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System dynamics modeling of the influence of the TN/TP concentrations in socioeconomic water on NDVI in shallow lakes

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ABSTRACT

It is critically important to investigate the influence of the total nitrogen (TN) and total phosphorus (TP) concentrations in socioeconomic water on the Normalized Difference Vegetation Index (NDVI) for the regional-scale utilization of water resources and ecosystem management in shallow lakes, which are easily disturbed by high-intensity human activities. In this study, we proposed a new system dynamics model with a coupled modeling structure to analyze a comprehensive influencing relationship between the NDVI and the concentrations of TN and TP from the socioeconomic water circulation during the growing season from 2000 to 2010 in Baiyangdian Lake, the largest shallow lake in northern China. The results show that, (1) there is a good comprehensive correlation between TN, TP and NDVI, with a correlation coefficient of 0.979; (2) compared to the industrial, domestic, and ecological water demand, the agricultural water demand exhibits the largest amount and the strongest ability in the creation of TN and TP, and the factor of agricultural wastewater affects the most. Therefore, the regulation of the agricultural wastewater would be the most efficient way to build a healthy environment for vegetative growth. This study contributes to the water resources planning and ecosystem management with the aim of improving both the water quality and the ecological functions in Baiyangdian Lake.

1. Introduction

Recently, rapid socioeconomic development has induced changes in the environment. Unprecedented water usage, sewage, and other human activities affect the water quality (Tan et al., 2011). For example, the nutrients mainly originating from socioeconomic water, such as the total nitrogen (TN) and the total phosphorus (TP) in the water body, affect the ecosystem status (Rastetter et al., 2013; Garnier et al. 2005; Zhao et al., 2013). Meanwhile, water pollution, coupled with water shortage, has made the intensive conflicts over water resources between human and ecosystems (Cai et al., 2011; Yang et al., 2013). Therefore, for the planning and management of regional water resources, it is extremely important to systematically analyze the impacts of socioeconomic water usage on the water environment and ecosystem, particularly in shallow lakes. Overall, shallow lakes are mostly located in densely populated areas, and are more likely to be disturbed by excessive human activities (Gao et al., 2009; Huang and Liu, 2009; Matt et al., 2014; La et al., 2013). Compared to deep lakes, they have more vulnerable ecosystems; not only its ecosystem services but also its balance of water supply and demand are more susceptible to be disturbed. In addition, shallow lakes usually have a low pollution load capacity, making them prone to eutrophication (María et al., 2013; Wang et al., 2009, 2013; Wu et al., 2014). Therefore, the promotion of a harmonious development between the environment and the eco-efficiency has become an important issue. It is necessary to study the influence pathways and mechanisms through which socioeconomic water in shallow lakes produces TN and TP and thus affects the ecosystem status for water resources planning and ecosystem management.

The previous studies on how water resources disturbed by human activities impact the ecosystem mainly focused on the water quantity or quality separately. In terms of water quantity, most studies considered the process of industrial, agricultural, and domestic water diverted to the ecological water use from the perspective of supply and demand balance (Kondili and Kaldellis, 2008; Yin and Yang, 2011; Zhu et al., 2004; Amalia et al., 2013). In contrast, in the analysis of the water quality, many researchers have proven that a change in the nutrients in a water body affects the ecosystem (Sanches and Guariento et al. 2011; Roselli et al. 2009; Panigrahi et al. 2009; Wang et al., 2012a). Furthermore, because

