADAA to carry on the water resources security evaluation in the Yellow River basin in order to provide support for water management in the basin.

2 Overview of the Yellow River basin

The Yellow River is the second longest river in China. In total, the river flows over 5400 km, passing through nine provinces and autonomous regions. As the biggest basin in northwest and North China, the Yellow River basin is of utmost importance for China in terms of food production, natural resources, and socioeconomic development. The Yellow River basin covers an approximately 0.752 million km^2 area (not including inland), accounting for eight percent of the total area of China. Most areas of the Yellow River basin are in arid, semi -arid, and semi-humid climate zones, and it is one of the regions in China with the least water (Fig. 1). Affected by human activities and climate change, the Yellow River water resource has decreased significantly in recent years. Hence, water security problems, especially the disparity between supply and demand of water, and the gradual deterioration of the water eco-environment are particularly prominent and seriously affect economic and social development. Meanwhile, future climate change may further exacerbate regional droughts and floods, affecting the water supply and security of the Yellow River.

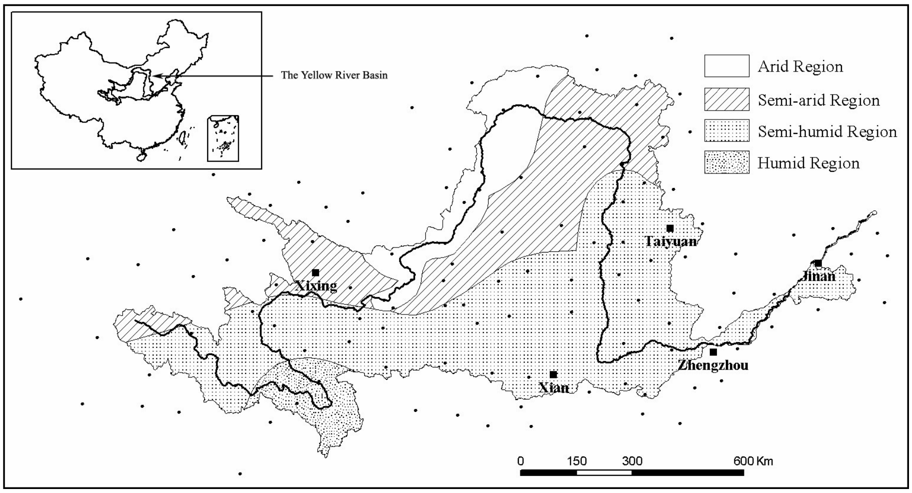

Fig. 1. The Yellow River basin.

Considering the data availability, we selected 2006 to be the evaluation year to analyze the current situation of water resources security in the Yellow River basin. Meanwhile, the data are derived from "Comprehensive Planning in the Yellow River Basin" (Yellow River Conservancy Committee of the Ministry of Water Resources, YRCC, MWR, 2009), "Water Resources Comprehensive Planning in the Yellow River Basin" (Yellow River Conservancy Committee of the Ministry of Water Resources, YRCC, MWR, 2009), related materials and statistical yearbook of the Yellow River (Yellow River Conservancy Committee of the Ministry of Water Resources, YRCC, MWR, 2006).

3 Development of a water security evaluation system

3.1 Evaluation indicators

We established the "pressure–state–response" water resources security evaluation model system which covered the indicators reflecting the water security situation in the Yellow River basin. "Pressure" system refers to those resources and social and economic factors which may cause pressure on the system, where the indicators are the decisive factors of the security of system. "State" system is the system status under the action of resources and social and economic indicators. "Response" system refers to the sensitivity and adaptability of the system to the actions of resources and social and economic indicators as well as the various measures taken to decrease the aggravation of water resources security. Each sub-system is established from three aspects, including water resources, socio-economic and water environment (Jia et al., 2002).

The indicator selection methods used in this paper contain a frequency statistical method, theoretical analysis and expert consultation (Delphi method). Based on the feedback from experts, a fuzzy analytic hierarchy process (FAHP) is adopted as the system analysis method to determine the water security evaluation indicator system (Zhang, 2000). Hence, the indicator system can be established, with the connotations and calculations of indicators shown in Table 1.

The evaluation criteria of the Yellow River basin has only a relative sense; we took the national data as a benchmark to set the evaluation criteria. The main references for determining the criteria mainly include the statistical data, relevant standards, norms, procedures, development plan, existing research results and so forth. In this paper, five interval evaluation criteria have been formulated, followed by absolute security, security, critical security, insecurity and absolute insecurity. Based on the evaluation criteria, the standards of the evaluation system were determined, which are shown in Table 2. A fuzzy analytic hierarchy process (FAHP) is adopted to determine the weights of indicators, and the calculation steps are the same as in the establishment of the water resources security evaluation indicator system. The weights of indicators were also obtained, which are shown in Table 3.

3.2 Fuzzy multi-attribute decision analysis approach

A fuzzy multi-attribute decision analysis approach (FMADAA) is applied for security evaluation. The proposed FMADAA is composed of four phases. In the first phase, the evaluation alternatives should be established. The second phase is fuzzy impact transformation, which consists of two major steps: (1) linguistic-term conversion that transforms the impact values into a fuzzy set if they are verbal terms; and (2) conversion from a fuzzy set to a crisp value set where all the fuzzy sets are assigned crisp scores. The result of this phase is to produce a new impact matrix that only contains numeric data. In the third phase, classical MADM methods can be utilized to determine the ranking order of alternatives. Finally, in the fourth phase, when the results of different

Table 1. Water resources security evaluation indicator.

Evaluation indicator				Calculation formula	Indicator unit	Indicator meaning	Indicator type
Pressure indicators B1	Water resources pressure indicators C1	D1	Water production coefficient	Total amount of water resources/precipitation		Reflect the amount of water resources	positive
		D2	Annual runoff	Regional runoff/evaluation area	mm	Reflect the amount of water resources	positive
		D3	Modulus of groundwater resources	Groundwater resources amount/evaluation area	10^4 m^3 km^{-2}	Reflect the amount of groundwater resources	positive
		D4	Modulus of water resources	Total amount of water resources/evaluation area	10^4 m^3 km^{-2}	Reflect the amount of water resources	positive
		D5	Water utilization rate	Water consumption amount with the exception of eco-environmental water consumption/total amount of water resources × 100 %	%	Reflect the development and utilization of water resources	negative
	Socio-economic pressure indicators C2	D6	Development degree of surface water	Exploitation amount of surface water/surface water resources amount	%	Reflect the development and utilization of surface water resources	negative
		D7	Development degree of groundwater	Exploitation amount of groundwater/groundwater resources amount	%	Reflect the development and utilization of groundwater resources	negative
		D8	Water consumption per 10 000 Yuan of GDP	Total amount of water consumption/GDP	m^3/10 000 Yuan	Reflect the economic water consumption level	negative
		D9	Water consumption per 10 000 Yuan of industrial output	Total amount of water consumption/industrial output	m^3/10 000 Yuan	Reflect the economic water consumption level	negative
	Water environment pressure indicators C3	D10	Ratio of pollutants (COD and ammonia nitrogen) dumped into the river	Pollutants (COD and ammonia nitrogen) amount/annual runoff	t/10^4 m^3	Reflect the discharge condition of the contaminants from the waste water	negative
		D11	Area ratio of excessive extraction of groundwater	Excessive extraction area of groundwater (depression funnel)/evaluation area × 100 %	%	Reflect the excessive extraction condition of groundwater	negative
State indictors B2	Water resources state indicators C4	D12	Index of water resources demand–supply balance (IWDS)	Average water demand amount/water supply amount		Reflect the water demand–supply balance condition	negative
		D13	Water resources amount per capita	Total amount of water resources/total population	m^3/person	Reflect the amount of water resources and water scarcity condition	positive
	Socio-economic state indicators C5	D14	Water supply modulus	Water consumption amount/evaluation area	10^4 m^3 km^{-2}	Reflect the intensity of water supply	positive
		D15	Water supply amount per capita	Water consumption amount/total population	m^3/person	Reflect the intensity of water supply	positive
		D16	GDP per capita	GDP/total population	10 000 Yuan/person	Reflect the overall economic condition	positive

Table 1. Continued.

