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ORIGINAL ARTICLE

Catastrophe theory to assess water security and adaptation strategy in the context of environmental change

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Abstract Economic development, population growth, urbanization and climate change have led to an increasing water shortage across the globe. Ensuring water security under changing environment will be the greatest challenge for water resources managers in near future. In this paper, catastrophe theory based multi-criteria evaluation model has been proposed to assess water security under different management strategies to recommend the best water management strategy to achieve water security in the context of global environmental change. The assessment model involves future scenarios of climate change, population growth and economic development. Total 16 indicators related to climate, socio-economy and water availability and consumption have been proposed to measure water security under three management strategies viz. business-as-usual, water demand management and water supply management. The model has been applied to Yulin city of North West China to assess water security as well as to identify the water management strategy under changing environment. The results show that under business-as-usual situation the water shortage rate will reach up to 44 % by the year 2020 and up to 70 % by the year 2030 in Yulin. Water supply is required to increase by 41 % to meet the water demand under supply management strategy which is beyond the safe baseline rate. The study reveals that water demand management can reduce the gap between water supply and demand to a reasonable

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amount and therefore, can be considered as the most effective approach for adapting with environment change.

Keywords Water security · Water resources management · Climate change · Catastrophe theory · Multi-criteria evaluation system

1 Introduction

Water security broadly refers to reliable access to enough safe and affordable water to satisfy basic human needs, food production, livelihoods and ecosystem services (Molden 2007; Greya and Sadoff 2007; Schultz and Uhlenbrook 2007; WaterAid 2012). Global water security is under severe pressure due to many factors such as, population explosion, urbanization, economic development, changes in living standard, increasing water pollution, over-abstraction of groundwater and climate change (Engineering the Future 2010; Wang et al. 2012a, b, c). Water insecurity and scarcity are already visible in many parts of the world. Currently, 1.2 billion people or almost one-fifth of the world's population live in areas of physical water scarcity, while another 1.6 billion people or almost one quarter of the world's population face economic water shortage (OCHA 2010). This situation will become worse in the coming decades with population growth, economical develop, urbanization, agricultural and industrial expansion and climate change. Urban areas in developing countries will house 87 % of population by 2015 and 95 % in 2030 (UN-HABITAT 2006). Due to excessive demand of water, many cities of the world will experience water scarcity (McDonald et al. 2011). Worldwide population growth and economic development will also lead to greater water shortages in all over the world (Vörösmarty et al. 2000). According to Oki et al. (2003), with the increase of population only, the future population under strong water scarcity will increase by 90 % in 2050 compared to the situation in 1995. An additional threat to water security will come from climate change. Climate models project increased aridity in the 21st century over most of Africa, southern Europe and the Middle East, most of the Americas, Australia, and Southeast Asia (Dai 2011). Projections indicate that by 2025, 800 million people will be living in countries or regions with absolute water scarcity and two-thirds of the world's population could be under water stress conditions (OCHA 2010).

Though it is not possible to prevent global changes, measures should be taken to mitigate the impacts (Zou et al. 2012; Wang et al. 2012c). One of the key aspects of water security is its relation to food security, economic development and poverty alleviation (Schultz and Uhlenbrook 2007). Therefore, the importance of water security to national security should be a core component of policy making (Engineering the Future 2010). The technologies, practices and management approaches that are required to address water security issues must be identified and supported through research and development (Wang et al. 2012b, c). This needs reliable assessment of water security under different adaptation strategies. Since water security can have both physical and socio-economic origins, it should be assessed in a broader context considering all physical and socio-economic issues (Wang et al. 2012a). Assessment of water security in the context of climate change, economic development, population growth and urbanization should be considered to recommend adaptation measure for mitigating impacts of global environmental change on water scarcity.