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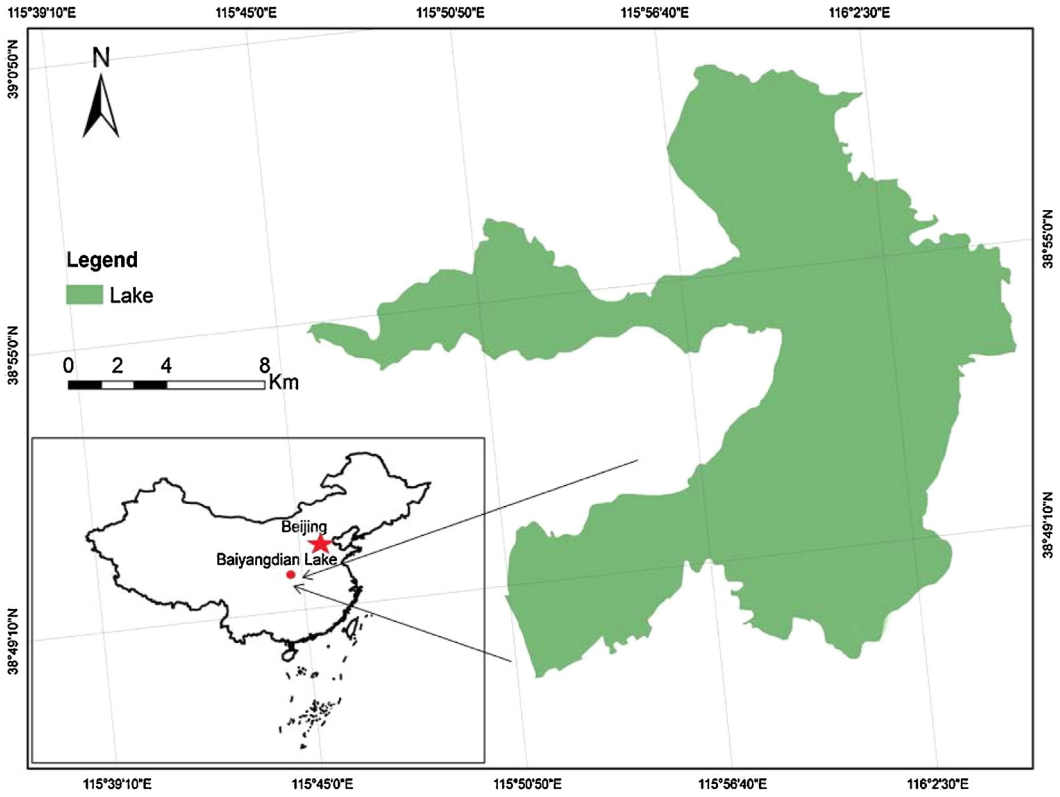

Fig. 1. Geographic map of Baiyangdian Lake, northern China.

the Normalized Difference Vegetation Index (NDVI) is an important indicator that reflects the ecosystem status, many researchers have studied the relationships between the nutrients conditions and the NDVI. For example, Ouyang et al. (2009) analyzed the temporal-spatial interactions of the land cover and the non-point source nutrient pollution using the Soil and Water Assessment Tool (SWAT) to simulate the temporal-spatial features of the nutrient loading in the upper stream of the Yellow River catchment. Schubert et al. (2010) used time-series satellite sensor-derived data in a light use efficiency model to determine the gross primary productivity. It has been proved that the NDVI exhibits a strong linear relationship with both nitrogen and phosphorus from socioeconomic water emission (Griffith et al. 2002). However, since the study of how socioeconomic changes in water usage influence nutrient changes requires the simultaneous consideration of a variety of factors associated with economic development, population growth, and wastewater reuse, it is very complicated to simulate the combined influences of the quantity and quality of socioeconomic water on the NDVI. Probably just for this reason, few studies on the influence of socioeconomic water usage on the NDVI in shallow lakes have been reported.

System dynamics (SD) models are useful tools that can handle complex problems associated with high-order, nonlinear, and time-varying systems with multiple feedbacks to analyze the driving mechanism and the mutual restraints in changing systems. SD is also a suitable method to explore management options for a complex system (Wu et al., 2013; Ali et al., 2012; Hu et al., 2013). A number of SD models have been developed to describe the dynamics of environmental elements involved in a water resources system. For example, Li et al. (2008) applied an SD approach to analyze the carrying capacity of water resources. George and Michael (2005) developed an SD model to simulate the current chemical and biological properties and to analyze the complex eutrophication of Lake Washington. Qi and Chang (2011) developed an SD model to estimate the municipal water demand. However, few studies have focused on establishing the influencing mechanisms of socioeconomic water usage on the NDVI in shallow lakes; more specifically, there is an absence in studies on the establishment of reliable and immediate forecasting methods associated with the interrelated nature of the TN and TP concentrations in effluents and the changes in the NDVI. Therefore, an SD model is desired to reveal the mechanisms through which the usage of socioeconomic water influences the NDVI in shallow lakes using the TN and TP load variations as a linkage.

The objectives of this study were to (i) explore a comprehensive influencing relationship between the nutrient conditions in a water body and the growing status of vegetation by building an equation between the TN/TP concentrations and the NDVI of reeds during the growing season in Baiyangdian Lake, northern China; and (ii) develop an SD model to describe the specific intermediate processes and thus clarify the influencing mechanism and determine key influencing factors. Taking TN/TP concentrations in socioeconomic wastewater as a linkage, this paper analyzed the interaction and feedback mechanisms between socio-economic water resources system and ecosystem through developing an SD model for Baiyangdian Lake, called as "the Kidney of North China". By regulating these key factors that influenced ecosystem state according to a certain order, the efficiency of water resources management would be improved with the aim of the insurance of the ecosystem health. Thus it can promote the harmony of social development and eco-environment protection.

2. Materials and methods

2.1. Study area

Baiyangdian Lake (38°43′N to 39°02′N, 115°45′E to 116°07′E; Fig. 1), which is the largest freshwater lake in North China, plays an

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