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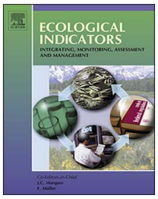

Original Articles

Optimizing best management practices for nutrient pollution control in a lake watershed under uncertainty

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ABSTRACT

In this research work, soil and water assessment tool (SWAT) and fuzzy credibility chance-constrained programming (FCCP) model were integrated into an optimization framework for supporting nutrient pollution control in a lake watershed. The framework, so-called SWAT-based FCCP (SFCCP) model, was advantageous in simulating non-point sources (NPS) pollution, optimizing best management practices (BMPs), and addressing system uncertainties. SFCCP was solved by genetic algorithm (GA) for searching optimal placement schemes of BMPs at a lower system cost, where the related uncertainties were addressed as fuzzy parameters. The developed SFCCP model was applied to seek optimal types, sizes and locations of BMPs for nutrient pollution control in a lake watershed system, i.e. Lake Dianchi watershed, China. The study results indicated that when the credibility level increased from 0.55 to 0.95, the total system cost would increase from \$8.89 to \$12.27 × 10^6; meanwhile, the total nitrogen (TN) load discharged into the lake would decrease from 1.22 to 1.19 × 10^6 kg/yr and the total phosphorus (TP) load would reduce from 51.37 to 50.11 × 10^3 kg/yr, respectively. It appeared that a higher credibility level would lead to a stricter control requirement, namely a higher reduction of nutrient load by BMPs and a higher system cost. The proposed model could be used to help generate a series of BMPs placement schemes under various credibility levels; this ensures that the nutrient load brought into the lake and tributaries could drop to an acceptable level, with a proper tradeoff between system cost and risk being considered.

1. Introduction

Nonpoint sources (NPS) pollution may bring unrestrained nutrient loading into receiving water bodies like rivers, lakes, and estuaries, and has been a major cause of aquatic environment degradation worldwide in recent years (Ongley et al., 2010; Robinson and Melack, 2013; Tan et al., 2011; Ullrich and Volk, 2009; Worrall et al., 2012; Xu et al., 2013). Best management practices (BMPs) proposed by the U.S. Clean Water Act, have been effective tools for NPS pollution control, and widely applied in many watersheds (Arabi et al., 2006; Gaddis et al., 2014; Shen et al., 2015; Sweeney et al., 2004). Identification of potential types, sizes and locations for the implementation of BMPs requires many expectations, such as a low system cost and a high nutrient reduction effect. However, such an effort may be fraught with complexities due to the spatial diversities of landscapes, weather, and NPS conditions and the contradictory nature between efficiency and cost of BMPs (Veith et al., 2004). This poses many challenges in handling the problems associated with the hydrological cycle, water quality protection, and ecological preservation and construction. Therefore, it is desired to have a systems approach to obtain effective BMP placement schemes for NPS pollution control.

Soil and water assessment tool (SWAT) is a developed watershed model, which can be used to estimate the effectiveness of various BMP combinations in reducing pollutant losses (Santhi et al., 2006). Previously, many SWAT-based optimization methods were advanced to investigate BMPs placement and seek watershed management strategies (Ahmadi et al., 2013; Chen et al., 2015; Kaini et al., 2012). For example, Panagopoulos et al. (2013) embedded the river basin SWAT model into an optimization framework, and utilized multi-objective genetic algorithm (GA) to obtain optimal configurations of BMPs in ensuring acceptable river water quality. With three different sediment and nutrient reduction cases, Kaini et al. (2012) used SWAT and GA to find an optimum arrangement of BMPs for the Silver Creek River watershed in Illinois, United States. Ahmadi et al. (2013) presented a simulation-optimization approach by integrating the mixed integer multi-objective genetic algorithm and SWAT to determine optimal BMP types and locations for nutrient and pesticide control in the Eagle Creek River Watershed, Indiana. Chen et al. (2015) proposed

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a preference-based multi-objective optimization model coupled with SWAT to find out the best locations of BMPs for nutrient reduction in the Daning River watershed, China. These studies revealed that the SWAT-based optimization method was a useful tool for the spatial optimization of BMPs placement at the watershed scale. However, most of these previous studies focused on NPS pollution control for river watersheds, and rarely considered the direct interaction between watersheds and lakes for the lake watershed systems.

Furthermore, the system uncertainty has been another concern in BMP management systems due to incompleteness and/or unavailability of required information. Among many alternatives, fuzzy possibility theory can effectively deal with uncertain information through fuzzy sets and has been widely applied in many applications (Cai et al., 2011a,b; Karsak and Kuzgunkaya, 2002). In a BMP management system, many input parameters (e.g., the expected improvement rate related to the nutrient load into lake) could be described by fuzzy membership functions. Previously, Huang (2006) proposed a fuzzy credibility chance-constrained programming (FCCP) model which could help reflect the vagueness of information by adopting the credibility to quantity the occurrence possibility of a fuzzy event. More recently, FCCP model was applied to support the water resources management problems by handling the fuzziness of pollution load capacities (Li et al., 2013) and surface water amount (Dai et al., 2016a; Zhang and Huang, 2011). However, there are still limited applications of FCCP to address the uncertainties linked with watershed-scale water quality modeling and BMP placement management.