In the past three decades many indices have been developed to quantitatively evaluate water security and scarcity by integrating physical threat to water resources with adaptive capacity (Falkenmark 1989; Ohlsson 2000; Vörösmarty et al. 2005; Rijsberman 2006;

Chaves and Alipaz 2007; Sullivan and Meigh 2007; Pfister et al. 2009; McNulty et al. 2010). Several assessment models have also been developed for the analysis of water security such as, the analytical hierarchy model (Fan et al. 2004; Gao and Hailu 2012), fuzzy comprehensive evaluation model (Ou et al. 2012; Huang et al. 2009; Bajpai et al. 2010), matter-element analysis (Zhong 2005), the projection pursuit model (Zhang et al. 2006), etc. The existing models have some drawbacks in evaluation of water security. Water security analysis involves several dynamic and static indicators as well as many qualitative and quantitative indicators (Liu et al. 2007; Xia and Zhang 2008; Ma et al. 2010; Simon 2009; EI-Sadek 2010). This makes the indicator selection process to be selective and restrictive. Another major problem arises during weighting of indicators according to their influence on water security. Generally, the weight of an indicator is drawn from the perception of the expert carrying out the analysis (Shahid et al. 2000; Benke et al. 2010; Zarkesh et al. 2011). Consequently, the model shows poor credibility due to the selective nature of the evaluation. To overcome these drawbacks a multi-criteria evaluation system based on catastrophe theory has been proposed in this paper.

Despite proliferation in the number of water security related indicators and assessment models, relatively little progress has been made in the systematic application of indicator assessment methods or the translation of the results into water resources management strategies (Falkenmark 1989; UNWWAP 2006; Norman et al. 2012). These indicators are rarely commensurate at a scale that is meaningful at management level (Norman et al. 2012). Water security should be assessed in an evocative way so that it can provide adaptation policy option to mitigate the global change impacts on water security.

Therefore, the objective of the present paper is to use a catastrophe based multi-criteria evaluation system for the assessment of water security under different water management scenarios in the context of global environmental change to identify the best water management strategy in order to achieve sustainability is water resources. A case study of Yulin city of Northwest China is presented with an aim to proved guidance for the sustainable water resources management of the city. Nonlinear, open and dynamic features of the water supply and demand system have been combined to assess water security. Following the entity-association concept, an indicator system has been developed which features the external environmental water resources, water-society, water-economy, water-environmental security, qualitative and quantitative analysis, and operability in the context of population growth, economic development and climate change. It is expected that the research will help water managers, policy makers, water development and management authorities as well as other related individuals or organizations to improve their understanding on adaptable water resources management strategies to adapt with growing water scarcity in the context of environmental change.

2 Methodology

2.1 Catastrophe theory based multi-criteria evaluation system

Catastrophe theory originated as a branch of topology designed to deal with discontinuous dynamic systems governed by a potential energy-like function (Kozak and Benhamt 1974; Zeeman 1977; Saunders 1985; Zhao and Xiang 2002; Wang et al. 2011a). In catastrophe theory, system function variables are divided into dependent state variables which are the internal token variables of system, and control variables which are the external influence factors while system is running (Hui 2008). For example, in the present study, the level of water security is the state or response variable and climate change, economic growth, population growth, etc. are control variables. Catastrophe theory studies on the potential function $V(x_i c_a)$, in which x_i is the state variable and c_a is the control parameter. The system which contains the potential function is in balance. The control variables are assumed to change relatively slowly compared to state variables (Loehle 1989).

Multi-criteria evaluation method explicitly considers multiple criteria for the evaluation of impacts of control variables on state variable. In catastrophe theory based multi-criteria evaluation system, the dependency of state variable on control variables is determined by the catastrophe fuzzy membership functions. In real world systems, the decision-making problems are very often uncertain or vague in a number of ways. Due to lack of information, the future state of the system might not be known completely. This type of uncertainty has long been handled appropriately by probability theory and statistics. However, in many areas such water security, water scarcity, etc., human judgment, evaluation, and decisions often employ linguistic variables or subjective perception which cannot be solved with probability theory. Fuzzy numbers are introduced to appropriately express subjective perception. In classical theories, the statement used can define something as either yes or no, but not both of them, such as the climate change impact on water security is either can be yes or no. On the contrary, in fuzzy set theory approach, a statement can have values in the range of [0, 1], thus the climate change impact on water security can be expressed as very high, high, moderate, poor, very poor and so on. This approach gives more option in measuring subjective criteria to improve expressions and assessments under the fuzzy environment. Therefore, fuzzy set theory provides an effective way to formulate decision problems in a fuzzy environment where the information available is subjective and imprecise (Othman et al. 2008). As the fuzzy logic presumes uncertain knowledge about the processes affecting water resources, nowadays it is widely used to understand climate change impacts on water resources and identify adaptation measures (Armah et al. 2011; Prato 2008). In the present paper, catastrophe theory is used to determine fuzzy membership functions that define the relationship between state variable (water security) and control variables (climate change, economic development, population growth, etc.).