Evaluation indicator				Calculation formula	Indicator unit	Indicator meaning	Indicator type
		D17	Ratio of agricultural water consumption to total consumption	Agricultural water consumption amount/ water consumption amount × 100 %	%	Reflect the agricultural water consumption level and the structure of water consumption	negative
		D18	Domestic water consumption per capita	Domestic water consumption amount/total population/365	L/(d · person)	Reflect the living water security condition	positive
		D19	Eco-environment water consumption ratio	Eco-environment water consumption amount/total population × 100 %	%	Reflect the eco-environment water security condition	positive
	Water eco-environment state indicators C6	D20	Ratio of soil erosion area to the total area	Soil erosion area/ evaluation area × 100 %	%	Reflect the soil erosion condition	negative
		D21	Up-to-standard rate of water quality in water function area	Number of up-to-standard water function area/total number of water function area × 100 %	%	Reflect the water quality condition in the function area	positive
		D22	Ratio of up-to-standard river length of water quality to the total river length	Up-to-standard river length of water quality/ total evaluation river length × 100 %	%	Reflect the river water quality condition	positive
		D23	Ratio of class I, II and III groundwater area of water quality to the total area	Class I, II and III groundwater area of water quality/total evaluation area × 100 %	%	Reflect the groundwater quality condition	positive
Response indictors B3	Socio-economic response indicators C7	D24	Water conservancy investment rate	Water conservancy investment amount/ GDP × 100 %	%	Reflect the water conservancy investment condition	positive
		D25	Industrial water re-utilization rate	Industrial water re-utilization amount/ industrial water consumption amount × 100 %	%	Reflect the industrial water-saving condition	positive
		D26	Effective irrigation coverage rate	Effective irrigation area/cultivated land area × 100 %	%	Reflect the irrigation level	positive
		D27	Water irrigation efficiency	Field water consumption amount/water intake amount in the field		Reflect the quality of the irrigation project, the level of irrigation technology and the water irrigation management condition	positive
		D28	Water-saving irrigation rate	Water-saving irrigation area/effective irrigation area × 100 %	%	Reflect the irrigation water-saving condition	positive
		D29	Leakage rate of water supply pipe network	(Urban water supply amount − effective water supply amount)/urban water supply amount × 100 %	%	Reflect the urban water-saving condition	negative

Table 1. Continued.

Evaluation indicator		Calculation formula	Indicator unit	Indicator meaning	Indicator type
D30	Water-saving appliances penetration rate	Water-saving appliances penetration families/total families × 100 %	%	Reflect the urban water-saving condition	positive
D31	Ratio of urban population access to up-to-standard drinking water to the total urban population	Urban population access to up-to-standard drinking water/total urban population × 100 %	%	Reflect the urban drinking water condition	positive
D32	Ratio of rural population access to up-to-standard drinking water to the total rural population	Rural population access to up-to-standard drinking water/total rural population × 100 %	%	Reflect the rural drinking water condition	positive
D33	Perfection degree of management system and legal system	Management system and legal system		Reflect the water resources management condition	positive

MADM methods are inconsistent, a further aggregation is needed.

In this paper, nine provinces in the Yellow River basin and evaluation criteria constituted the alternatives. Then the numerical approximation system and the modified left–right scoring approach were adopted to cope with the uncertainties in the acquired information. Four commonly used multi-attribute decision-making (MADM) methods were implemented in the evaluation model for impact evaluation, including the simple weighted addition (SWA) method, weighted product (WP) method, cooperative game theory (CGT) method and technique for order preference by similarity to ideal solution (TOPSIS) method. These MADM methods helped to rank the nine provinces and the criteria alternatives, and three aggregation methods, including average ranking procedure, Borda and Copeland methods, were used to integrate the ranking results. The details of the four phases are listed below.

3.2.1 Alternatives establishment

First, the alternatives to be ranked in the MADM methods should be fixed. In this paper, the nine provinces in the Yellow River basin were considered to be the nine alternatives (see Fig. 2). Because the MADM method adopted in this paper is aimed to evaluate the water resources security of the Yellow River basin, the evaluation criteria should also be transformed into different alternatives in order to be compared with the security of the basin. Therefore, 13 criteria alternatives A_a, A_b, A_c, A_d, A_e, A_f, A_g, A_h, A_i, A_j, A_k, A_l and A_m were obtained here, among which A_a, A_e, A_i and A_m are critical values of the 5 interval criteria. In addition, three criteria alternatives were added between A_a and A_e, A_e and A_i, as well as A_i and A_m, respectively. It is worth noting that the criteria alternatives can be selected according to different conditions or different evaluation purposes.

3.2.2 Fuzzy impact transformation

(a) Linguistic-term conversion

A numerical approximation system is proposed by Hwang and Chen (1992) to systematically transform linguistic terms to their corresponding fuzzy sets. According to Hwang, the transformation requires eight conversion scales. The conversion scales are proposed by synthesizing and modifying the work of Baas and Kwakemaak (1977), Bonissone (1982) and Chen (1988). It is assumed that the given figures can adequately cover all expressions of any specific feature –“high” vs. “low”. One of the figures is employed when certain terms are provided and the principle is to simply select a scale figure that contains all the verbal terms given by the decision-maker and use the membership function set for that figure to represent the meaning of the verbal terms. For example, if the given certain terms include “low”, “medium” and “high”, the scale shown in Fig. 3 is to be selected.

(b) Conversion from fuzzy sets to crisp values

A modified left–right scoring approach based on Jain’s (1976, 1977) and Chen’s (1985) works is introduced. In order to determine a crisp score, it is necessary to compare the fuzzy sets with a maximizing fuzzy set (fuzzy

Table 2. Criteria of basin water resources security evaluation.

