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Simulation-based inexact chance-constrained nonlinear programming for eutrophication management in the Xiangxi Bay of Three Gorges Reservoir

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ABSTRACT

Although integrated simulation and optimization approaches under stochastic uncertainty have been applied to eutrophication management problems, few studies are reported in eutrophication control planning where multiple formats of uncertainties and nonlinearities are addressed in forms of intervals and probabilistic distributions within an integrated framework. Since the impounding of Three Gorges Reservoir (TGR), China in 2003, the hydraulic conditions and aquatic environment of the Xiangxi Bay (XXB) have changed significantly. The resulting emergence of eutrophication and algal blooms leads to its deteriorated water quality. The XXB becomes an ideal case study area. Thus, a simulation-based inexact chance-constrained nonlinear programming (SICNP) model is developed and applied to eutrophication control planning in the XXB of the TGR under uncertainties. In the SICNP, the wastewater treatment costs for removing total phosphorus (TP) are set as the objective function; effluent discharge standards, stream water quality standards and eutrophication control standards are considered in the constraints; a steady-state simulation model for phosphorus transport and fate is embedded in the environmental standards constraints; the interval programming and chance-constrained approaches are integrated to provide interval decision variables but also the associated risk levels in violating the system constraints. The model results indicate that changes in the violating level (q) will result in different strategy distributions at spatial and temporal scales; the optimal value of cost objective is from [2.74, 13.41] million RMB to [2.25, 13.08] million RMB when q equals from 0.01 to 0.25; the required TP treatment efficiency for the Baisha plant is the most stringent, which is followed by the Xiakou Town and the Zhaojun Town, while the requirement for the Pingyikou cement plant is the least stringent. The model results are useful for making optimal policies on eutrophication control planning and water quality improvement in the XXB.

1. Introduction

Eutrophication is a common pollution problem caused by enriched nutrients and increased biological productivity in rivers, lakes, estuaries and coastal areas. Surveys conducted by the International Lake Environment Committee (ILEC) showed that 54, 53, 48, 41 and 28% of lakes and reservoirs were eutrophic in the Asian–Pacific Region, Europe, North America, South America and Africa, respectively (ILEC, 1988–1993). Eutrophication could lead to deteriorated water quality, degraded water safety, and declined water availability. To facilitate efficient eutrophication management, a number of studies for systems analysis to support eutrophication management were undertaken through development of various simulation and optimization methods. Simulation models are commonly ecological models which describe the temporal and spatial changes of species and nutrient fractions, such as algae, zooplankton, phosphorus, and nitrogen components (van der Molen et al., 1994; Cioffi and Gallerano, 2001; Marques et al., 2003; and Chao et al., 2006). Optimization models attempt to determine the best or “optimal” outcomes combined with alternative control measures (Kao and Tsai, 1997). Furthermore, several authors integrated simulation and optimization methods in their eutrophication management practices (Kuo et al., 2008; Hsieh et al., 2010; Karamouz et al., 2010).

Nevertheless, uncertainties generally exist in many system components and their interrelations in eutrophication control planning, such as pollutant discharge rates, hydrologic and meteorologic conditions, treatment costs, abatement strategies, and decision makers’ preferences. To deal with uncertainties in general water quality management problems, a variety of optimization methods were developed through fuzzy programming (FP) (Sii

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et al., 1993; Lee and Chang, 2005), interval programming (IP) (Huang, 1996; Qin et al., 2009) and stochastic programming (SP) (Pintér, 1991). FP could deal with fuzzy goals/constraints and express ambiguous information as fuzzy sets; IP could handle interval parameters with known lower and upper bounds, but unknown memberships or distribution functions; SP could reflect various random uncertainties through probability distributions. Furthermore, integrated interval, fuzzy and/or stochastic programming methods were developed to deal with multiple formats of uncertainties in the practical management of water quality (Chang et al., 1997; Huang, 1998; Karmakar and Mujumdar, 2006, 2007; Zheng and Keller, 2008; Qin and Huang, 2009a, 2009b). Especially, some efforts were made in dealing with eutrophication management problems through integrated simulation and optimization approaches under stochastic uncertainty (Pintér and Somlyódy, 1986; Somlyódy and Wets, 1988). However, few studies are reported in managing eutrophication problems where multiple formats of uncertainties and nonlinearities were addressed in forms of intervals and probabilistic distributions within an integrated framework.

Therefore, this study aims to develop a simulation-based inexact chance-constrained nonlinear programming (SICNP) model and apply it to eutrophication management The model contains a nonlinear least-cost objective and a set of eutrophication management constraints, including effluent discharge standards, surface water quality standards and eutrophication control standards. The inexact information associated with decision-making processes is expressed as intervals and probability distributions. The Xiangxi Bay of the Three Gorges Reservoir in China was taken as the case study. The optimal solutions of controlling pollutant discharges can help local decision makers identify flexible cost-efficient eutrophication management strategies under various uncertainties.

