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Monte Carlo simulation based interval chance-constrained programming for regional ecosystem management – A case study of Zhuhai, China

J.P. Lv[a], Y.P. Li[b,c,*], J. Sun[a]

[a] Sino-Canada Resources and Environmental Research Academy, North China Electric Power University, Beijing, 102206, China
[b] State Key Laboratory of Water Environment, School of Environment, Beijing Normal University, Beijing, 100875, China
[c] Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, Sask, S4S 7H9, Canada

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ABSTRACT

A Monte Carlo simulation based interval chance-constrained programming (MC-ICCP) model is developed for planning regional ecosystem under uncertainty. MC-ICCP cannot only deal with uncertainties described as discrete intervals and probability distributions, but also examine the risk of violating system constraints. MC-ICCP is then applied to planning regional ecosystem sustainable development in the City of Zhuhai, where different ecosystem service value (ESV) assessment measures, risk levels and eco-environmental indicators are investigated. Solutions of land-use pattern, system benefit, and ecosystem service value under 192 scenarios have been obtained. Results reveal that (i) different ESV assessment measures result in different grass and forest areas; (ii) ESV assessment measure can affect land-use pattern and system benefit; (iii) risk level (p) is the most impact factor. Decisions at a lower risk level (a lower p level) would lead to an increased reliability in fulfilling ecosystem requirements but with a lower system benefit. Results also disclose that forest and grass coverage has more significant effect on land-use pattern than reclamation intension and soil erosion. More attention should be paid on ecosystem land-use that could facilitate regional ecological sustainability. The findings could help decision makers balance system benefit and constraint-violation risk, adjust land-use pattern with consideration of ecosystem sustainability and protect regional ecological environment.

1. Introduction

Ecosystem is essential for human well-being due to its values in offering natural surroundings for economic productivity, quality of life, safety, and public health (MEA, 2005; Grêt-Regamey et al., 2013; Schröter et al., 2017). However, with the rapid development of economy and the expansion of human activities, ecosystem as well as the corresponding service value has suffered from enormous loss and deterioration. In detail, intervention of human activities exacerbates the conflicts between high requirements for natural resources and limited land reserves, alters land-use pattern, and destroys biogeochemical and hydrological cycles (Metzger et al., 2006; Ferreira et al., 2017). For solving such conflicts, China's government has conducted many reclamation projects during the past thirty years. The total area of reclaimed land in China has increased from 8241 km^2 with a rate of 285 km^2/year; with the rapid urbanization, it is predicted that the rate of reclamation will increase by 500 km^2/year in the following thirty years (Duan et al., 2016). However, the reclamation projects have seriously influenced the integrality of costal ecosystem and led to landscape fragmentation, loss of species biodiversity, eco-hydrological disconnection, and ecosystem service value degradation. These problems have brought a number of negative impacts on ecosystem sustainability (Buhl-Mortensen et al., 2017). It is then urgent to manage human activities effectively for maintaining ecosystem integrity and achieve sustainable development between socio-economy and ecosystem.

Previously, a number of research works were conducted for identifying, assessing and planning regional ecosystem with the consideration of ecosystem service and the relationship between human activities and natural ecosystems (Pinto et al., 2014; Ahmadi et al., 2015; Tammi et al., 2016; Dočekalová et al., 2017; Li et al., 2017; Liang et al., 2017). These works could help seeking participatory and innovative policy, governance and management options for regional ecosystem. However, ecosystem involves various factors such as economic, social, political and environmental. These factors are plagued with unpredictable natural processes, spatiotemporal heterogeneities, dynamic evolutions and complicated communications and interactions that lead ecosystem into a complex network system (La Notte et al., 2017). Moreover, planning ecosystem is perturbed by a majority of uncertainties, which are associated with the random character of natural processes governing

* Corresponding author at: State Key Laboratory of Water Environment, School of Environment, Beijing Normal University, Beijing, 100875, China.
E-mail address: yongping.li@iseis.org (Y.P. Li).

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resources, the estimation errors in parameters, insufficient data information, risk preference of policymakers and their interrelationships (Rougé et al., 2013; Zulueta et al., 2017). These uncertainties can be expressed as stochastic parameters and/or interval values to prevent from needless error resulted from inappropriate simplification (Li et al., 2015). These complexities and uncertainties can result in difficulties to decision makers for generating optimal solutions to support the regional ecosystem sustainable development.

Consequently, a number of stochastic mathematical techniques were introduced to address these uncertainties and complexities (Li and Huang, 2009; Lv et al., 2010; Johnson et al., 2012; Roy et al., 2014; Haddad et al., 2015; Garnier et al., 2016; Huang et al., 2016; Favretto et al., 2017). For example, Dowd (2007) proposed a stochastic assimilation approach based on Markov Chain Monte Carlo to estimate the randomness on time evolving probability distribution of the ecosystem state, which was effective to characterize ecosystem properties. By integrating chance-constrained programming (CCP) and the relevant Kuhn-Tucker conditions, Rabotyagov (2010) solved the constrained optimization problem and provided a magnitude of uncertainty discount for soil carbon offsets and the budget margin of safety in regional ecosystem. Li et al. (2013) proposed an inexact two-stage stochastic credibility constrained programming method, which could provide scientific bases for solving eco-environmental systems problems by supporting the adjustment of the local economic targets, mitigating schemes of several pollutants under varied levels of system-failure risk. Kangas et al. (2014) used a two-stage stochastic programming method to define the optimal measurement strategy to maximize the net present value of the forest holding of ecosystem. For handling problem of ecological water resources under the stochastic uncertainty, Nematian (2016) developed an extended interval-parameter two-stage stochastic programming approach based on the idea of possibility theory. Zhang et al. (2016) presented an interval stochastic credibility-constrained programming method for planning regional ecosystem sustainability in the City of Dongying (China), in which ecosystem service valuation approach was directly incorporated within the optimization processes. Zeng et al. (2017) proposed a fuzzy-stochastic method with Hurwicz criterion for planning land utilization in a wetland ecosystem for dealing with natural stochastic uncertainties represented as random variables under uncertainty.

