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Space–time approach to water environment carrying capacity calculation

Xi-Yin Zhou [a], Kun Lei [b, *], Wei Meng [b], Soon-Thiam Khu [c], Jian Zhao [b], Mingna Wang [d], Junfeng Yang [b]

[a] School of Environment, Tsinghua University, Beijing, 100084, PR China
[b] Chinese Research Academy of Environmental Sciences, Beijing, 100012, PR China
[c] Civil Engineering, School of Engineering, Monash University, Sunway Campus, Malaysia
[d] China Institute of Water Resources and Hydropower Research, PR China

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ABSTRACT

China has faced the challenge of defending its water environment in the face of rapid economic development. This fact highlights the urgency to adopt water environment carrying capacity (WECC) as a measure for the sustainable development of human society. Recent scientific research tends to focus on the interaction of whole systems in a macro top-down way based on statistical data and an index setting in a uniform study unit, whereas its internal spatial heterogeneity and the spatial function between each subsystem, such as population, economy and water environment, have received little attention. An integrated model is presented based on the system dynamics (SD) and cellular automaton (CA) models in this study. Spatiotemporal water environment carrying capacity analysis during the process of urban evolution is attempted and realized in Changzhou, China. In 2010 y and 2025 y, the control units 1, 2, 5, 6, 9, 11 are in a relative worse status of water environment and should be taken measures to increase local water environment carrying capacity, the control unis 4, 8, 12, 13 are still in a good status of water environment, while the overall water environment carrying capacity of study region is overloaded. In 2050 y, the control units 3, 4, 8, 10, 12, 13 are in a good status of water environment which are consistent with the status of the whole study region, the control units 1, 2, 5, 6, 7, 9, 11 are opposite and should still be adopted measures. The results would provide a basis for reasonable industry and population patterns according to water environment capacity.

1. Introduction

Rapid economic development, urban expansion and explosive levels of population growth observed in many Asian countries have led to vast quantities of water been abstracted for human consumption, goods production and improvement of quality of life. At the same time, a significant amount of pollutants have been generated and discharged into rivers and other water bodies, causing severe water pollution problems in these countries. In certain instances, the deterioration of the local environment has constrained or affected the respective local/regional economic development (Zhu et al., 2010). The concept of sustainable development was developed specifically to address and avoid such predicaments, but there is inevitably strong local opposition favoring development over environmental protection.

A number of concepts and tools have since been developed to model the effect and impact of coupled human and natural systems (CHANS) for sustainable development, and the concept of “carrying capacity” has been widely discussed in China. It was first proposed in the fields of animal ecology in 1838 (Odum et al., 1971) and has been widely used in many fields of ecosystem management, including water environmental carrying capacity (WECC). WECC can be defined as “the largest population and economic scale that the water environment can support in a specific region during a period of time without an adverse impact on the local water environment” (Zeng et al., 2011). WECC can be regarded as a complex function related to water environment, population, economy, technology, policy, space, time, etc. The WECC value would be changed along with the variation of any of the above factors (Yang et al., 2015a).

* Corresponding author.
E-mail address: watereconomy@163.com (K. Lei).

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Modeling WECC is inherently complex because of the interactions between anthropogenic activities and natural processes and the different types and levels of feedback mechanisms that exist. Previous research method on WECC can be categorized into four types: index evaluation method, DPSIR framework, water footprint, System Dynamics. First, index evaluation method were adopted to analyze WECC such as hierarchical multi-criteria methods (Giupponi and Rosato, 2002), fuzzy comprehensive evaluation methods (Gong and Jin, 2009). More detailed research frameworks were then put forward including the pressure–-state–response (PRS) and driving force-–pressure–state–impact–response (DPSIR) frameworks to research the WECC of CHANS, with consideration of each factor including human activities, natural environment, the influences of natural states on human society, the management policy (Chen et al., 2005). Another widely developed method for WECC was ecological footprint or water footprint, which vividly expressed the links between human consumption and water resources and indicated the state of WECC. Rees (1992) introduced ecological footprint to research the carrying capacity during urban development. Hoekstra (2009) analysis how human occupied natural capital through the approach of ecological footprint and water footprint. Hubacek et al. (2009) reveal the carrying capacity of China during urbanization through water footprint analysis. The main weakness of index evaluation method, DPSIR framework and water footprint method is lack of ability to reveal the nonlinear interaction mechanism of different factors in the WECC (Wolfslehner and Vacik, 2008). System dynamics (SD) was an approach to simulate the behavior of real-world nonlinear complex systems over time (Winz et al., 2009). The application of the SD model in WECC analysis suggested a temporal dynamic interaction between social–human systems and natural systems. Yang et al. (2015b) used a system dynamics model to reveal the temporal change of WECC in Tieling City of China. Zhang et al. (2014) combined system dynamics with analytic hierarchy methods to indicate the WECC change in Siping City of China. However, in the above-mentioned four kinds of methods, the administrative regions were always taken as study regions due to limitation of statistical data. The study regions were regarded as a sole homogeneous entity and was not suitable for denoting the spatial function and interaction.

