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RESEARCH ARTICLE

Integrated water resource security evaluation of Beijing based on GRA and TOPSIS

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Abstract Security evaluation has become a hot topic in the research field of water resource management. In this paper, we established a novel water resource security indicator system based on the Pressure-Status-Response (PSR) framework using gray relation analysis (GRA) and technique for order preference by similarity to ideal solution (TOPSIS). A case study of Beijing from 1996 to 2007 was conducted to verify the evaluation system. Results showed that the gray relative closeness degrees of water resource security to the positive ideal solution were low, with the least one of 0.360 in 1999 and the largest one of 0.527 in 2007, implying that Beijing was facing severer challenges with water resources during the concerned time. Also, the analysis of water resource security indicated that the pressure of water resource was constantly increasing. Finally, factor analysis was employed to calculate the gray relation degrees of evaluating indices with the ideal solutions so as to reveal the relativity of water resource security of Beijing, which may contribute to a better understanding of the urban water resource management and regulation.

Keywords water resource security, grey relation analysis (GRA), technique for order preference by similarity to ideal solution (TOPSIS), factor analysis

1 Introduction

The increasing impacts of human activities and climate change have imposed great challenges on water resource security in many areas of the world. It is estimated that 2.7 billion people will have to be confronted with water scarcity by 2025 (Lyla, 2007). People in developing countries are particularly at risk because of severe water pollutions, environmental damages, poor water supply conditions, and even social conflicts caused by water problems.

There exist literatures on water resource security evaluation using various methods, e.g., system dynamics (Zhang et al., 2002), multiobjective and multilevel fuzzy optimization model (Han et al., 2003), set pair analysis (Lu et al., 2006), and matter-element evaluation model (Li et al., 2006). Compared with traditional statistical regression methods, which require more data and time, the gray relation analysis (GRA), originally formulated by Deng, can obtain reasonable and precise results (Lin et al., 2007). According to the gray system theory, water resource system is regarded as a gray system including resource, society, and economy subsystems. Recently, GRA has been widely applied in many fields, such as agricultural, socioeconomic, and environmental systems (Fu et al., 2001; He and Hwang, 2007; Lin et al., 2007; Wang, 2007; Zeng et al., 2007; Kuo et al., 2008).

Meanwhile, as one of the most useful multiattribute decision making (MADM) methods, technique for order preference by similarity to ideal solution (TOPSIS) has been widely used in areas of economy and environment (Montanari, 2004; Shyur, 2006; Li, 2009), manufacturing (Bhangale et al., 2004), waste management (Wu et al., 2009, Cheng et al., 2003), tourist analysis (Hsu et al., 2009), water resource management (Simonovic and Verma, 2008), transportation (Tzeng et al., 2005), project management (Kao et al., 2006, Wolfslehner and Vacik, 2008), inventory planning (Tsou, 2008), and airline service evaluation (Tsaur et al., 2002). Therefore, TOPSIS method can be combined with GRA to calculate water resource security performance scores and outranking.

In this study, TOPSIS based GRA was introduced with a case study of Beijing city. The temporal evaluation of water resource security was conducted to reveal the

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pressure of water scarcity on Beijing. Finally, factor analysis was also employed to calculate the gray relation degrees of selected indices with the ideal solutions so as to quantify the relativity of water resource security of Beijing.

2 Methodology

2.1 GRA and TOPSIS method

The concept of gray relational space was proposed based on the combined concepts of system theory and space theory, which emphasized the ‘grayness’ as incomplete information. Grey relations refer to the uncertain relations between things, elements of systems, or between elements and behaviors (Kuo et al., 2007). The aim of the GRA is to measure the relation among elements based on the degree of similarity or difference of development trends among these elements (Feng and Wang, 2000).

Hwang and Yoon introduced the TOPSIS method, assuming that the best alternative should have the shortest distance from the positive ideal solution (PIS) and the largest distance from the negative ideal solution (NIS) (Ahi et al., 2009; Thakker et al., 2008; Wang and Elhag, 2006). The ideal solution comprises all the best achievable values of the criteria, while the worst solution is composed of the worst criteria values achievable. TOPSIS simultaneously considers the distances to both PIS and NIS, a preference order is ranked according to their relative closeness, and a combination of these two distance measures. In fact, TOPSIS is a utility-based method that compares each alternative directly depending on data in the evaluation matrices and weights.

