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Dynamic successive assessment method of water environment carrying capacity and its application

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ABSTRACT

Water environment carrying capacity (WECC) is an important foundation of sustainable socioeconomic development and may be affected by many factors such as water resources, water quality, economy, population and environmental protection. This article focuses on the temporal and spatial variability of WECC to explore a method of dynamic successive assessment. First, the Pressure-State-Response (PSR) framework is used to develop a systematic and causal indicator system representing the three aspects of water environment pressure carrying capacity (WEPCC), water environment state carrying capacity (WESCC) and water environment response carrying capacity (WERCC). The Variable Fuzzy Pattern Recognition (VFPR) model and an analytic hierarchy process (AHP) model are combined to successively and dynamically assess WEPCC, WESCC and WERCC, and after that the weighting method is used to calculate WECC. Furthermore, WECC is divided into 27 classes on the basis of WEPCC, WESCC and WERCC contributions. The proposed method is applied to the dynamic successive assessment of WECCs in China, including inter-province comparisons. The results show that the dynamic successive WECC assessment method is reasonable, and it can be used not only to accurately understand the changes of WECC through time but also to distinguish qualitative differences masked by similar WECC values.

1. Introduction

The World Commission on Environment and Development (WCED) (1987) put forth the concept of sustainable development: to satisfy current needs without compromising the ability of future generations to satisfy their own needs. Since then, the harmonious development of society, economy and the environment has been a key issue for regional sustainable development (Arrow et al., 1995; Bouwer, 2002; DuĈ and Urbaniec, 2012). The concept of carrying capacity originated from ecology and has given rise to a series of concepts and measures now used in sustainability assessments, such as water environment carrying capacity (Zhu et al., 2010; Na and Wang, 2011), water resources carrying capacity (Feng and Huang, 2008; Li and Jin, 2009; Meng et al., 2009), soil carrying capacity (Johnson et al., 2011) and population carrying capacity (Shi et al., 2013). The assessment of WECC is an important method to research sustainable development of social economy and environment (Lu et al., 2011). At present, water environment crises have become a significant issue for social development because both socioeconomic development and improvement of the human living environment require the quality of the water environment to be improved. Since the 1990s, researchers have focused on studying the relation between the water environment and social economy. It is noted that WECC, which consists of two aspects, i.e., water quality and quantity (Li et al., 2011), exhibits spatio-temporal variability due to both social development and environmental change (Li et al., 2011; Na and Wang, 2011). This coupling of human and natural systems makes WECC outcomes complicated and uncertain (Huang and Qin, 2008). Moreover, it has the character of threshold and variation (Na and Wang, 2011; Gao et al., 2012). There is ongoing debate about how to define WECC. Majority of researchers think that WECC should be defined in terms of the capacity to support socioeconomic development and that its concept should comprise many aspects, such as water resources, water quality, economy, population and environmental protection (Guo and Tang, 1995; Tang et al., 1997; Chen et al., 2000; Na and Wang, 2011). Others think of WECC more narrowly, in sole terms of the processes and capacities of aquatic systems (Gao et al., 2012).

Previous studies have indicated that dynamic assessment has the advantages of succession and accuracy (Feng et al., 2010). However, most current studies on WECC are inconsecutive and partial assessments (Feng and Huang, 2008; Li and Jin, 2009; Na and Wang,

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2011). In reality, WECC is dynamically affected by the coupling of socioeconomic changes with changes in the water environment. In addition, the traditional assessments of WECC are powerless to interpret similar values of WECC in different times or areas, which may be characterized by different economic levels, development models and other factors. Although inconsecutive or partial assessments contribute to understanding WECC, it is difficult for them to reflect trends over time and differences between regions. Therefore, it is urgent to explore a method of dynamically and successively assessing WECC to identify its temporal trends and regional differences. In this context, WECC mapping is a more efficient method for analyzing changes of WECC because it contains more information. Fortunately, geostatistical methods have the advantage of producing maps (El-Fadel et al., 2014) and are convenient for processing the data (Abdideh and Ghasemi, 2014). These tools contribute to the analysis of temporal and spatial variability and have been applied to many issues, such as analyzing the evaluation results of the crop production system in the 31 provinces of China (Tao et al., 2013), and studying the environmental carrying capacity of the Bohai sea rim area in China (Lu et al., 2011). The objective of this paper is to explore the method of dynamic successive assessment and its potential application for the study of the temporal and spatial variability of WECC, which can be used not only to accurately understand the changes of WECC in various areas but also to give more informative interpretations of WECC values that happen to be similar.