Evaluation indicator				Indicator unit	Evaluation criteria				
					Absolute security (class I)	Security (class II)	Critical security (class III)	Insecurity (class IV)	Absolute insecurity (class V)
Pressure indicator B1	Water resources pressure indicators C1	D1	Water production coefficient		≥ 0.3	$0.24 \sim 0.3$	$0.18 \sim 0.24$	$0.12 \sim 0.18$	< 0.12
		D2	Annual runoff	mm	≥ 130	$90 \sim 130$	$50 \sim 90$	$10 \sim 50$	< 10
		D3	Modulus of groundwater resources	$10^4\ m^3\ km^{-2}$	≥ 5.5	$4 \sim 5.5$	$2.5 \sim 4$	$1 \sim 2.5$	< 1
		D4	Modulus of water resources	$10^4\ m^3\ km^{-2}$	≥ 50	$38 \sim 50$	$16 \sim 38$	$4 \sim 16$	< 4
		D5	Water utilization rate	%	< 1	$1 \sim 2$	$2 \sim 3$	$3 \sim 4$	≥ 4
	Socio-economic pressure indicators C2	D6	Development degree of surface water	%	< 30	$30 \sim 50$	$50 \sim 70$	$70 \sim 90$	≥ 90
		D7	Development degree of groundwater	%	< 30	$30 \sim 50$	$50 \sim 70$	$70 \sim 90$	≥ 90
		D8	Water consumption per 10 000 Yuan of GDP	$m^3/10^4$ Yuan	< 100	$100 \sim 200$	$200 \sim 300$	$300 \sim 400$	≥ 400
		D9	Water consumption per 10 000 Yuan of industrial output	$m^3/10^4$ Yuan	< 30	$30 \sim 60$	$60 \sim 90$	$90 \sim 120$	≥ 120
	Water environment pressure indicators C3	D10	Ratio of pollutants (COD and ammonia nitrogen) dumped into the river	$t/10^4\ m^3$	< 0.5	$0.5 \sim 1$	$1.0 \sim 1.5$	$1.5 \sim 2$	≥ 2
		D11	Area ratio of excessive extraction of groundwater	%	< 0.6	$0.6 \sim 1$	$1 \sim 1.4$	$1.4 \sim 1.8$	≥ 1.8
State indictors B2	Water resources state indicators C4	D12	Index of water resources demand–supply balance (IWDS)		< 0.8	$0.8 \sim 1$	$1 \sim 1.2$	$1.2 \sim 1.4$	≥ 1.4
		D13	Water resources amount per capita	m^3/person	≥ 1000	$750 \sim 1000$	$500 \sim 750$	$250 \sim 500$	< 250
	Socio-economic state indicators C5	D14	Water supply modulus	$10^4\ m^3\ km^{-2}$	≥ 16	$12 \sim 16$	$8 \sim 12$	$4 \sim 8$	< 4
		D15	Water supply amount per capita	m^3/person	≥ 800	$600 \sim 800$	$400 \sim 600$	$200 \sim 400$	< 200
		D16	GDP per capita	10^4 yuan/person	≥ 1.6	$1.4 \sim 1.6$	$1.2 \sim 1.4$	$1 \sim 1.2$	< 1
		D17	Ratio of agricultural water consumption to total consumption	%	< 55	$55 \sim 65$	$65 \sim 75$	$75 \sim 85$	≥ 85

Table 2. Continued.

Evaluation indicator				Indicator unit	Evaluation criteria				
					Absolute security (class I)	Security (class II)	Critical security (class III)	Insecurity (class IV)	Absolute insecurity (class V)
	Water eco-environment state indicators C6	D18	Domestic water consumption per capita	L/(d · person)	≥ 150	125 ∼ 150	100 ∼ 125	75 ∼ 100	< 75
		D19	Eco-environment water consumption ratio	%	≥ 3.6	2.7 ∼ 3.6	1.8 ∼ 2.7	0.9 ∼ 1.8	< 0.9
		D20	Ratio of soil erosion area to the total area	%	< 15	15 ∼ 35	35 ∼ 50	50 ∼ 75	≥ 75
		D21	Up-to-standard rate of water quality in water function area	%	≥ 80	65 ∼ 80	50 ∼ 65	35 ∼ 50	< 35
		D22	Ratio of up-to-standard river length of water quality to the total river length	%	≥ 80	65 ∼ 80	50 ∼ 65	35 ∼ 50	< 35
		D23	Ratio of class I, II and III groundwater area of water quality to the total area	%	≥ 75	60 ∼ 75	45 ∼ 60	30 ∼ 45	< 30
Response indictors B3	Socio-economic response indicators C7	D24	Water conservancy investment rate	%	≥ 5	4 ∼ 5	3 ∼ 4	2 ∼ 3	< 1
		D25	Industrial water re-utilization rate	%	≥ 80	70 ∼ 80	60 ∼ 70	50 ∼ 60	< 50
		D26	Effective irrigation coverage rate	%	≥ 40	30 ∼ 40	20 ∼ 30	10 ∼ 20	< 10
		D27	Water irrigation efficiency		≥ 0.65	0.55 ∼ 0.65	0.45 ∼ 0.55	0.35 ∼ 0.45	< 0.35
		D28	Water-saving irrigation rate	%	≥ 90	75 ∼ 90	60 ∼ 75	45 ∼ 60	< 45
		D29	Leakage rate of water supply pipe network	%	< 10	10 ∼ 13	13 ∼ 16	16 ∼ 19	≥ 19
		D30	Water-saving appliances penetration rate	%	≥ 60	50 ∼ 60	40 ∼ 50	30 ∼ 40	< 30
		D31	Ratio of urban population access to up-to-standard drinking water to the total urban population	%	≥ 99	96 ∼ 99	93 ∼ 96	90 ∼ 93	< 90
		D32	Ratio of rural population access to up-to-standard drinking water to the total rural population	%	≥ 85	75 ∼ 85	65 ∼ 75	55 ∼ 65	< 55
		D33	Perfection degree of management system and legal system		absolute good	good	medium	poor	absolute poor

Table 3. Weights of water resources security evaluation indicator.

	C1	C2	C3	C4	C5	C6	C7	D-B weights	B1	B2	B3	D-A weights
	C-B weights								B-A weights			
	0.4444	0.3222	0.2333	0.3778	0.3111	0.3111	1.0000		0.4111	0.3333	0.2556	
D1	0.1880							0.0836				0.0344
D2	0.1720							0.0764				0.0314
D3	0.2160							0.0960				0.0395
D4	0.2320							0.1031				0.0424
D5	0.1920							0.0853				0.0351
D6		0.2313						0.0745				0.0306
D7		0.2313						0.0745				0.0306
D8		0.2813						0.0906				0.0373
D9		0.2563						0.0826				0.0339
D10			0.6250					0.1458				0.0600
D11			0.3750					0.0875				0.0360
D12				0.5500				0.2078				0.0693
D13				0.4500				0.1700				0.0567
D14					0.2040			0.0635				0.0212
D15					0.2080			0.0647				0.0216
D16					0.2000			0.0622				0.0207
D17					0.1920			0.0597				0.0199
D18					0.1960			0.0610				0.0203
D19						0.2200		0.0684				0.0228
D20						0.2120		0.0660				0.0220
D21						0.1960		0.0610				0.0203
D22						0.1960		0.0610				0.0203
D23						0.1760		0.0548				0.0183
D24							0.0940	0.0925				0.0236
D25							0.0950	0.0938				0.0240
D26							0.0950	0.0938				0.0240
D27							0.0950	0.0938				0.0240
D28							0.0950	0.0938				0.0240
D29							0.0890	0.0863				0.0220
D30							0.0950	0.0938				0.0240
D31							0.1170	0.1213				0.0310
D32							0.1170	0.1213				0.0310
D33							0.1080	0.1100				0.0281

max) and a minimizing fuzzy set (fuzzy min) (Hwang and Chen, 1992). These two fuzzy sets are defined as

$$\mu_{\max}(x) = \begin{cases} x, \ 0 \leq x \leq 1 \\ 0, \ \text{otherwise} \end{cases} \tag{1}$$

$$\mu_{\min}(x) = \begin{cases} 1 - x, & 0 \leq x \leq 1 \\ 0, \text{otherwise} \end{cases} . \tag{2}$$

The right score refers to the intersections of the fuzzy set M with max. The right score of M can be determined using (see Fig. 3)

$$\mu_R(M) = \sup_x \left[\mu_M(x) \wedge \mu_{\max}(x)\right]. \tag{3}$$

Similarly, the left score of M can be determined using

$$\mu_L(M) = \sup_x \left[\mu_M(x) \wedge \mu_{\min}(x)\right]. \tag{4}$$

Given the left and right scores of M, the total score of M can be calculated using

$$\mu_T(M) = \left[\mu_R(M) + 1 - \mu_L(M)\right]/2. \tag{5}$$

Consequently, the set of μ_{total} can substitute the original linguistic terms and impact matrix with only the crisp values that are formed.