2.2 TOPSIS-based GRA model

Assume the integrated water resource security multi-attribute evaluation as $Q = \{S, M, H\}$, in which $S = \{s_k\}$ ($k = 1, 2,\ldots, i$) is the time series, s_k is the k-th year, and $M = \{m_r\}$ ($r = 1, 2,\ldots, n$) is the indicator system. Thus, the decision matrix will be $H = \{H_{kr}\}\ i \times n$, of which H_{kr} is the value of m_r in s_k. We set the comparative solution as $X_k = \{X_1(r), X_2(r),\ldots, X_k(r),\ldots, X_{11}(r)\}$, of which $X_k(r)$ is the value of water resource in the k-th year that include n indices. The reference solutions are constituted by the ideal solution ($M^* = \{M^*(1), M^*(2),\ldots, M^*(r),\ldots, M^*(n)\}$) and the worst solution ($M_0 = \{M_0(1), M_0(2),\ldots, M_0(r),\ldots, M_0(n)\}$), and they are composed of the best and worst values of the n indices, respectively. The gray correlation integrated water resource security evaluation model can be established with the following steps:

1) Calculate the weight of each index, and set it as $W = \{w_r\}$ ($r = 1, 2,\ldots, n$).

2) Unify the evaluation matrix composed by comparative solutions and reference solutions, and set the standard comparative solution, ideal solution, and worst solution as $Y_k = \{Y_1(r), Y_2(r),\ldots, Y_k(r),\ldots, Y_i(r)\}$ ($k = 1, 2, 3,\ldots, i$), $Y^* = \{Y^*(1), Y^*(2), Y^*(r),\ldots, Y^*(n)\}$, $Y_0 = \{Y_0(1), Y_0(2),\ldots, Y_0(r),\ldots, Y_0(n)\}$, respectively.

3) Calculate the gray correlation degree between comparative solutions and ideal solution (r_k*), and the gray correlation degree between comparative solutions and worst solution ($r_k{}^0$). The gray correlation degree of r index in X_k with this index in ideal and worst solution is calculated as follows:

$$r(Y^*,Y_{kr}) = \frac{\min\limits_{k\in i,r\in n}\min |Y^*(r)-Y_k(r)| + \varepsilon \max\limits_{k\in i,r\in n}\max |Y^*(r)-Y_k(r)|}{|Y^*(r)-Y_k(r)| + \varepsilon \max\limits_{k\in i,r\in n}\max |Y^*(r)-Y_k(r)|}, \tag{1}$$

$$r(Y^0,Y_{kr}) = \frac{\min\limits_{k\in i,r\in n}\min |Y^0(r)-Y_k(r)| + \varepsilon \max\limits_{k\in i,r\in n}\max |Y^0(r)-Y_k(r)|}{|Y^0(r)-Y_k(r)| + \varepsilon \max\limits_{k\in i,r\in n}\max |Y^0(r)-Y_k(r)|}, \tag{2}$$

where $\varepsilon\ (0<\varepsilon<1)$ is the distinguishing coefficient, equal to 0.5. Then, the gray correlation degree of X_k with ideal and worst solution can be given by

$$r_k^* = r(M^*,X_K) = \sum_{r=1}^{n} w_r r(Y^*,Y_{kr}), \tag{3}$$

$$r_k^0 = r(M^0,X_K) = \sum_{r=1}^{n} w_r r(Y^0,Y_{kr}). \tag{4}$$

4) Calculate the gray relative closeness degree q_k ($0 < q_k < 1$), which is used as a comprehensive indicator of water resource security. A larger value of q_k indicates a better situation of water resource.

$$q_k = r_k^*/(r_k^* + r_k^0). \tag{5}$$

3 Case study

3.1 Study site and data

Beijing (39°28′–41°05′ N, 115°25′–117°30′ E), the capital of China, lies on the northern edge of the North China Plain, with the total area of 16807 km^2, composed by four city districts, four suburb districts, and ten outer suburbs or counties. The per-capita water resource in Beijing is 300 m^3, about one eighth of the national average and one thirtieth of the world’s average. Beijing has been hit by continuous droughts since 1999; the most serious dry weather in 50 a, with the annual rainfall of 428 mm on the average, which is only 70% of the annual rainfall in normal years (Chen and Yang, 2009). A time series from 1996 to 2007 was chosen as the study period for the evaluation of the water resource security in this paper. Related data are collected from official yearbooks and reports.