As different control variables have different impacts on state variable (Li et al. 2007), the water security system is first divided into several subsystems. Each subsystem consists of a number of factors or indicators related to water security. Initially, each indicator is assigned with original data such as population growth or urbanization under certain scenario. Since the range and units of original data are different from each other, indictor values are normalized to dimensionless number ranges from 0 to 1 by using catastrophe theory and fuzzy mathematics (Chen et al. 2006). There are seven catastrophe models viz. fold catastrophe, cusp catastrophe, swallowtail catastrophe, butterfly catastrophe, hyperbolic umbilical catastrophe, oval umbilical catastrophe and parabola umbilical catastrophe. The models are illustrated in Table 1. In the table, x represents state variable and a, b, c and d represent control variable. After normalization, both the state variables and control variables are in the range of 0 to 1. The normalized values in the range of [0, 1] represent the catastrophe fuzzy membership functions of each sub-system.

2.2 Catastrophe theory for water security assessment

For the assessment of water security, the system is divided into number of subsystems; each consists of a number of evaluation indices. Catastrophe model type of sub-system

Table 1 Seven types of catastrophe model

Catastrophe model	Control parameters dimension	State variable dimension	Potential function
Fold	1	1	$V_a(x) = \frac{1}{3}x^3 + ax$
Cusp	2	1	$V_{ab}(x) = \frac{1}{4}x^4 + \frac{1}{2}ax^2 + bx$
Dovetail	3	1	$V_{abc}(x) = \frac{1}{5}x^5 + \frac{1}{3}ax^3 + \frac{1}{2}bx^2 + cx$
Butterfly	4	1	$V_{abcd}(x) = \frac{1}{6}x^6 + \frac{1}{4}ax^4 + \frac{1}{3}bx^3 + \frac{1}{2}cx^2 + dx$
Oval umbilici point	3	2	$V_{abc}(x,y) = x^3 + y^3 + axy + bx + cy$
Elliptic umbilici point	3	2	$V_{abc}(x,y) = x^3 - xy^2 + a(x^2 + y^2) + bx + cy$
Parabolic umbilici point	4	2	$V_{abc}(x,y) = x^2y + y^4 + ax^2 + by^2 + cx + dy$

is then determined based on the number of indices the sub-system contains. According to number of evaluation indices, the sub-system can be regarded as fold (one-indicator), cusp (two-indicator), swallowtail (three-three indicator) and butterfly (four-indicator). Data of each indicator of a sub-system are normalized by using corresponding catastrophe model to get the fuzzy membership function of corresponding sub-system. The processes are repeated to obtain fuzzy membership functions for all sub-systems. Steps followed for the development of fuzzy comprehensive evaluation model based on catastrophe theory for the evaluation of water security are discussed below in details.

Step-1: Establishment of indicator system

Water security includes every interaction between water and nature, society, economy and many other factors. Climate change may alter precipitation patterns and exacerbate water supply problems. Population growth and economic development may cause a steadily increase of demand for new clean water supplies. It is also necessary to achieve harmony among the stakeholder groups to ensure equity in water supply. Therefore, to assess water security it is necessary to understand all the factors influence the water security.

In the present paper, it is considered that the economic, social and environmental factors of the water resources work independently, but at the same time the factors interact and restrain one another within the system. As a result, these factors greatly affect water security. When these factors are considered in relation to specific steps required to achieve equity in water supply, it can be found that the system comprises of several interdependent parts which are connected organically to achieve a certain function. Therefore, combining the concept of entity and association model, water security system is divided into five sub-systems in the present study viz. external environment security, water resources security, water-society security, water-economic security and water-environment security. It is considered that sub-systems are separate entities, but associated with each other. This enables us to reflect upon each of the entities and their subsequent implications for water management. Each sub-system consists of a number of factors or indicators related to economic development, population growth, urbanization and climate change. These indicators are used to assess water security. List of indicators under each subsystem are given in Table 2.