Therefore, this research aims to develop a SWAT-based fuzzy credibility chance-constrained programming (SFCCP) method to help seek the spatially optimal configurations (e.g. types, sizes and locations) of BMPs for NPS pollution control. In this method, SWAT model will be employed to forecast the fate of nutrient loading under various BMPs implementations, while the FCCP model is adopted to handle fuzzy uncertainties and seek optimal combinations between efficiency and cost of BMPs. The proposed method is applied to a lake watershed system in China, where four BMP implementation schemes over 139 subwatersheds are investigated to meet the expected improvement of water quality indicators.

2. Materials and methods

2.1. Overview of the study system

Lake Dianchi, a senile and shallow plateau lake with an average altitude of 1887 m, is situated around the central to southwest of Kunming, the capital city of China's Southwestern Yunnan Province (as shown in Fig. 1a). It has a surface area of more than 300 km^2, with a length of 40 km from south to north and a width of 7 km from east to west (Dai et al., 2016a). Before 1980s, Lake Dianchi used to have a qualified water quality level (i.e., Grade II) and served as a drinking water source for the Kunming city (Gao et al., 2014). However, following the rapid agricultural development and urban expansion, the over-discharging of nutrients has significantly deteriorated the lake water quality (Yang et al., 2010). Based on the statistical analysis of the monitoring data, the total nitrogen (TN) and the total phosphorus (TP) loadings to the lake were about 2.18×10^6 kg and 0.13×10^6 kg in 2009, respectively; both of which were higher than the lake's tolerance limits. Facing this fact, the total maximum daily load (TMDL) plan was launched to reduce the external nutrient loading for the Lake Dianchi and improve its pollution condition (Dai et al., 2016b). Due to the complexity of TMDL guidelines and preference of local authorities, the requirement of mitigating the nutrient loading may have variations. To enhance the flexibility of decisions, the improvement rates of TN and TP loadings are assumed to be triangular fuzzy sets of (35%, 40%, 45%) and (50%, 55%, 60%), respectively. The middle values in the brackets represent the most likely values of the improvement rates (with a membership degree of 1). The lower and upper bounds of the values (i.e. left- and right-side values in the bracket) have a membership degree of 0.

Lake Dianchi watershed has an area of approximately 2900 km^2. In this study, we divide this watershed into two parts, including the reservoir watershed and tributary watershed (as shown in Fig. 1a). The reservoir watershed has an area of 1029 km^2 and is controlled by eight reservoirs (i.e., R1–R8 as shown in Fig. 1a) to provide water resources for irrigation and drinking. The tributary watershed contains 17 rivers named from PLJ to XSS clockwise, which are the main tributaries of the Lake Dianchi. Table 1 shows the information and target on water quality protection for the tributaries. The water quality protection grade and the corresponding emission permits were assumed. The protection objective of the PLJ tributary is grade IV, and the TN and TP emission permits are set as 1.5 and 0.3 mg/L, respectively. The water environment function of DQH tributary belongs to the drainage channel and is set as inferior grade V. In 2009, the TN and TP exceedance frequencies of the PLJ tributary are 91.5% and 17.3%, respectively. Similar to the improvement rate related to the nutrient loading, the improvement rates related to the nutrient exceedance frequency are expressed as fuzzy sets as they are normally estimated by decision makers.

The nutrient loading from the tributary watersheds may deteriorate the water quality of the 17 tributaries and the Lake Dianchi, while the nutrient loading from the reservoir watershed is accumulated into the eight reservoirs and has limited effect on the Lake Dianchi. Also, the mountainous and complex terrain of the reservoir watershed compounds the difficulty of water quality management. Thus, in practice, the scope of the TMDL management only covers the tributary watershed. During the eleventh five-year plan from 2006 to 2010, many industrial point sources have moved to the downstream of the Lake Dianchi watershed and the remaining point sources mainly include four wastewater treatment plants (see Fig. 1a). At present, the nutrient reduction efforts of TMDL only concentrate on the NPS by taking the measures of best management practices (BMPs), and leave the discharge of point sources maintaining status quo (Dai et al., 2015a). Table 2 shows four potential BMPs including parallel terrace (PT), grade stabilization structure (GS), filter strips (FS) and detention wetland (DW) for consideration, where they are of different unit construction cost (Arabi et al., 2006; Dai et al., 2015b; Karamouz et al., 2010). For technical details of these four practices, readers could refer to Kaini et al. (2012), Karamouz et al. (2010), Park et al. (2013) and Maringanti et al. (2011).

2.2. SWAT model set up and representation of BMPs

SWAT is a spatially-distributed catchment model that has been widely used in many studies (Arnold et al., 1998; Srinivasan et al., 1998). In the SWAT model, a watershed is separated into subwatersheds based on the stream network and user defined outlets, and then each subwatershed needs to be further subdivided into hydrologic response units (HRU) in reference to the information of land use condition, soil type and slope. The hydrological process along with sediment transport, water quality, plant growth and nutrient cycling are simulated at the level of HRU, and the detailed modeling theory can be referred to Neitsch et al. (2011). Application of SWAT mainly requires 3 types of data: (i) spatial data, such as the digital elevation model (DEM), the land cover and the soil map, for delineating the physical characteristics of watershed; (ii) driving data, such as the meteorological data, for supporting the hydrological cycling; and (iii) observed data, such as the flow and nutrient time series, for the calibration efforts.

The relevant DEM, land cover, and soil map of the tributary watershed for this study can be found in Fig. S1 of the Supplementary material. The resolution of the DEM is 25 × 25 m, and the minimum and maximum elevations are 1375 and 2783 m, respectively. Land cover with the scale of 1:10000 is reclassified into 7