3.2 Indicator system

According to the Pressure-Status-Response (PSR) model, the indicator system of water resource security can be established by factors of system pressure, status, and response, in which pressure indices indicate the pressures facing the water resource system, status indices reveal the state of water resource system, and response indices demonstrate how human being respond to water problems, including the related management and technology. Originally presented by the Organization for Economic Co-operation and Development (OECD), the PSR framework was proved to be a logical and comprehensive tool to describe the environmental issues from an anthropocentric perspective (Wolfslehner and Vacik, 2008) and has been widely used to establish indicator systems (Carbtree and Bayfield, 1998; Murray, 2004; Bricker et al., 2003).The water resource security indicator system was then set up according to PSR framework and correlation analysis. Entropy method was chosen to establish the weights of evaluating indices. The indicators and weights are listed in Table 1.

The values of ideal and worst solutions were determined by referring to some principles, including the criterion of eco-city in China or values suggested by international organization, e.g., the ideal value of fertilizer used per hectare; the ideal value in current China or the other countries, e.g., the ideal value of Water used per 10000 yuan GDP according to the most economic value in China 2007; related previous results, e.g., rate of water fare to annual dominative revenue of per-capita; and the ideal or worst values that can be achieved with the current technology, such as the proportion of reusable water reused and the proportion of water saving instruments.

4 Results and discussion

4.1 Water resource security evaluation of Beijing

The water resource security status of Beijing from 1996 to 2007 is calculated according to the proposed method and listed in Table 2, where r^* and r^0 are gray relation degrees with the ideal and worst solution, respectively, and q is the gray relative closeness degree of water resource security with the ideal solution.

In Table 2, it can be seen that during the evaluation

Table 1 Indices of water resource security evaluation

object	guides	factors	indices	weight
index system of WRSA	pressure indices	water resource pressure, P1	water resource per capital, P11/(m^3 per capita)	0.1000
			water resource per hectare, P12/($m^3 \cdot ha^{-1}$)	0.0621
		water environment pressure, P2	fertilizer used per hectare, P21/($kg \cdot ha^{-1}$)	0.0416
			load of waste water discharge, P22/($t \cdot km^{-2}$)	0.0346
		society and economy pressure, P3	water used in daily life per capita, P31/ (L per capita)	0.0380
			water used per dd GDP, P32/ ($m^3 \times 10^{-4}$ CNY)	0.0311
	state indices	water resource state, S1	ratio of water supply to water demand, S11	0.0473
			water used per cultivated land, S12/($m^3 \cdot mu^{-1*}$)	0.0601
		water environment state, S2	compliance rate of water quality in reservoir, S21	0.0248
			compliance rate of water quality in lake, S22	0.0501
			compliance rate of water quality in river, S23	0.0267
		society and economic state, S3	disposal rate of sewage, S31	0.0654
			pass rate of industry wastewater, S32	0.0409
			repeat use rate of industrial water, S33	0.0438
			per capita gross domestic products, S34/ (yuan per capita)	0.0438
	response indices	water resource management, investment, policy, R1	proportion of tertiary industry, R11	0.0271
			proportion of environmental invest, R12	0.0497
			rate of fare for water to annual dominative revenue per capita, R13	0.0228
			proportion of reusable water reused, R14	0.1820
			proportion of water saving instrument, R15	0.0081

Note: * 1 mu = 666.67 m^2

Table 2 Water resource security state by TOPSIS-based GRA for Beijing

year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
r^*	0.528	0.413	0.468	0.429	0.453	0.453	0.452	0.453	0.467	0.501	0.561	0.576
r_0	0.696	0.731	0.678	0.764	0.715	0.701	0.731	0.717	0.650	0.616	0.560	0.518
q	0.431	0.361	0.408	0.360	0.388	0.393	0.382	0.387	0.418	0.449	0.500	0.527

period, q has been keeping in a quite low position, with the smallest and largest values in 1999 and 2007, respectively. Meanwhile, r_0 was much larger than r^* in the evaluation period, which demonstrated that the water resource was in a bad situation from 1996 to 2007. Generally, the water resource situation kept a steady trend from 1997 to 2001. Afterward, there was a slight increasing trend in q, which indicated that the water resource situation has been improving slowly since 2002.