Table 2 Indicators for water security assessment

Sub-system	Indicators	Code
External environment security	GDP growth rate	C1
	Urbanization rate	C2
	Temperature	C3
Water resources security	Water shortage rate	C4
	Surface water supply proportion	C5
	Other water supply proportion	C6
Water-society security	Per capital water resources	C7
	Domestic use Gini coefficient	C8
	Per capital water consumption	C9
Water-economic security	Irrigation water Quota	C10
	Water consumption for per 10^4 Yuan	C11
	Water Use and Economic Elasticity	C12
	Water price	C13
Water-environment security	Dilution-ratio	C14
	Water resource utilization rate	C15
	Water resource consumption rate	C16

Step-2: Normalization of indices

Since the range and units of original data are different from each other, the value of index is converted to a dimensionless number ranges from 0 to 1 by raw data standardization. Normalization is done by using different formulas for different types of indicators. For the indicators which indicate better condition when their values are large, a formula known as "larger is better" (ILB) is used, which is as follows:

$$Y = \begin{cases} 1 & 0 \le X \le a_1 \\ (a_2 - X)/(a_2 - a_1) & a_1 < X < a_2 \\ 0 & X \ge a_2 \end{cases} \quad (1)$$

For the indicators which indicate better condition when their values are smaller, a formula known as "smaller is better" (ISB) is used, which is as follows:

$$Y = \begin{cases} 1 & X \ge a_2 \\ (X - a_1)/(a_2 - a_1) & a_1 < X < a_2 \\ 0 & 0 \le X \le a_1 \end{cases} \quad (2)$$

For the indicators which cannot be categorized according to above two groups, a formula known as "All is ok" (IOB) is used, which is as follows:

$$Y = \begin{cases} 2(X - a_1)/(a_2 - a_1) & a_1 \le X \le a_1 + (a_2 - a_1)/2 \\ 2(a_2 - X)/(a_2 - a_1) & a_1 + (a_2 - a_1)/2 < X \le a_2 \\ 0 & X > a_2 \ or \ X < a_1 \end{cases} \quad (3)$$

Where, a_1 and a_2 are the upper and lower bounds of the function. In practical evaluation, 10 % lower than the maximum value of a quantitative indicator is considered as its upper bound and 10 % higher than the minimum value of a quantitative indicator is considered as its lower bound.

Step-3: Fuzzy membership function
After normalization of data, catastrophe fuzzy membership functions of each indicator are calculated as follows:

$$\text{The cusp catastrophe(for two indicators in a sub} - \text{system)} : \mathrm{x_a} = \mathrm{a}^{1/2} \text{ and } \mathrm{x_b} = \mathrm{b}^{1/3}.$$

$$\text{The swallowtail catastrophe(for three indicators)} : \mathrm{x_a} = \mathrm{a}^{1/2}, \mathrm{x_b} = \mathrm{b}^{1/3}, \text{ and } \mathrm{x_c} = \mathrm{c}^{1/4}.$$

$$\text{The butterfly catastrophe(for for indicators)} : \mathrm{x_a} = \mathrm{a}^{1/2},\ \mathrm{x_b} = \mathrm{b}^{1/3}, \text{ and } \mathrm{x_c} = \mathrm{c}^{1/4} \text{ and } \mathrm{x_d} = \mathrm{d}^{1/5}.$$

During calculation following principles are applied:

(a) Un-comparative principles: The function of the control variables can’t be replaced with each other within the system. Therefore, the smallest value of control variables (a, b, c, d) can be used for the system, i.e. $x = \min\{x_a, x_b, x_c, x_d\}$.
(b) Comparative principles: The control variables can fill up the deficiency of each other. Therefore, their mean value can be used for the system, i.e. $x = (x_a+x_b+x_c+x_d)/4$.

Step-4: Calculation of water security
By incorporating the data, the final assessment result is obtained through successive calculations in accordance with the priority of the levels.