3.2.3 Multi-attribute decision-making (MADM) methods

MADM methods are management decision aids in evaluating competing alternatives defined by multiple attributes. In this paper, four MADM methods are adopted in the evaluation system. The reason for applying these four methods is because they use the same type of input parameters, whereas other MADM methods use different ones. Before presenting

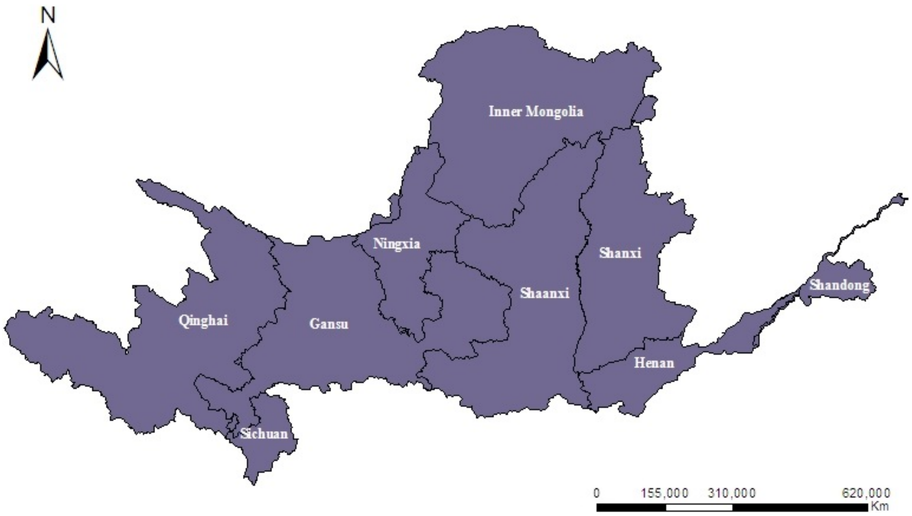

Fig. 2. Administrative regions to be evaluated in the Yellow River basin.

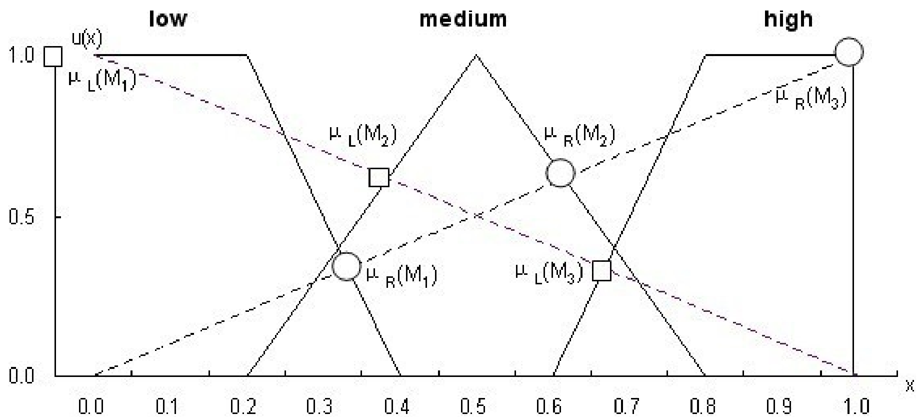

Fig. 3. One scale for the graph of membership function (Hwang and Chen, 1992).

the details of these methods, some basic concepts of decision weight and data normalization should be introduced.

Firstly, almost all MADM problems require information regarding the relative importance of each attribute, including the methods used in the evaluation system here. The relative importance is usually given by a set of weights which are standardized to a sum equal to 1. Weight set is usually represented as follows:

$$W^T = (w_1, w_2, \ldots, w_n) \tag{6}$$

$$\sum_{i=1}^{n} w_i = 1, \tag{7}$$

where n represents the number of attributes, T represents a set of the traverse form, W^T is a set of weights with n attributes. The weights can be assigned by different methods (Saaty, 1977; Chu et al., 1979; Nijkamp et al., 1990). In this paper, FAHP is adopted as referred to above.

Then, according to Hwang and Yoon (1981), some methods such as SWA must apply the normalization method to normalize values in the impact matrix so that any effect introduced by different measurement units is neutralized. In the evaluation system, two ways of normalization are applied to cope with different MADM methods. The linear normalization adopted here is a modified process by Hwang and Yoon (1981). The normalized value r_{ij} can be defined as follows:

$$\text{for impact value of benefit attributes, } r_{ij}^b = \frac{x_{ij} - x_i^{\min}}{x_i^* - x_i^{\min}}, \tag{8}$$

$$\text{for impact values of cost attributes, } r_{ij}^c = \frac{x_i^* - x_{ij}}{x_i^* - x_i^{\min}}, \tag{9}$$

where $x_i^* = \max_j x_{ij}$ and $x_i^{\min}$ is the least acceptable impact value of i attribute. The worst outcome of a certain attribute implies $r_{ij} = 0$, while the best outcome implies $r_{ij} = 1$. The vector normalization divides the impact value of each attribute by its norm, so that each normalized value r_{ij} can be calculated as

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}}, \tag{10}$$

where m is the total number of alternatives. Several MADM methods will be adopted, including:

(a) Simple weighted addition (SWA) method

The SWA method is the simplest MADM method to handle cardinal data (Hwang and Yoon, 1981). Linear transformation is applied, which normalizes the impact matrix, and the utility function can be written as

$$U_j = \sum_{i=1}^{n} w_i r_{ij},\ j = 1,\ 2,\ \ldots,\ m, \tag{11}$$

where w_i is the importance weight of the attributes and r_{ij} is the normalized impact matrix. The alternative with the highest score is the most preferable one. However, since complementarity often exists among attributes, the assumption of preferential independence may be unacceptable, and ignoring the dependence among attributes may cause a misleading result (Hwang and Chen, 1992).

(b) Weighted product (WP) method

The WP method was introduced long ago (Starr, 1972; Yoon, 1989) and normalization is not necessary (Yoon and Hwang, 1995). Formally, the utility value U_j of each alternative is given by

$$U_j = \prod_{i=1}^{n} x_{ij}^{w_j},\ j = 1,\ 2,\ \ldots,\ m, \tag{12}$$

where w_j is the importance weight of the ith attribute and x_{ij} is the impact value of the jth alternative. Similarly, the alternative with the largest utility value is considered the most preferable one to the decision-maker. Theoretically, the utility value may become infinite due to the characteristic of multiplication and the distance between the utility values of the most and second most preferable alternatives would be greater than that derived from the SWA method.