From 1999 to 2005, Beijing has suffered a lasting drought period, during which the average water resource volume was only one half of the normal value (Fig. 1(a)). Meanwhile, both the population (Fig. 1(b)) and GDP (Fig. 1(c)) has experienced a significant increase, imposing more pressure on the water resource. Still, the water resource security status of Beijing has achieved gradual improvement instead of prominent deterioration under the severe pressure, which indicated that the water resource planning and regulation measures taken by Beijing government has played a positive role for the water resource conservation. In fact, since the tenth five year period (2001–2005), aiming to construct a water saving society, the Beijing government has taken a series of measures in view of administration, economy, and legislation aspects to alleviate the serious conflict between the water resource supply and demand.

4.2 Factor analysis

The gray relation degrees of evaluating indices with the ideal solution were selected to analyze the impacts of the indices and their dynamic status from 1996 to 2007, of which the gray relation degrees of 1996, 2000, 2004, and 2007 were given in Fig. 2.

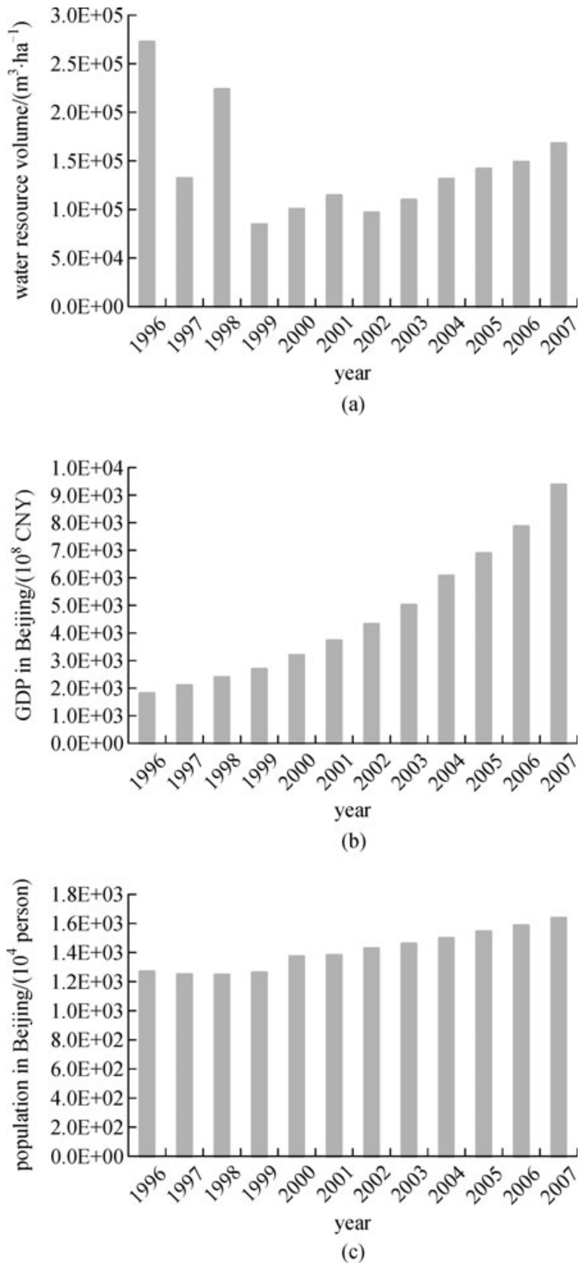

Fig. 1 Water resource (a), GDP (b), population (c) of Beijing from 1996 to 2007

5 Conclusions

In this paper, we introduced the method that combines GRA and TOPSIS for the integrated water resource security evaluation of Beijing city. Results showed that it is a favorable method in the water resource evaluation field. On one hand, the gray relative closeness degree with the ideal solution can be used to demonstrate the status of water resource security during a long period. Implementing a comprehensive indicator system on water resource security, combined with the consideration of water resource security from both the ideal solution and the worst solution perspectives, enables the evaluation of water resource security carried out comprehensively. The values of ideal and worst solutions, chosen according to the