3 Environmental changes and water resources management in Yulin

3.1 Changing environment of Yulin city

Yulin located in an arid and semi-arid region of Loess Plateau in northwest China (Wang et al. 2009, 2011b). Geographic coordinates of the city are 36°57′–39°35′N and 107°28′–111°15′E. With the development of mineral resources and the establishment of a chemical engineering base, especially after the large-scale economic construction in recent decades, the difference between water supply and demand has become more evident in Yulin. Predictions indicate that urbanization will increase by 37.5 % in the city by 2030. In addition to that, with development of the chemistry industry and industrial output will increase sharply. Gross Domestic Product (GDP) growth rate is predicted to reach up to 14 %. As there is a direct relation between GDP growth and water demand, it can be anticipated that there will a sharp increase of water demand due to economic development. These will cause serious water shortage in the city. Besides that future climate change scenarios developed by the National Climate Centre showed that the temperature of Yulin will increase continuously (CNCCP 2007) which in turn may further increase the water demand.

3.2 Data and sources

This study uses provincial or municipality level projection data of climate change, population growth, GDP growth, water demand, water supply, etc. of Yulin city. Data are obtained from provincial/municipal planning reports (NWAFU 2008; SWEI 2005) or existing literatures (Wang et al. 2009, 2011b) or based on the research previously carried out at our research unit. Climate model projections are obtained from National Climate Center of China (CNCCP 2007).

3.3 Water resources management strategy in Yulin city

In the context of economic development and population growth, Yulin city is supposed to face number of challenges in future. Using an updated model entitled YulinSD, three potential strategies for the future water resources management are proposed. The strategies are discussed below:

(1) Business-as-Usual: According this strategy, the total water supply will reduce because of engineering depreciation, but the demand will increase sharply due to economic development. Consequently, water shortage will be more acute. By 2020, it is expected that the total water demand will rise to $9.95 \times 10^8 m^3$ in Yulin, and consequently, the water shortage rate will be 44 %. This will put constraints on of economic development. By 2030, the total water demand will rise to $19.1 \times 10^8 m^3$ and the water shortage rate will reach up to 70 %. Water shortages will become a bottleneck for continuous economic development by the year 2030.

(2) Water Supply Management (WSM): According to Water supply management strategy, water managers augment water supply through engineering projects such as dam building, pipelines, diversions and distribution systems when the water demand grows (Butler and Memon 2006; Wang et al. 2009; Yue and Tang 2011; Wang et al. 2012a, b, c). Water supply management strategy presumes that water shortage problem can be solved by increasing the water supply. However, as the water use efficiency will not improve, water demand will reach to $10.25 \times 10^8 m^3$ by 2020 and $21.04 \times 10^8 m^3$ by 2030. Though water supply have to be elevated through engineering investments affecting the consumer water price, water shortages will still prevail. It is anticipated that present water shortage in Yulin will ease after diverting water from Yellow River. But by 2020, the balance between supply and demand will become critical and diversion of water from Yellow River will not be enough to meet the water demand.

(3) Water Demand Management (WDM): Water Demand Management is defined as the development and implementation strategies with an aim to reduce the demand in order to achieve sustainability in water resources (Butler and Memon 2006; Zhang 2005; Wang et al. 2009). According to this model, greater recognition of water-saving measures and technologies will stabilize water consumption gradually. The water price will become the key parameter for maintaining the balance between supply and demand. Although many measures have been applied to achieve water balance in Yulin city, there is still a gap between the supply and the demand. If the present trend continues, the amount of water shortage will be $0.7 \times 10^8 m^3$ by 2020 and $5.16 \times 10^8 m^3$ by 2030. Therefore, demand of water diversion from Yellow River will still required.

4 Results and discussion

Different water resources management strategies have implications on water usage as well as on the economic and social development of Yulin City. The water shortage rate will reach up to 43 % by 2020 under business-as-usual management strategy. On the other hand, under water supply management and water demand management strategies the water shortage is supposed to be stabilized. In case of water supply management, supply is required to increase up to 41 % through exploitation of water resources by engineering construction. The rate exceeds the safe baseline rate of 40 % as recognized by international organizations (Wang et al. 2009). Therefore, it will cause a threat to ecological environment. According to Chinese standards, it may also cause significant levels of water pollution. On the other hand, water demand management is limited and challenged at industrial level, affecting the rate of economic growth. However, it will reduce the gap between water supply and demand. It is envisaged that wastewater re-use will increase to provide additional supplies.