Recent scientific research has tended to focus on the interaction of whole systems in a macro top-bottom way based on statistical data and index setting in a uniform study unit (Cao et al., 1998). Internal spatial heterogeneity and the spatial function between each subsystem such as population, economy and water environment have received little attention. Long and Jiang (2003) thought that the related landuse pattern and industrial structure analysis should be considered in WECC research, Tan et al. (2011) put forward that the concept of regionalism and periodization was a key point and that the WECC research should be developed based on aquatic ecological function regionalization. Synthesis of the factors including time, space, material, energy, and information would become inevitable trends in the subsequent WECC research (Zeng et al., 2011). In conclusion, they all thought that the spatial analysis was the weakness point in current WECC research and that it should be strengthened in the future.

The current research of WECC has not considered the spatial factors. Due to lack of spatial structure concept in WECC analysis, the phenomenon of unbalanced spatial structure of WECC may be ignored. The detailed situation including: (1) Its spatial pattern and spatial process cannot be revealed if the study area is too large, and only statistical data are used (Wang et al., 2010). (2) The irrational situation would occur in which some development mode is suitable and the maximum population amount and GDP value are allowable for a study region considering the WECC; however, the WECC in partial space is actually overloaded. (3) The other opposite unreasonable circumstance may be that the total population and gross economy seems to exceed its permissible value that the water environment can support. Population, economy, water resources and water environment capacity all possess spatial patterns, and each subsystem has spatial linkages. The spatial pattern influences the interaction of inner subsystems and inter-subsystems. Every subsystem produces spatial interaction and spatial evolution as time goes by. Finally, it causes spatiotemporal dynamic change of socioeconomic–natural systems in the field of WECC. As a result, compared with the temporal dynamic process of index change in the WECC, it is urgent to carry on spatiotemporal dynamic change analysis in the WECC considering spatial heterogeneity and spatial evolution.

The objective of this paper is to create an adaptive integrated model (a space–time approach) with the following functions: (1) analyze the WECC along with urban evolution, (2) uncover the spatiotemporal evolution of the social–natural complex systems, and (3) quantitatively indicate the function of spatial factors in the WECC of study regions. To achieve these objectives while satisfying the need to improve the insufficiency in WECC research, some problems must be solved: (1) a better subarea method to integrate both the SD model and the cellular automaton (CA) model must be found, rather than considering only the research region as a sole homogeneous district in SD models and abiding by the uniform transition rules of each cell in the SLEUTH model; (2) realize spatiotemporal WECC analysis; the input–output between the SD model and the SLEUTH model should be advanced; (3) attempt to represent the spatial heterogeneity of water pollution based on gridded GIS technology and the outputs of the SD model and CA model. In this research, a spatiotemporal model has been developed to analyze the WECC. The gridded GIS technology is applied to realize spatial expression of the WECC based on the outputs of the SD model and CA model. It also achieves an analysis among the different spatial scales such as grid, control unit and administrative regions.

This paper is organized as follows: Section 3 emphasizes the methodology, including the establishment of the SD model and CA model, construction of the SD–CA coupled model, model calibration, and spatial expression of economy, population and water pollution. Section 4 illustrates urban evolution, model calibration results, and the spatiotemporal pattern forecast of water pollution and the WECC. The last section evaluates the value and deficiency of the coupled model.

2. Data sources and study area

Changzhou City, located in Taihu Lake in China, is a prefecture-level city in southern Jiangsu province (Fig. 1) and is used as the study area. It contains an urban district and two county areas named Liyang and Jintan situated in the affluent Yangtze Delta region of China. The three sub-regions are divided into 7, 4 and 2 control units according to the comprehensive assessment of natural and social characteristics. The Urban District contains control units 7, 8, 9, 10, and 11; Liyang contains control units 1, 2, 3, and 4; and Jintan contains control units 5 and 6. The locations of control units are shown in Fig. 1. The areas of the Urban District, Liyang, and Jintan are 1871 km^2, 1536 km^2 and 976 km^2. Moreover, their total populations are 3.36 m, 0.76 m and 0.55 m, and their gross domestic products are 3,021,600 m yuan, 559,200 m yuan, and 373,800 m yuan. It is a city with highly developed industry and is especially advanced in the industries of manufacturing, textile, chemicals, etc. It is also a city with a water-rich environment, containing abundant reservoirs in Liyang, lakes in Jintan and the Changjiang River in the Urban District. As a result, although