2. Dynamic successive assessment method of WECC

2.1. Developing indicator system for WECC using the PSR framework

Developing an indicator system is an important step in WECC assessment. The PSR framework shows causal relationships between pressure, state and response indicators (OECD, 1998), and because it systematically represents important indicators of sustainable development in a causal manner (Wang et al., 2010), it has been widely used in various types of assessments, e.g., of water resources' carrying capacity, environmental impact and sustainable development. This paper considers WECC in terms of the capacity to support socioeconomic development and as a coupled human-natural system. Rapid socioeconomic development will increase water environment pressure (WEP) and degrade water environment state (WES). In turn, these changes will restrict socioeconomic development. Under such circumstances, implementing water environment response (WER) measures to reduce WEP and improve WES will enhance WECC, which forms a virtuous cycle that promotes socioeconomic development, and vice versa. Furthermore, WEP represents the direct factors that degrade WECC, mainly water consumption and pollutant discharge resulting from population increase and socioeconomic development (Feng et al., 2009). WES is the core of WECC and represents the potential for water quality and quantity to support socioeconomic development (Zhou et al., 2011). Forest coverage is an important factor influencing the cycling and purification of water (Stasik et al., 2011). The exploitation and utilization ratio of water resources can indicate the degree to which water resources are consumed and exploited. Rivers not only are important water resources but also greatly influence water quality and quantity in lakes and reservoirs (Wu et al., 2012). Rainfall is uncertain and is significantly correlated with water quantity (Huang and Qin, 2008; Feng et al., 2009). WECC also can be improved by WER in two types of ways. One such way is to improve WES directly by increasing investment in environmental protection and the ratio of ecological water consumption (Zhou et al., 2011). The other is to improve WES indirectly by reducing WEP through strengthening scientific research, promoting adjustments in industrial systems and practices, and decreasing industrial and agricultural water consumption (Zhou et al., 2011). 17 indicators were selected for the construction of the gross WECC index; each is closely related to WECC and has previously been used in the literature (Duan et al., 2009; Feng et al., 2009; Zhou et al., 2011). These indicators are further divided into three subsystems, i.e., WEPCC, WESCC and WERCC, following the PSR framework. The details are shown in Table 1. For each indicator, five grades are developed to judge the level of carrying capacity based on literature. Grades 1–2 of the carrying capacity are at a fine level, grades 2–3 of the carrying capacity are at an acceptable level and grades 3–5 of the carrying capacity are at a poor level.

2.2. Assessment method based on VFPR and AHP model

The assessment of WECC can be regarded as the problem of grading each sample with respect to every indicator. The process of comparing the sample indicators with indicator standards has an imprecise character, so the Variable Fuzzy Pattern Recognition (VFPR) model is a better choice for the dynamic successive assessment of WECC. VFPR theory was presented by Professor Chen and is developed from the theory of variable fuzzy sets (Chen and Guo, 2006; Chen, 2009). This theory grades samples by calculating a synthetic relative membership degree in each grade for each sample. This process is more reliable than a definite assignment of grade (Zhou et al., 2009; Wang et al., 2011; Ke and Zhou, 2013). VFPR has been successfully and widely applied to many different problems, such as water resources evaluation (Duan et al., 2009), water renewal assessment (Chen and Guo, 2006), and groundwater evaluation (Zhou et al., 2009). This paper explores a dynamic successive assessment method of the WECC based on VFPR model and AHP model.

In the first step, Eqs. (1) and (2) are used to normalize (r_{ij}, s_{hj}) the indicators (x_{ij}) and standards (y_{hj}) so as to remove the influence of inverse indices and different dimensions respectively.

$$r_{ij}=\begin{cases}0 & x_{ij}\le y_{cj}(\text{positive index}),\ x_{ij}\ge y_{cj}(\text{inverse index})\\ \dfrac{y_{cj}-x_{ij}}{y_{cj}-y_{1j}} & \text{positive index or inverse index}\\ 1 & x_{ij}\ge y_{1j}(\text{positive index}),\ x_{ij}\le y_{1j}(\text{inverse index})\end{cases}\tag{1}$$

$$s_{hj}=\begin{cases}0 & y_{hj}=y_{cj},\ \text{positive index or inverse index}\\ \dfrac{y_{cj}-y_{hj}}{y_{cj}-y_{1j}} & \text{positive index or inverse index}\\ 1 & y_{hj}=y_{1j},\ \text{positive index or inverse index}\end{cases}\tag{2}$$

where x_{ij} is the value of indicator j of the sample i, i is the number of samples and j is the number of indicators; y_{hj} is the value that defines standard h of indicator j, where $h = 1, 2, \ldots, c$, c representing the highest grade of standard; r_{ij} and s_{hj} are the results of normalization of the indicators (x_{ij}) and standards (y_{hj}), respectively; the positive indices (X3, X7, X8, X9, X10, X12, X13, X14 and X17) are those that are positively correlated with carrying capacity; the inverse indices (X1, X2, X4, X5, X6, X11, X15 and X16) are those that are negatively correlated with carrying capacity.

In the second step, the judgment matrices used in the AHP (Singh et al., 2006; Hosseini and Kaneko, 2011) are defined in accordance with the relative importance of the different indicators. The local weights of the indicators are then obtained by calculating the eigenvalues and eigenvectors of the judgment matrices.

In the third step, Eq. (3) is used to calculate the synthetic relative membership degree for sample i belonging to standard h. Eq. (3) has