(c) Cooperative game theory (CGT)

Developed by Szidarovszky and Yakowitz (1978), and it is described as the hybrid of the WP and TOPSIS method. By using CGT, the decision-maker looks for a solution that would be as far away from the worst solution as possible. Therefore, the safety of the solution is guaranteed. To define a worst solution, one way is to use the worst impact value of each attribute. Given a set of non-dominant alternatives, the set of worst impact value, denoted as A^-, is defined as

$$A^- = \left\{\left(\min_j x_{ij} \,|i \in I\right),\ \left(\max_j x_{ij} \left|i \in I^*\right.\right)|j = 1,\ 2,\ \cdots,\ m\right\} = \left\{x_1^-,\ x_2^-,\ \ldots,\ x_i^-,\ \ldots\ x_n^-\right\}, \tag{13}$$

where x_{ij} is the impact value of attribute i and x_i^- is considered as the worst outcome for each attribute. Once the worst solution is defined, the utility values U_j for each attribute can be measured by the following formula (Gershon, 1984):

$$U_j = \prod_{i=1}^{n} \left|x_{ij} - x_i^-\right|^{w_i},\ j = 1,\ 2,\ \ldots,\ m, \tag{14}$$

where w_i is the importance weight for each attribute. After calculating the utility values, the most preferable alternative can then be defined as the one with the greatest utility; the result is given by ranking the values in descending order. However, due to the fact that multiplying any value by 0 equals 0, using CGT will automatically screen out all the alternatives that carry at least one worst impact value. Even if those alternatives might result in better outcomes (impacts) in other attributes, they still will not be considered.

(d) Technique for order preference by similarity to ideal solution (TOPSIS)

TOPSIS is a technique that was developed by Hwang and Yoon (1981). They explain that a MADM problem may be viewed as a geometric system. The m alternatives that are evaluated by n attributes are similar to m points in the n-dimensional space. Therefore, the most preferable alternative should satisfy a condition such that it has the "shortest distance" from the positive-ideal solution and the "longest distance" from the negative-ideal solution.

3.2.4 Ranking result aggregation

Due to the different characteristics of the four MADM methods, the outcomes from applying them to solve a decision-making problem might be diverse. If the diversity is small, then the outcome is considered reliable. If the outcomes are inconsistent, further aggregations have to be done. Different approaches of MADM aggregation were adopted in this paper, including:

(a) Average ranking procedure

The average ranking procedure is the simplest technique among the three aggregation methods. This technique is based on the concept of statistical calculation and ranks the alternatives according to the average rankings from the MADM methods.

(b) Borda method

It is based on the concept of voting and it compares each pair of alternatives separately and forms an $N \times N$ matrix. For each pair of alternatives A_j and $A_{j'}$, the number of votes is defined as the number of "supporting" methods in which A_j is more preferable than $A_{j'}$. Then an $N \times N$ matrix X is generated such that $x_{jj'} = 1$, if A_j receives more votes than $A_{j'}$, $x_{jj'} = 0$, otherwise. S_j indicates the number of "wins" that A_j has received against other alternatives and it is calculated by summing the $x_{jj'}$ in each row of the matrix. Hence, the alternative with the highest S_j is considered the most preferable.

(c) Copeland method

This is an extension of the Borda method, which is also based on the voting concept. It is believed that the aggregation utility of A_j does not only depend on the number of "wins", but the number of "losses" also needs to be taken into account. The number of "losses", denoted as $S_{j'}$, is used to compensate the utility value of S_j. $S_{j'}$ is calculated by summing the values of each column of the matrix and the aggregation utility is simply defined as the difference of S_j from $S_{j'}$. As with the Borda method, the Copeland method ranks the alternatives in descending order of their aggregation utilities from largest to smallest. Although using these aggregation methods may still result in inconsistencies among the rankings, some useful patterns can easily be observed by the decision-maker according to the analyzed information.

4 Results

4.1 Indicator value of nine provinces in the Yellow River basin

First, the D_{33} indicator –"perfection degree of management system and legal system", which involves the fuzzy data – was transformed into numeric data by applying the conversion scale, including five terms (see Fig. 3). The indicator refers to the five terms as "absolute good", "good", "medium", "poor" and "absolute poor", which correspond to the selected scale involving "high", "medium high", "medium", "medium low" and "low". Thus, the membership functions of M_1, M_2, M_3, M_4 and M_5 can be presented as

$$\mu_{M_1}(x) = -\frac{1}{0.3}x + 1, \quad 0 \le x \le 0.3 \tag{15}$$

$$\mu_{M_2}(x) = \begin{cases} \frac{1}{0.25}x & 0 \le x < 0.25 \\ -\frac{1}{0.25}x + 2 & 0.25 \le x < 0.5 \end{cases}, \tag{16}$$

$$\mu_{M_3}(x) = \begin{cases} \frac{1}{0.2}x - \frac{3}{2} & 0.3 \le x < 0.5 \\ -\frac{1}{0.2}x + \frac{7}{2} & 0.5 \le x < 0.7 \end{cases}, \tag{17}$$

$$\mu_{M_4}(x) = \begin{cases} \frac{1}{0.25}x - 2 & 0.5 \le x < 0.75 \\ -\frac{1}{0.25}x + 4 & 0.75 \le x < 1 \end{cases}, \tag{18}$$

$$\mu_{M_5}(x) = \frac{1}{0.3}x - \frac{7}{3}, \quad 0.75 \le x \le 1. \tag{19}$$

Table 4. Determination of μ_{total}.

i	$\mu_R(M_i)$	$\mu_L(M_i)$	$\mu_T(M_i)$
1	0.2308	1.0000	0.1154
2	0.6667	0.8000	0.4334
3	0.5833	0.5833	0.5000
4	0.8000	0.4000	0.7000
5	1.0000	0.2308	0.8846

Using Eqs. (3)–(5), the total utility scores were calculated and the set of μ_{total} can substitute the original linguistic terms, which are shown in Table 4. Hence, "absolute good", "good", "medium", "poor" and "absolute poor" were replaced with the values: 0.8846, 0.7000, 0.5000, 0.4333 and 0.1154.

Water resources security in the Yellow River basin is in the middle and the lower level in China, so there is no need to add the four standard samples (A_a, A_b, A_c and A_d) in order to simplify the calculation process. Therefore, 18 alternatives were determined in the evaluation, including the 9 provinces alternatives and 9 criteria alternatives. The values of the 18 alternatives are shown in Tables 5 and 6.

4.2 MADM ranking results

After the evaluation indicator system was established, the values of indicators were normalized by using Eqs. (8)–(9). Hence, the ranking results were obtained under the four MADM methods. By using Eq. (11), the SWA ranking results are *Ae*/,> *Af* > Sichuan > *Ag* > Henan > *Ah* > Shandong > Qinghai > *Ai* > Shaanxi > *Aj* > Gansu > Shanxi > *Ak* > Inner Mongolia > *Al* > *Am* > Ningxia. By using Eq. (12), the WP ranking results are Qinghai > Sichuan > Gansu > *Ae* > Shandong > *Af* > *Ag* > *Ah* > Inner Mongolia > Henan > Shaanxi > *Ai* > *Aj* > *Ak* > Shanxil > *Al* > *Am* > Ningxia. It is worth noting that when the negative indicator equals 0, its negative power does not make sense. Therefore, in order to rank all the provinces in the basin and the standard alternatives, we used 0.00001 to replace the indicator which equals 0 and the influence on the results can be ignored. By using Eq. (14), the CGT ranking results are *Ae* > *Af* > *Ag* > *Ah* > Henan > *Ai* > *Aj* > Shaanxi > *Ak* > *Al* > Gansu > Shandong > Qinghai > *Am* > Inner Mongolia > Shanxi > Sichuan > Ningxia. Specifically, U_j is 0 when the alternative includes at least one indicator that was selected to be the worst sample, which is not conducive to rank all the alternatives. Under this consideration, the positive indicator in the worst sample was decreased by 0.00001, and the negative indicator was increased by 0.00001 during the data processing. By using TOPSIS, the ranking results are Sichuan > *Ae* > *Af* > Qinghai > Henan > *Ag* > *Ah* > Shaanxi > Gansu > Shandong > *Ai* > Shanxi > *Aj* > *Ak* > Inner Mongolia > *Al* > *Am* > Ningxia.