According the above analysis, each of the three management systems consist of pros and cons. Tables 3 and 4 provide an evaluation for the three management systems and their suitability as the water management strategy for Yulin City under B1 scenario. The B1 scenario describes a convergent world with the same global population that peaks in midcentury and declines thereafter, with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies (IPCC 2007)

For clarity, assignment of indicator values is described here in details. Let consider, indictors under water resource security sub-system, namely, water shortage rate (C4), surface water supply proportion (C5) and other water supply proportion (C6) in 2020 under business-as-usual strategy. Using the corresponding equations, $X_{c4}=(0.43)^{1/2}=0.66$; $X_{c5}=(0.65)^{1/3}=0.87$; and $X_{c6}=(0.03)^{1/4}=0.42$. In this equation, three indicators can complement each other which mean the control variables can fill up the deficiency of each other. Therefore, according the rule mentioned earlier, their mean value can be used for the system, $S_{wr}=(X_{c4}+X_{c4}+X_{c4})/3=0.65$. Similarly, we can get external environment security $SER=0.867$, water-society security

Table 3 Values of indicators under different water management strategies in 2020

	Indicators	Management strategy		
		Business-as-usual	WSM	WDM
External environment security	GDP growth rate C1 (%)	14	15	14
	Urbanization rate C2 (%)	28.8	28.8	28.8
	Temperature C3	10.4	10.4	10.4
Water resources security	Water shortage rate C4 (%)	43	0	0
	Surface water supply proportion C5 (%)	65	63	60
	Other water supply proportion C6 (%)	3	1	5
Water-society security	Per capital water resources C7	710	710	710
	Domestic use Gini coefficient C8	0.38	0.35	0.32
	Per capital water consumption C9	105	105	105
Water-economic security	Irrigation water Quota C10	109	130	90
	Water consumption for per 10^4 Yuan C11	43	43	38
	Water Use and Economic Elasticity C12	0.007	0.007	0.007
	Water price C13	2.75	2.75	3.80
Water-environment security	Dilution-ratio C14 (%)	0.06	0.11	0.06
	Water resource utilization rate C15 (%)	31	41	29
	Water resource consumption rate C16 (%)	46	47	37

Table 4 Values of indicators under different water management strategies in 2030

	Indicators	Management strategy		
		Business-as-usual	WSM	WDM
External environment security	GDP growth rate C1 (%)	14	15	14
	Urbanization rate C2 (%)	37.5	37.5	37.5
	Temperature C3	10.7	10.7	10.7
Water resources security	Water shortage rate C4 (%)	70	5	0
	Surface water supply proportion C5 (%)	63	70	50
	Other water supply proportion C6 (%)	4	2	9
Water-society security	Per capital water resources C7	610	610	610
	Domestic use Gini coefficient C8	0.45	0.41	0.35
	Per capital water consumption C9	110	110	110
Water-economic security	Irrigation water Quota C10	99	105	80
	Water consumption for per 10^4 Yuan C11	36	36	30
	Water Use and Economic Elasticity C12	0.008	0.009	0.006
	Water price C13	2.75	2.75	9
Water-environment security	Dilution-ratio C14 (%)	0.14	0.22	0.04
	Water resource utilization rate C15 (%)	59	62	33
	Water resource consumption rate C16 (%)	48	49	43

SWS=0.752, water-economic security *SWE*=0.711 and water-environment security *SWER*=0.896. The values of water security parameters under different management strategies in years 2020 and 2030 are shown by radar charts in Figs. 1 and 2, respectively.