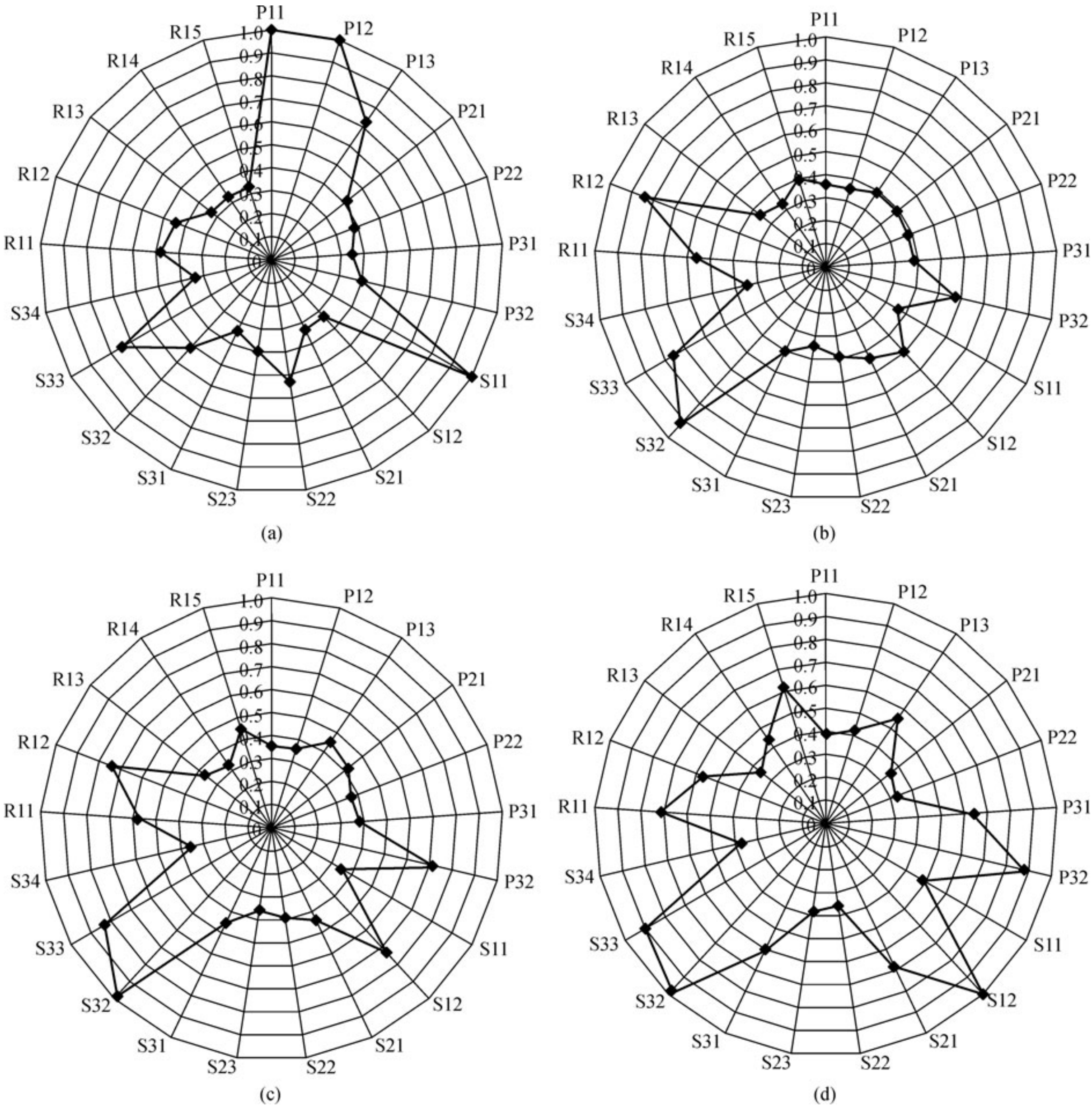

Fig. 2 Grey relation degree of the water resource security status of Beijing. (a) 1996; (b) 2000; (c) 2004; (d) 2007

relatively ideal or worst values in the present conditions of natural, economy, and society, can give an appropriate standard objectively. On the other hand, the gray relation degree of water resource security with the ideal solution can be used to analyze the indices of water resource security, which provides useful information on the efficient water resource management and water resource regulation.

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