In conclusion, stochastic mathematical programming (SMP) methods have been used widely and are effective in dealing with the uncertainties expressed as probability density functions (Li et al., 2015). Chance-constrained programming (CCP), an effective way to deal with random uncertainty on the right-hand sides of constraints, is an alternative for performing risk analysis in regional ecosystem management (Li et al., 2009; Mills et al., 2016; Suo et al., 2017). Based on given probabilities of constraint violation, CCP can not only transform the stochastic programming model into the equivalent deterministic version, but also integrate other uncertain optimization methods within a general framework. It is difficult that CCP reflects the uncertainties independently, which exist in the left-hand-side coefficients of the constraints or the objective function (Huang, 1998). Interval-parameter programming (IPP) is one possible approach to deal with these uncertainties by integrated IPP with the CCP method. IPP can handle uncertainties expressed as discrete intervals that generally cannot be quantified as either distribution functions or membership functions (Li et al., 2008). Hybrid of interval chance-constrained programming (ICCP) is effective for handling uncertainties expressed as probability distributions and discrete intervals. Additionally, as a probabilistic method that uses random numbers to simulate and estimate a stochastic behavior, Monte Carlo simulation (MCS) is a more reliable method that could capture the full range of the possible alternatives performances without requiring many assumptions about the model structure (Baudry et al., 2017; Chen et al., 2017). MCS also has strong flexibility in handling distribution function and helps overcome the subjective elements in quantifying the random parameter due to the insufficient information. Unfortunately, few research works focused on Monte Carlo simulation based ICCP approach for planning regional ecosystem.

Therefore, this study aims to develop a Monte Carlo simulation based interval chanced-constrained programing (MC-ICCP) model for planning regional ecosystem. In MC-ICCP, Monte Carlo simulation is used for producing distribution functions of random parameters; interval chance-constrained programing is capable of addressing uncertainties expressed as probability distributions and discrete intervals. MC-ICCP could also examine the risk of violating system constraints. A case study of the City of Zhuhai will then be used for demonstrating its applicability in identifying ecosystem planning strategies under uncertainty. Ecosystem service valuation approaches will be incorporated into the optimization process for pursuing a sustainable ecological pattern. Results obtained are expected for generating desirable decision alternatives for policymakers.

2. The study system

The City of Zhuhai (ranging from 21°48′N – 22°27′N to 113°03′E – 114°19′E), located in southwest of the Pearl River Delta, covers 1732 km^2 and owns the longest coastline in Guangdong province, China (as shown in Fig. 1). The city consists of three districts (e.g., Xiangzhou, Jinwan, Doumen); the population was approximately 1.67 million in the end of 2016 with a growth rate of 1.7% per year. Currently, the city is a new economic development platform and driving force for economic incentive in Pearl River Delta region; it is an industrial produce base dominated by six pillar industries (i.e., electronic information industry, biological medicine, electrical appliances, electric energy, petrochemical industry, and precision mechanical system). The gross domestic product (GDP) of Zhuhai was $ 31.8 billion in 2016, and occupied about 3.2% of total GDP of the Pearl River Delta (SYD, 2016).

In recent years, the limited land resources in the City of Zhuhai could hardly satisfy the rapid development of economy, growth of population, and shift of industrial structure. From 1994 to 2009, the total area of sea reclamation reached 110.7 km^2 in Zhuhai, which were mainly used for municipal, industrial, traffic and agricultural developments (Liu et al., 2011). In order to mitigate the continuous conflicts between rapid development and limited land resources, the local government has set a goal to reclaim 167.6 km^2 of sea area in the following ten years. It is undeniable that reclamation has become an important manner to produce goods, provide living space for human, as well as develop the local economy (Tian et al., 2016). However, large-scale sea reclamation project has resulted in a number of issues in Zhuhai (e.g., permanently changing the intrinsic natural quality, altering the hydrodynamic effect of sediment transport, as well as endangering the animals and plants). Since 2000, due to reclamation, natural mangrove has destructed from 14.5 km^2 to 1.1 km^2; the area of tidal flat wetland has decreased from 45.6 km^2 to 29.4 km^2; the mean abundance of benthos has decreased from 342.0 Ind/m^2 to 153.3 Ind/m^2. Especially at the seaside, the natural coastal wetlands could be turned into farmlands or municipal and industrial land after reclamation, resulting in severe degradation of regional ecosystem conditions and reduction of ecosystem service value (Wang et al., 2010). In general, with the influences of land reclamation projects in Zhuhai, it is indispensable for decision makers to develop a reliable regional ecosystem management manner to promote regional sustainable development.

Planning regional ecosystem requires socioeconomic and ecological data. Socioeconomic data include the production yield and product benefits of chemical industry, machine industry, marine chemical industry, energy industry, petrochemical industry, and electronic information industry as shown in Table 1, which are uncertain and expressed as intervals. These parameters are obtained from government official reports and related literatures, such as Zhuhai statistic yearbooks (2005–2016), Zhuhai comprehensive land use planning (2006–2020) and Zhuhai thirteenth five-year plan (2016) from Zhuhai Environmental Protection Bureau (http://www.zhepb.gov.cn/). The