Table 5. Indicator value of nine provinces in the water resources security evaluation system in the Yellow River basin.

Indicator	A_1 Qinghai	A_2 Sichuan	A_3 Gansu	A_4 Ningxia	A_5 Inner Mongolia	A_6 Shaanxi	A_7 Shanxi	A_8 Henan	A_9 Shandong
D1	0.28	0.30	0.15	0.08	0.13	0.14	0.11	0.25	0.21
D2	114.73	164.59	63.19	16.01	9.18	47.74	31.51	105.51	78.31
D3	0.08	0.00	0.28	0.46	1.88	1.91	2.43	4.63	5.04
D4	11.55	16.46	6.60	2.06	2.80	6.68	5.58	15.18	12.88
D5	0.12	0.01	0.46	7.46	2.32	0.70	0.74	1.01	1.13
D6	9.28	0.79	42.58	908.40	533.79	49.62	48.21	105.96	763.57
D7	339.02	100.00	163.19	212.30	85.95	122.89	108.92	177.87	150.58
D8	441.77	134.08	304.19	1128.89	353.94	195.75	133.50	185.66	153.68
D9	312.00	182.00	235.00	228.00	84.00	92.00	67.00	101.00	71.00
D10	0.05	0.00	0.17	2.44	2.16	0.75	0.96	0.46	1.32
D11	0.00	0.00	0.00	0.97	0.00	0.07	2.19	1.16	0.00
D12	1.11	0.71	1.18	1.14	1.09	1.24	1.41	0.97	1.13
D13	3900.74	31123.47	518.24	175.58	496.71	312.89	245.96	321.24	218.17
D14	1.34	0.14	3.08	15.53	6.52	4.71	4.16	15.65	14.58
D15	451.99	266.96	242.26	1321.36	1156.91	220.68	183.56	331.21	247.08
D16	1.02	1.99	0.80	1.17	3.27	1.13	1.38	1.78	1.61
D17	76.02	83.33	58.56	90.19	87.16	61.42	59.82	69.56	57.59
D18	68.63	60.95	63.88	69.40	80.83	75.58	66.69	73.35	75.78
D19	0.29	0.00	0.91	0.86	0.56	1.15	0.69	1.59	0.61
D20	15.27	21.18	58.44	74.81	82.86	66.30	78.12	54.05	52.20
D21	78.00	50.00	55.00	37.00	43.80	47.10	34.00	48.20	27.60
D22	90.50	58.40	59.90	54.00	38.20	41.80	32.20	44.10	20.00
D23	94.00	100.00	44.83	61.34	49.95	79.14	17.28	18.80	6.06
D24	5.09	0.18	2.38	2.89	0.47	1.29	2.65	1.82	0.50
D25	57.00	65.00	45.00	55.00	58.00	60.00	76.00	72.00	70.00
D26	38.47	2.14	16.34	40.53	60.19	41.93	34.15	59.49	87.71
D27	0.38	0.46	0.47	0.34	0.44	0.57	0.60	0.55	0.62
D28	27.90	0.00	46.80	30.97	42.84	54.61	68.67	34.89	46.00
D29	13.50	18.70	17.80	22.00	16.30	19.00	15.60	18.00	20.00
D30	36.30	22.00	45.50	22.40	55.10	60.30	50.10	53.50	55.00
D31	96.00	100.00	89.00	96.00	54.00	94.00	86.00	90.00	100.00
D32	54.13	64.88	58.54	44.37	58.27	60.92	46.75	60.81	70.87
D33	0.70	0.70	0.50	0.43	0.43	0.50	0.50	0.50	0.50

4.3 MADM aggregation results

The alternatives were ranked according to the mean rankings from the four MADM methods, which are shown in Table 7.

According to average ranking procedure, the final ranking order is $Ae > Af > Ag >$ Sichuan $> Ah$, Henan > Qinghai > Shandong > Gansu > Shaanxi $> Ai > Aj > Ak >$ Inner Mongolia > Shanxi $> Al > Am >$ Ningxia. According to Borda, each pair of alternatives were compared separately and the $N \times N$ matrix X was formed, which is shown in Table 8. According to the value of S_j, the final ranking order is $Ae > Af >$ Sichuan $> Ag > Ah$, Henan > Qinghai > Shaanxi, Shandong $> Ai$, Gansu $> Aj > Ak >$ Shanxi, and Inner Mongolia $> Al > Am >$ Ningxia. For the Copeland method, according to the value of $S_j - S_{j'}$, the final ranking order is $Ae > Af$, Sichuan $> Ag >$ Qinghai $> Ah$, Henan > Shaanxi, Shandong $> Ai$, Gansu $> Aj > Ak >$ Shanxi > Inner Mongolia $> Al > Am >$ Ningxia.

Based on the ranking results of the three aggregation methods, the water resources security degrees of the nine provinces in the Yellow River basin are shown in Table 9. Copeland aggregation results are shown in Fig. 4 and Table 10.

Among the nine provinces in the Yellow River basin, water resources security evaluation conditions are relatively poor in Shanxi, Inner Mongolia and Ningxia province. Ranking results of the 33 indicator values are included in Table 11.

5 Discussions

In the four MADM methods in FMADAA, CGT ranking results are significantly different to the other three methods.

Table 6. Indicator value of nine standards in the water resources security evaluation system in the Yellow River basin.

Indicator	A_e	A_f	A_g	A_h	A_i	A_j	A_k	A_l	A_m
D1	0.22	0.21	0.20	0.18	0.17	0.16	0.15	0.13	0.12
D2	80.00	71.25	62.50	53.75	45.00	36.25	27.50	18.75	10.00
D3	4.00	3.63	3.25	2.88	2.50	2.13	1.75	1.38	1.00
D4	35.00	31.25	27.50	23.75	20.00	16.25	12.50	8.75	5.00
D5	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00
D6	50.00	55.00	60.00	65.00	70.00	75.00	80.00	85.00	90.00
D7	50.00	55.00	60.00	65.00	70.00	75.00	80.00	85.00	90.00
D8	200.00	220.00	240.00	260.00	280.00	300.00	320.00	340.00	360.00
D9	65.00	71.25	77.50	83.75	90.00	96.25	102.50	108.75	115.00
D10	0.90	1.00	1.10	1.20	1.30	1.40	1.50	1.60	1.70
D11	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20
D12	1.00	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40
D13	750.00	712.50	675.00	637.50	600.00	562.50	525.00	487.50	450.00
D14	12.00	11.00	10.00	9.00	8.00	7.00	6.00	5.00	4.00
D15	600.00	550.00	500.00	450.00	400.00	350.00	300.00	250.00	200.00
D16	1.80	1.75	1.70	1.65	1.60	1.55	1.50	1.45	1.40
D17	65.00	67.50	70.00	72.50	75.00	77.50	80.00	82.50	85.00
D18	125.00	118.75	112.50	106.25	100.00	93.75	87.50	81.25	75.00
D19	2.70	2.48	2.25	2.03	1.80	1.58	1.35	1.13	0.90
D20	35.00	40.00	45.00	50.00	55.00	60.00	65.00	70.00	75.00
D21	65.00	61.25	57.50	53.75	50.00	46.25	42.50	38.75	35.00
D22	65.00	61.25	57.50	53.75	50.00	46.25	42.50	38.75	35.00
D23	60.00	56.25	52.50	48.75	45.00	41.25	37.50	33.75	30.00
D24	4.00	3.75	3.50	3.25	3.00	2.75	2.50	2.25	2.00
D25	75.00	72.50	70.00	67.50	65.00	62.50	60.00	57.50	55.00
D26	70.00	67.50	65.00	62.50	60.00	57.50	55.00	52.50	50.00
D27	0.55	0.53	0.50	0.48	0.45	0.43	0.40	0.38	0.35
D28	75.00	71.25	67.50	63.75	60.00	56.25	52.50	48.75	45.00
D29	13.00	13.75	14.50	15.25	16.00	16.75	17.50	18.25	19.00
D30	55.00	52.50	50.00	47.50	45.00	42.50	40.00	37.50	35.00
D31	96.00	95.25	94.50	93.75	93.00	92.25	91.50	90.75	90.00
D32	75.00	72.50	70.00	67.50	65.00	62.50	60.00	57.50	55.00
D33	0.70	0.50	0.50	0.50	0.43	0.43	0.43	0.12	0.12