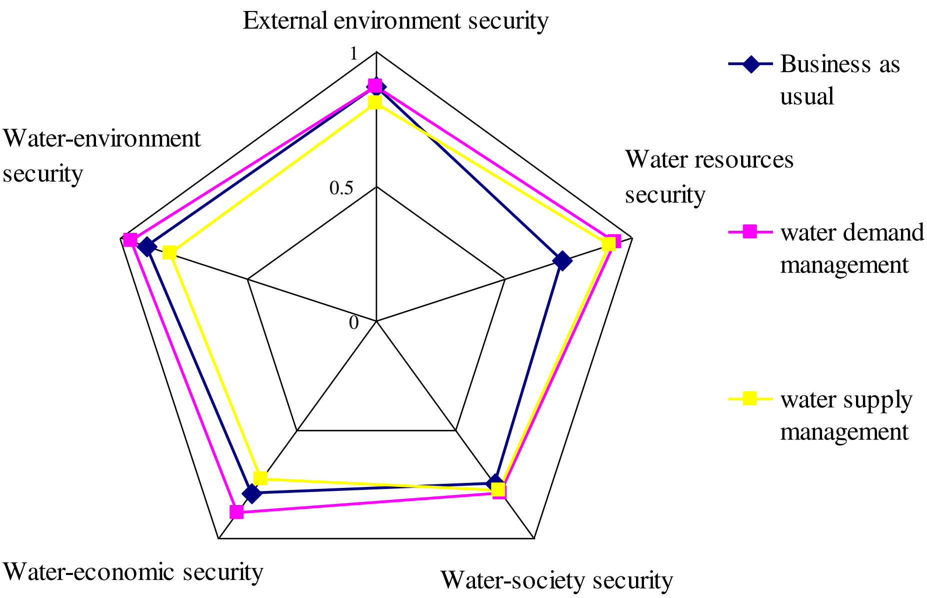

Fig. 1 Water security under different management strategies in 2020

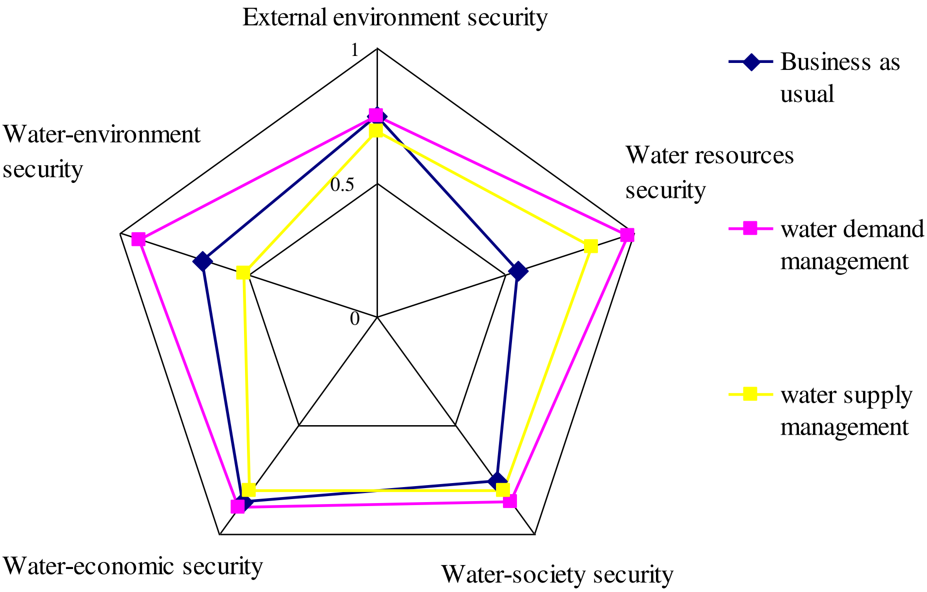

Fig. 2 Water security under different management strategies in 2030

Comparing Figs. 1 and 2, we observe that water security of Yulin city is poor under the business-as-usual management strategy. Increasing water consumption due to population growth, economic development and climate change will put more pressure on water supply. Increased population, urbanization and industrial development may also deplete the existing water bodies, which will in turn make it difficult to continue the present amount of supply under business-as-usual strategy. Consequently, water supply will be required to increase. On the other hand, under water supply management strategy, water use efficiency will be low as no measure will be taken to increase efficiency in water use. Consequently, water demand will continue to increase under water supply management strategy. Water supply will be increased by building more infrastructures and therefore, both the supply and demand of water will be intensified. The pressure on the Yellow River Basin will increase significantly to ensure continuous supply. At the same time, it will affect the cost of the water supplies due to huge investment in new infrastructure projects to enhance supply. Other factors may arise due to increase pressure on water supplies, such as environmental degradation, reduction of water quality due to reduced flow rate, etc. All of these factors will affect sustainability of environment and the society. Therefore, it will be difficult for the water managers to meet the increased water demand through water supply management strategy. Water transfer from the Yellow River could be an option to meet the increased demand. However, Yellow River has dried up several times in the past years. Therefore, huge transfer of water from Yellow river would have negative impacts on eco-systems.

