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Inexact fuzzy chance-constrained programming for community-scale urban stormwater management

Yanpeng Cai [a, b, c, *], Xuan Lin [d], Wencong Yue [e], Pingping Zhang [a, c]

[a] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing, 100875, China
[b] Institute for Energy, Environment and Sustainable Communities, University of Regina, 120, 2 Research Drive, Regina, Saskatchewan, S4S 7H9, Canada
[c] Beijing Engineering Research Center for Watershed Environmental Restoration & Integrated Ecological Regulation, School of Environment, Beijing Normal University, Beijing, 100875, China
[d] Department of Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke Street West, Montreal, QC, H3A 0C3, Canada
[e] School of Ecological Environment and Civil Engineering, Dongguan University of Technology, Dongguan, 523808, China

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ABSTRACT

Due to frequent and serious waterlog and environmental pollution in cities in recent years, urban stormwater management (USM) has become an essential issue of urban sustainable development in China. Low Impact Development (LID) technologies are effective and popular measures of USM, and can be used to reduce urban waterlog and the associated environmental pollution. In this paper, in order to identify an optimal strategy of LID technologies based on economic efficiencies and environmental performances, the construction costs and environmental benefits of the four LID technologies (including grass swales, bioretention cells, green roofs, and permeable pavement) were analyzed. Then, due to the uncertain feature of rainfall, concentration of pollutants and many social-economic factors, an inexact fuzzy chance-constrained programming (IFCCP) model was developed. Multiple uncertainties that can be expressed as interval parameters, fuzzy sets, and stochastic distribution can be addressed effectively and incorporated directly into the modeling process. Based on the analysis of the precipitation probability distribution and land use data, the developed model was applied to a university campus with relatively high building density and plot ratio in Beijing. Then, optimal solutions of multiple precipitation probabilities (p_m) under varying USM goals were obtained. The four LID technologies were chosen to meet multiple USM goals based on multiple p_m values. When $p_m = 0.1, 0.05, 0.02$ and 0.015, the total construction investments would be 1.46 to 4.66, 1.46 to 5.25, 2.31 to 8.54 and 3.95 to 12.7 million yuan, respectively. The relationship between construction costs and p_m represented the relationship between economic benefit and system risk. The results indicated that USM was influenced by the rainfall capacity, construction costs would increase with the increase of precipitation, and the risks of constraint violation would decrease as the construction costs increase. When considering the four LID technologies during the planning stage of USM, the preferred selection order would be bioretention cells, permeable pavements, grass swales and green roofs. Therefore, the solutions under each p_m level could provide the references for desired USM plans.

1. Introduction

Along with rapid expansions of permeable areas due to urbanization, dramatic changes are occurring for many hydrological processes in cities, such as evaporation, infiltration, groundwater recharge, and surface runoff (Paul and Meyer, 2001; Xu et al., 2010). At the same time, due to high-intensity human activities such as transportation, the initial runoff in cities contains a great amount of harmful materials such as heavy metals, suspended solids, and organics. Such pollutants, being discharged to any receiving water bodies, would deteriorate quality of both surface and ground water, resulting in harmful effects on water security and the corresponding sustainability of cities (Davis et al., 2001; Gobel et al., 2007; Hatt et al., 2004; Lee and Bang, 2000; Sansalone and Buchberger, 1997). As one of an effective technologies dealing

* Corresponding author. State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing, 100875, China.
E-mail address: yanpeng.cai@bnu.edu.cn (Y. Cai).

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with such water quality and quantity issues associated with stormwater runoff, low impact development (LID) technologies are frequently employed. Practically, many factors and parameters need to be determined by decision-makers to assess and identify such technologies to obtain the minimized costs and pollution discharge, which is also subject to changes of construction costs and uncertainties of precipitation events. This is leading to a variety of challenges for decision makers, desiring effective decision-support tools.