This is because CGT will automatically rule out (or shrink) all the alternatives that contain at least one minimum indicator value of the worst sample although the other indicators are at a higher level in the whole basin. For example, water resources amount is abundant in Sichuan province, and many indicators of the evaluation system are better than the other provinces. However, the three indicator values are 0, including modulus of groundwater resources, eco-environment water consumption ratio and water-saving irrigation rate, which decreases overall water resources security in Sichuan province.

From Table 9, it can be seen that the ranking order is different from Borda and Copeland. This is because in FMADAA, four MADM methods' impacts on the results of average ranking procedure methods are the same, since they are determined by the mean rankings. Hence, we can see that compared with the Copeland aggregation method, the water resources security condition in Henan province is better than in Qinghai province, which is influenced by the results of the CGT method. Meanwhile, the condition in Gansu province is better than that in Shaanxi province and the Ai standard alternative because of the impact by the results of the WP method. We can also see that the results of Copeland are a little different from the Borda method as well because it considers both the "wins" and "losses" of the alternatives.

Although the results of the three aggregation methods are not exactly consistent, some certain and useful information can be obtained, such as the ranking order: $Ae > Af$, Sichuan, $Ag > Ah$, Qinghai, Henan $> Ai$, Shandong, Shaanxi, Gansu $> Aj > Ak >$ Shanxi, Inner Mongolia $> Al > Am >$ Ningxia. The water resources security in these provinces is in a critical state, including Sichuan, Qinghai and Henan. Shanxi and Inner Mongolia are in the insecurity state. Meanwhile, Ningxia province is in the absolute insecurity state. Shandong, Shaanxi and Gansu provinces are in the critical or insecurity state.

As to the ranking order of one province, because it is based on a voting principle, the Copeland method will

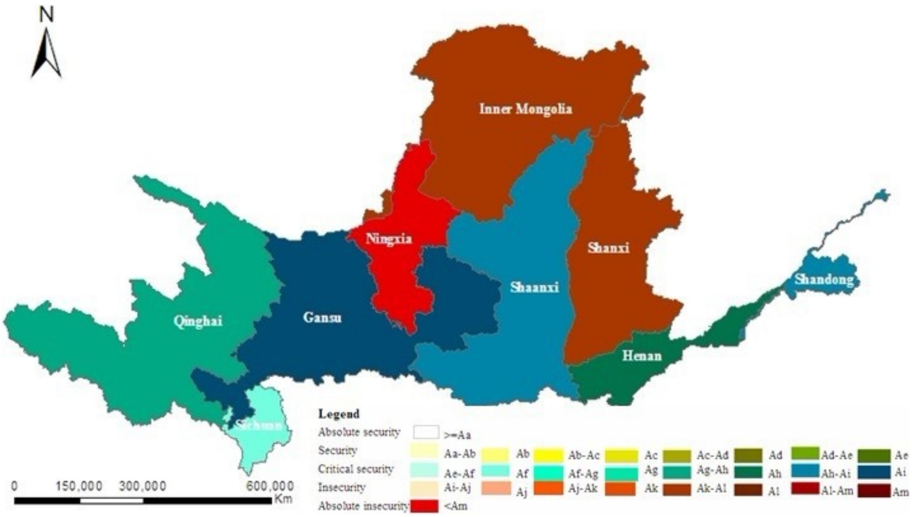

Fig. 4. Copeland aggregation results in the nine provinces.

Table 7. Summary of indicator values in average ranking procedure.

	MADM methods				Mean
	M1	M2	M3	M4	rankings
A_1 Qinghai	11	18	6	15	12.50
A_2 Sichuan	16	17	2	18	13.25
A_3 Gansu	7	16	8	10	10.25
A_4 Ningxia	1	1	1	1	1.00
A_5 Inner Mongolia	4	10	4	4	5.50
A_6 Shaanxi	9	8	11	11	9.75
A_7 Shanxi	6	4	3	7	5.00
A_8 Henan	14	9	14	14	12.75
A_9 Shandong	12	14	7	9	10.50
A_e	18	15	18	17	17.00
A_f	17	13	17	16	15.75
A_g	15	12	16	13	14.00
A_h	13	11	15	12	12.75
A_i	10	7	13	8	9.50
A_j	8	6	12	6	8.00
A_k	5	5	10	5	6.25
A_l	3	3	9	3	4.50
A_m	2	2	5	2	2.75

rule out the influence of the large difference of evaluation results between one MADM method and the others. Besides, it considers both the "wins" and "losses" of the alternatives, so to some extent, it is more reasonable. The ranking order by using the Copeland method is $Ae > Af$, Sichuan $> Ag >$ Qinghai $> Ah$, Henan $>$ Shaanxi, Shandong $> Ai$, Gansu $> Aj > Ak >$ Shanxi $>$ Inner Mongolia $> Al > Am >$ Ningxia. From the results shown in Fig. 4 and Table 10, we can see that the water resources security of the whole basin is in critical, insecurity and absolute insecurity states, which is at the lower level in China. The provinces whose water resources security is in a critical state include Sichuan, Qinghai, Henan, Shanxi, Shandong and Gansu. Shanxi and Inner Mongolia are in the insecurity state. Meanwhile, Ningxia province is in the absolute insecurity state.

For the regional distribution, we can see that water resources security of the provinces located upstream of the Yellow River is better than the other provinces such as Qinghai and Sichuan province. The southern provinces are better than the northern provinces such as Sichuan province. Meanwhile, the developed provinces are better than the other provinces such as Sichuan, Shandong and Henan province. This is because the amount of water resources that is relatively abundant in the upstream and the values of socio-economic-related indicators are higher in the developed provinces, which enhance its whole water resources security.

Among the nine provinces in the Yellow River basin, water resources security conditions are relatively poor in Shanxi, Inner Mongolia and Ningxia province. From Table 11 we can see that the indicator values of the water resources pressure system are smaller in the three provinces, which means that in the pressure system, water resources pressure is relatively high in the three provinces. Meanwhile, the indicator values' ranking results in water resources state and water eco-environment state of state system, and socio-economic response system are the worst in Shanxi province. It can be seen that the higher water resources pressure, the worse water resources and water eco-environment state, and the backward responses result in insecure water resources in Shanxi province. Similarly, the higher water resources and socio-economic pressure and worse water eco-environment state result in insecure water resources in Inner Mongolia province. Water resources have absolute insecurity in Ningxia province because of the higher pressure in water

Table 8. $N \times N$ matrix used in the Borda and Copeland methods.