2. Eutrophication Issues in the Xiangxi Bay of Three Gorges Reservoir

The Three Gorges Reservoir (TGR), located at the upper reach of the Yangtze River, is the largest hydroelectric project in China. The TGR is built for flood control, power generation, river navigation and drought prevention. It has a total capacity of 393 billion m^3 and a flood control capacity of 221.5 billion m^3 with the water elevation of 175 m. Accordingly, the backwater in TGR is about 660 km long and an average of 1.1 km wide, which forms a typical river-type reservoir from Three Gorges Dam (TGD) up to the Jiangjin district in Chongqing (Ji et al., 2010). The operation of TGR depends on the temporal and spatial conditions and many other factors, and the impoundment elevation ranges from 145 to 175 m annually. As the largest first order tributary of TGR in Hubei Province, the Xiangxi River (XXR) is the nearest tributary to the TGD as well. With an area of 3099 km^2, the XXR watershed possesses a subtropical continental monsoon climate, exhibiting big temperature differences in spring, concentrated heavy rain in summer, frequent cloud and rain in autumn, and some snow in winter. The annual average temperature is 16.6 °C, while the vertical temperature differences are large due to the big gradient differences and the complicated landforms. The mainstream of XXR is 94 km long. When the impoundment elevation of TGR reaches 135, 156 and 175 m, the backwater zone in XXR is respectively about 25, 30 and 40 km along the estuary (Yang et al., 2010). The backwater zone is named as the Xiangxi Bay (XXB), since it is similar to a lake but with characteristic hydraulic conditions.

Since the impoundment of TGR in 2003, its hydraulic conditions and aquatic environment have changed significantly, resulting in the emergence of eutrophication and algal blooms in some tributaries of TGR every year. Algae can grow rapidly in the environment of slow flow, proper water temperature, good underwater illumination, and enriched nutrients (e.g. phosphorus and nitrogen) (Voutsa et al., 2001). Decaying algae then sink to the bottom and cause oxygen depletion, leading to eutrophication and algal blooms. In XXB, eutrophication and algal blooms have occurred in different extents since 2003, due to slower water current, longer retention time and more nutrient releases from sediments (Maier et al., 2001). The intense algal development will clog the drinking water filters, raise the pH of water and release dissolved organic carbon (Dianous et al., 1995). And the oxygen depletion rendered by decaying algae will further induce heterotrophic conditions in the riverine sections (Garnier et al., 1999a, 1999b) and cause a dysfunction of the whole aquatic ecosystem. Thus, the control of eutrophication and algal blooms becomes a critical problem for XXB.

The XXR area is a rich phosphorus region, where large amounts of phosphorus are carried by runoffs into XXB every year. Total phosphorus (TP) is thus an important factor to evaluate the eutrophication status in XXB. According to the field investigation in XXB, 39.78 tons of phosphorus enters XXB from upstream, of which 60% comes from point sources. Therefore, it is desired to reduce the phosphorus discharges from point sources scattering along XXB.

As shown in Fig. 1, the XXR has two origins from Shennongjia National Forest Park located in the northwest of Hubei Province and flows southwardly, joining the mainstream of Yangtze River (YZR) at Xiangxi Town. The two branches flow down and gather together at the Zhaojun Bridge (ZJB). The Town of Gufu (GF), with a population of 19,000, lies on the east branch of XXR. The Baisha (BS) chemical plant lies on the west branch, which annually produces 22,500 tons of yellow phosphorus, 90,000 tons of phosphoric acid, 90,000 tons of sodium tripolyphosphate, 3000 tons of sodium hypophosphite, 10,000 tons of sodium hexametaphosphate, 10,000 tons of phosphorus pentasulfide, 10,000 tons of dimethyl sulfoxide, and 2600 tons of fire retardant. The Town of Zhaojun (ZJ),

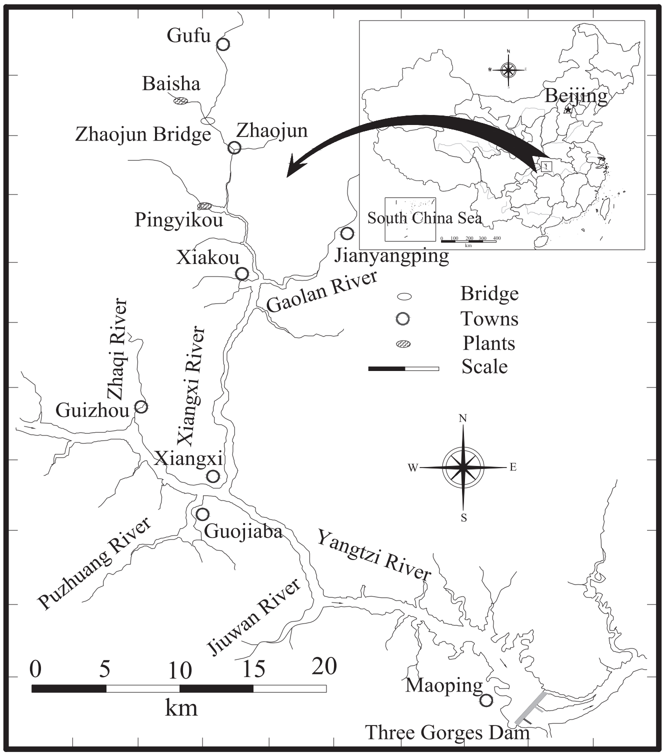

Fig. 1. Location of the Xiangxi Bay.