Originally, LID technologies and BMPs (Best Management Practices) were firstly advanced and implemented in USA. Compared with BMPs, LID technologies have the advantages of being utilized in small and scattered construction areas at relatively low costs (USEPA, 2000). Normally, over ten technologies are included in the LID directory such as bioretention cells (i.e., rain gardens), green roofs, grass swales, infiltration trench and permeable pavement (Niu et al., 2014). Till now, there have been many practical cases that have employed several LID technologies such as the natural drainage system planning in Seattle of USA, rain gardens in Portland, and rainwater square in Rotterdam of Netherland (Shen et al., 2012). Studies on the stormwater utilization and pollution control were undertaken in the late 1990s in China, the main focus was on pollution control and the construction of rainwater utilization demonstration projects. Since 2005, much attention was paid to the stormwater control of urban buildings and communities in major cities such as Beijing, Shanghai, and Tianjin (Shen et al., 2012). Particularly in 2013, the concept of sponge city was put forward to improve effectiveness in urban stormwater management (USM) based on multiple LID technologies. In 2015, Ministries of Finance, Water Resources and Housing and Urban Construction in China carried out multiple sponge city pilot projects through implementing multiple LID technologies in these projects. The first 16 pilots including Qian'An, Baicheng, and Zhenjiang (Ministry of Finance of the People's Republlic of China, 2015). Till now, there are many representative LID projects in China, such as Beijing Olympic Park, Heilongjiang Qunli National Urban Wetland Park, Jinhua Yan tail Island Park, Shanghai Hongqiao Airport, and Shenzhen Guangming District stormwater utilization demonstration project (Shen et al., 2012). Since the 1990s, extensive research has been carried out for an individual LID technology on efficiencies in runoff reduction and pollutant removal, as well as their costs and benefits. A large amount of experimental and monitoring data has been collected for supporting the establishment of BMPs and LID technology databases. For instance, studies on green roofs covered the impacts on processing efficiency with different factors such as types, slope, soil thickness, surface properties of the soil, vegetation and climatic conditions. At the same time, life-cycle approaches were employed to analyze the economic and environmental benefits of green roofs (Berndtsson, 2010; Carter and Keeler, 2008; VanWoert et al., 2005; Wong et al., 2003). Also, studies of bioretention cells mainly focused on impacts of plant species to the reduction efficiency of flood peak and pollutants (especially nitrogen and phosphorus; Hsieh and Davis, 2005; Hunt et al., 2008; LeFevre et al., 2014). At the same time, studies on permeable pavement were concentrated to specific design, strength design and water quality control, as well as the efficiencies under multiple climatic conditions (Asaeda and Ca, 2000; Scholz and Grabowlecki, 2007; Scholz, 2013). Due to the lack of long-term monitoring data and the needs of decision-making processes, simulation and optimization modeling of LID effects have become one of the hotspots.

According to the published literatures, there were approximately forty category of models that have been used in urban stormwater management and LID simulation (Elliott and Trowsdale, 2007). Many researchers employed process-oriented modeling for simulating the process of infiltration, precipitation, adsorption, evapotranspiration and pollutant migration of LID facilities, and calculating the reduction efficiency of stormwater runoff and pollutants under multiple conditions. Typical systems include SWMM (Storm Water Management Model), SUSTAIN (System for Urban Stormwater Treatment and Analysis Integration Model) and BMPDSS (Best Management Practice Decision Support System). Also, a number of researchers focused on technology-oriented modeling. In these models, the entire process of an individual LID technology can be characterized with comprehensive parameters (e.g., efficiencies of stormwater storage tanks, bioretention cells, green roofs, and permeable pavements), in order to simulate the runoff and water treatment effects of these technologies, a representative one was L-THIA-LID (Long-Term Hydrologic Impact Assessment-Low Impact Development Model; Ahiablame et al., 2012). At the same time, the existing optimization models and decision support systems were used based on monitoring data (Baker et al., 2007; Shafi et al., 2011, 2017; Chen et al., 2016). These models and systems could hardly reflect the uncertain features of rainfall, concentration of pollutants and many social-economic factors. Interval fuzzy optimization theory can fully consider the above-mentioned elements of uncertainty. A number of models have been developed to deal with the uncertainly in water quality management. For example, Li et al. (2013) developed an inexact two-stage credibility constrained programming method for water quality management. Li et al. (2014) developed a large-scale inexact two-stage waste-load allocation model to identify desired decision alternatives for supporting economic development and water quality management. Nematian (2016) developed a two-stage stochastic programming with fuzzy variables for water resource management under uncertainty. However, there are few research for LID technologies. Therefore, the establishment of interval fuzzy optimization theory based optimal model for LID technologies can provide effective decision support with enhanced robustness.

Therefore, in order to effectively identify optimal LID technologies according to their corresponding economic efficiencies and environmental performances, an inexact fuzzy chance-constrained programming (IFCCP) approach will be proposed for supporting USM and environmental pollution control at the community scale. This approach will represent an attempt to combine multiple programming methods to deal with complexities associated with LID technologies. In detail, grass swales, bioretention cells, green roofs and permeable pavements will be considered as potential technologies. At a representative community, an optimal model for urban stormwater management and environmental pollution reduction will be developed based on the IFCCP, with the minimum total construction cost as the goal and the reduction targets of runoff, suspended solids (SS), copper (Cu), total nitrogen (TN), and total phosphorus (TP) as constraints. Based on the analysis of the precipitation probability distribution and land use data, a case study will be carried out to identify the optimal strategy of LID technologies. This method has a) effectiveness in dealing with stochastic features of precipitation events, and b) incorporation of stochastic information directly into decision-making processes, improving robustness of decision making in the processes of urban stormwater management and runoff pollution reduction.

2. Methodology

2.1. Low impact development (LID) technologies

Generally speaking, LID technologies are considered as green and sustainable distributed source control ones that are mainly for small-scale regions. One of the overall goals is to minimize the impacts of permeable areas on natural hydrological processes under any random precipitation events (Fig. 1). For any undeveloped