		A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_e	A_f	A_g	A_h	A_i	A_j	A_k	A_l	A_m	S_j
A_1	0	0	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	10
A_2	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	14
A_3	0	0	0	1	1	0	1	0	1	0	0	0	0	0	0	1	1	1	7
A_4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3
A_6	0	0	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	8
A_7	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3
A_8	0	0	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	11
A_9	0	0	0	1	1	0	1	0	0	0	0	0	0	1	1	1	1	1	8
A_e	1	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	16
A_f	1	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	15
A_g	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	13
A_h	0	0	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	11
A_i	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	7
A_j	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	1	1	1	6
A_k	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	4
A_l	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
A_m	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
S'_j	2	0	8	17	13	7	12	4	7	0	1	3	4	8	10	12	15	16	
$S_j - S'_j$	8	14	−1	−17	−10	1	−9	7	1	16	14	10	7	−1	−4	−8	−13	−15	

resources, socio-economic, and water environment system and backward socio-economic responses.

Therefore, the future planning of the Yellow River basin should focus on soil erosion management, and improvement of water quality in water function areas, rivers and groundwater in order to improve the water eco-environment status in Shanxi and Inner Mongolia province. Meanwhile, the water utilization efficiency should be improved so that the socio-economic pressure is decreased and water management should be enhanced, such as increasing the water conservancy investment, industrial and agricultural water-saving intensity and the rural population access to up-to-standard drinking water. In addition, it is also important to raise the water supply capacity in Shanxi province in order to improve the water resources status as well as to enhance the control of sewage disposal in Ningxia province so that the water environment pressure can be decreased.

In summary, FMADAA can be successfully applied in water resources security evaluation in the Yellow River basin because it is a combination of fuzzy and different MADM methods; it also aggregates various results of MADM methods, which can provide a more rational result. In addition, the system can also deal with fuzzy information usually encountered in practical evaluation processes. The ranking results showed that the water resources security of the whole Yellow River basin is in critical, insecurity and absolute insecurity states, which is at the lower level in China, especially in Shanxi, Inner Mongolia and Ningxia provinces, whose water resources are in insecurity and absolute insecurity states. Hence, future planning of the Yellow River basin should focus on these three provinces in order to promote the overall water resources security and to guarantee coordinated development in the basin.

6 Conclusions

Through introducing the concept of water resources security, a "pressure–state–response" water resources security evaluation system was developed in this research. Multiple-level indicators were identified within the system. Also, a fuzzy multi-attribute decision analysis approach (FMADAA) was proposed not only for dealing with the evaluation based on the developed indicators, but also for tackling the inherent uncertainties. As for the ranking order of alternatives under different methods, Copeland aggregation was adopted. The evaluation system was then applied to the Yellow River basin. The results showed that the water resources security of the basin was in critical, insecurity and absolute insecurity states. The provinces whose water resources security was in the critical state included Sichuan, Qinghai, Henan, Shanxi, Shandong and Gansu. Shanxi and Inner Mongolia were in the insecurity state. Meanwhile, Ningxia province is in the absolute insecurity state. For regional distribution, water resources security of the provinces located upstream of the Yellow River was better than other provinces, such as in Qinghai and Sichuan province. The southern provinces were better than northern provinces such as Sichuan province. Normally, provinces with higher economic productivities were better than other provinces such as in Sichuan, Shandong and Henan province. This is because water resources amount

Table 9. Evaluation level of water resources security by three MADM aggregation methods in nine provinces in 2006.

	Absolute security	Security			Critical security						Insecurity		Absolute insecurity
	A_a	A_b	A_c	A_d	A_e	A_f	A_g	A_h	A_i	A_j	A_k	A_l	A_m
(a) Average ranking procedure method													
Qinghai									√				
Sichuan							√						
Gansu									√				
Ningxia													√
Inner Mongolia											√		
Shaanxi									√				
Shanxi											√		
Henan								√					
Shandong									√				
(b) Borda method													
Qinghai									√				
Sichuan						√							
Gansu										√			
Ningxia													√
Inner Mongolia											√		
Shaanxi									√				
Shanxi											√		
Henan								√					
Shandong									√				
(c) Copeland method													
Qinghai							√						
Sichuan					√								
Gansu										√			
Ningxia													√
Inner Mongolia											√		
Shaanxi									√				
Shanxi											√		
Henan								√					
Shandong									√				

Table 10. Water resources security levels in administrative regions in the Yellow River basin under the Copeland aggregation method (in 2006).

	Security level				
	Absolute security	Security	Critical security	Insecurity	Absolute insecurity
Provinces			Sichuan, Qinghai, Henan, Shaanxi and Shandong, Gansu	Shanxi and Inner Mongolia	Ningxia

Table 11. Ranking results of indicator values in Shanxi, Inner Mongolia and Ningxia provinces.

Evaluation indicator				Shanxi	Inner Mongolia	Ningxia
Pressure indictors B1	Water resources pressure indicators C1	D1	Water production coefficient	8	7	9
		D2	Annual runoff	7	9	8
		D3	Modulus of groundwater resources	3	5	6
		D4	Modulus of water resources	7	8	9
		D5	Utilization rate	5	8	9
	Socio-economic pressure indicators C2	D6	Development degree of surface water	4	7	9
		D7	Development degree of groundwater	1	3	8
		D8	Water consumption per 10 000 Yuan of GDP	1	7	9
		D9	Water consumption per 10 000 Yuan of industrial output	1	3	7
	Water environment pressure indicators C3	D10	Ratio of pollutants (COD and ammonia nitrogen) dumped into the river	6	8	9
		D11	Area ratio of excessive extraction of groundwater	9	2	7
State indictors B2	Water resources state indicators C4	D12	Index of water resources demand–supply balance (IWDS)	9	3	6
		D13	Water resources amount per capita	7	4	9
	Socio-economic state indicators C5	D14	Water consumption modulus	6	4	2
		D15	Water supply amount per capita	9	2	1
		D16	GDP per capita	5	1	6
		D17	Agricultural water consumption ratio	3	8	9
		D18	Domestic water consumption per capita	7	1	4
	Water eco-environment state indicators C6	D19	Eco-environment water consumption ratio	5	7	4
		D20	Ratio of soil erosion area to the total area	8	9	7
		D21	Up-to-standard rate of water quality in water function area	8	6	7
		D22	Ratio of up-to-standard river length of water quality to the total river length	8	7	4
		D23	Ratio of class I, II and III groundwater area of water quality to the total area	8	5	4
Response indictors B3	Socio-economic response indicators C7	D24	Water conservancy investment rate	7	2	8
		D25	Industrial water re-utilization rate	1	6	8
		D26	Effective irrigation coverage rate	7	2	5
		D27	Water irrigation efficiency	8	3	1
		D28	Water-saving irrigation rate	1	5	7
		D29	Leakage rate of water supply pipe network	2	3	9
		D30	Water-saving appliances penetration rate	5	2	8
		D31	Ratio of urban population access to up-to-standard drinking water to the total urban population	8	9	4
		D32	Ratio of rural population access to up-to-standard drinking water to the total rural population	8	6	9
		D33	Perfection degree of management system and legal system	5	8	9

was relatively abundant in the upstream and the values of socio-economic related indicators were higher in the developed provinces. Since the water resources security in Shanxi, Inner Mongolia and Ningxia was the worst in the basin, future planning and management should focus on water management in these three provinces.

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