Water demand management can potentially ease the rapid growth of water demand by growing awareness, increasing use of water-saving technologies, improving efficiencies within the production process, and controlling the consumer water price mechanism. Water demand management is a sustainable approach of water resources management. Nowadays, it is widely used in many countries of the world (Wang et al. 2012b, c). It aims to increase water efficiency through both wise use and reduction in use to limit or to postpone the need of building more dams and drilling more boreholes (Butler and Memon 2006; Wang et al.

2009, 2012b, c). Results showed that water use efficiency improved greatly after water demand management program in China (Wang et al. 2009). Therefore, it is very urgent for Yulin city to adopt water demand management through a wide range of structural and non-structural measures to lessen the negative impacts of environmental change on water demand. However, the economic growth may be challenged due to water saving measures. Furthermore, the results (Figs. 1 and 2) show that water demand management alone will not able to eliminate the water scarcity completely. Supply enhancement through water diversion from Yellow River will still be required. Therefore, it can be remarked that though water demand management is most effective strategy to reduce water scarcity in Yulin under changing environment, it should be implemented carefully by considering the impacts of water saving measures on economic growth. Reasonable amount of water shortage that will still exist after implementation of water demand management strategy can be met through limited diversion of water from Yellow river without hampering the eco-system.

There are some limitations of catastrophe theory that arise from the nature of the mathematics i.e., the model specifically focuses on the discontinuous events in a dynamic, there must be an underlying smooth potential or related function, and there can be no more than 4 control variables (Lockwood and Lockwood 1993). There also exist some philosophical difficulties of catastrophe theory. It is a descriptive allegory that provides little mechanistic insight into the physical phenomena that give rise to catastrophic behavior (Sussman and Zahler 1978). Therefore, the theory fails to explain the underlying phenomenological causes (Berryman and Stenseth 1984). However, from water management perspective, the water manager only needs accurate qualitative information regarding the effect of control variables on future dynamics, not a definitive mechanism that explains why the forecast works. As the catastrophe theory does not require a strict formulation of the mechanistic processes underlying the dynamics, it is possible to apply the theory to extremely complex systems (Lockwood and Lockwood 1993) like water security whose internal working mechanism is still not completely understandable. Evaluation of water security and related studies suffers from the problem of subjectivity and complexity associated with the weight determination procedure. The novelty of the catastrophe theory based multi-criteria evaluation method is that it only needs to sort the indicators by their inner logic relationships and their importance, and it does not need to determine the weights of the indicators. Thus, involvement of human perception in decision making can be reduced and therefore, water management strategy to achieve water security under changing environment can be selected more reliably.

5 Conclusions

Water shortages are gradually becoming more and more serious around that world with the rapid economic development and population growth. Ensuring water security will be a great challenge in the context of changing climate. A method has been proposed by using catastrophe theory for assessing water security under different management strategies. The model involves scenarios of future climate change, population growth and economic development, and their interrelationships. Application of the method in Yulin city reveals that the water security index is higher under water demand management strategy compared to other management strategies. This implies that water demand management can be an efficient method to achieve water security in Yulin.

However, some important points are to be noted. (1) The catastrophe theory based multi-criteria evaluation system has recently been introduced and therefore, only limited literatures are available on the topic. Further research is required to measure the efficacy of the method in water security analysis. (2) There are numerous factors that may affect future water security. Therefore, a holistic water security index should take into account of all possible physical and socio-economic factors that may influence water security. However, all the indicators are not readily obtainable and/or quantifiable in many cases. Therefore, only few socio-economic and physical indicators that are identified as important and pertinent to water security are used in the present study to assess water security in Yulin. More factors may be included according to their importance in defining regional water security for similar study in other locations. (3) There are many uncertainties regarding future environmental changes. The paper provides three management strategies to achieve water security. It is recommended that more strategies can be developed through research in order to increase our understanding on suitable water management strategies to achieve water security.

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