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Identifying low impact development strategies for flood mitigation using a fuzzy-probabilistic approach

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A R T I C L E I N F O

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A B S T R A C T

Low impact development (LID) includes strategies and practices that are designed to control surface runoff at its sources in a sustainable way. The performance of these strategies has been frequently addressed through curve number approach. This approach however subjects to a great deal of uncertainties owing to uncertain nature of curve numbers and temporal/spatial variability of flood events. This paper represents a novel methodology to deal with both inherent flood uncertainties and epistemic uncertainties identifying optimal LID strategies for flood mitigation. The proposed methodology integrates a great variety of mathematical tools including copula functions, MCS method, hydrological and hydraulic models, NSGA-II algorithm as well as ANN and fuzzy set theory. The obtained results from a case study clearly demonstrate that the proposed methodology not only presents cost-effective measures, but also can simultaneously handle both inherent and epistemic uncertainties in flood risk management.

1. Introduction

Population growth and urbanization have altered the stream flow regimes associated with frequent flood events. This has led to increase runoff volumes, flood damages and stream-bank erosions. Low impact developments (LIDs) and best management practices (BMPs) are a set of mitigation measures that can be considered for reducing the hydrologic consequences of urbanization (Karamouz and Nazif, 2013). In contrast of traditional procedures like dikes and floodwalls which try to evacuate excess waters as soon as possible and do not take into account cumulative damages of floods over long periods of times, LID or BMP measures seek a sustainable way which enable better management of runoff (in terms of both quality and quantity) at source by preserving natural drainage patterns and emulating the natural hydrological cycle.

LIDs includes a wide variety of measures such as runoff reuse, soak ways, infiltration trenches, swales, green roofs, land use change, permeable paving, wetlands, etc. For each case study, the forms of LIDs are determined by local conditions.

Application of LIDs for mitigating the hydrologic consequences has been reported in different research works. USEPA (2000) represented a literature review of low impact developments and their effectiveness for controlling stormwater volume and reducing pollutant loadings into receiving waters. Perez-Pedini et al. (2005) and Zhang (2009) developed and applied Simulation-optimization methodologies to allocate infiltration-based LID technologies based on the reduction of peak flow at the watershed outlet. Damodaram et al. (2010) demonstrated that a combination of LID and ponds is more efficient compared to LID or ponds alone. Damodaram and Zechman (2013) also developed a simulation–optimization approach for optimal allocation of permeable parking lots, rooftops and detention ponds for a few design storms. Oraei Zare et al. (2012) represented multi-objective optimization methods to select BMP measures for urban storm management considering both quality and quantity aspects of controlling surface runoff. Among different types of LIDs, land use change strategies are of great importance for flood mitigation due to their compatibilities with environmental conditions. More attention however has been paid to find out optimal land allocation from the soil conservation and agricultural-benefit viewpoint (see Onal et al., 1998; Amir and Fisher, 1999; Randhir et al., 2001; Mohseni Saravi et al., 2003, Ducourtieux et al., 2005; Gabriel et al., 2006; Luo and You, 2007; Sadeghi et al., 2009). Yazdi et al. (2013a) represented a methodology to find out the most suitable land use allocation for flood risk mitigation. The proposed methodology integrated a hydraulic model and a multi-objective optimization model for considering

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the interaction of various land use change actions on flood mitigation and finding out the best land use change strategies. Their work however did not involve the inherent and epistemic uncertainties.

Despite various research works on selecting LID strategies, there are still some challenges in design of LID and BMP measures concerning the significant flood uncertainties. Most of the previous works have represented LID strategies for one or a few design storms, separately. From decision making viewpoint, the question is which storm design should be considered to select the best strategies. Since floods or storms are naturally stochastic, instead of a scenario based approach, a risk based approach seems more appropriate to represent optimal practices considering flood uncertainties. Inherent uncertainties of floods in watershed scale include both temporal and spatial uncertainties. Temporal uncertainties are normally considered in flood risk management by flood frequency analysis of maximum annual time series and representing as the probability density functions (PDFs) of rainfalls or discharges which these PDFs can subsequently be used in Monte Carlo Simulation (MCS). Spatial uncertainties however, cannot easily be handled through MCS task, due to dependence structure of flood rainfalls in different parts of watersheds. Researches have shown that the assumption of independence can have a significant effect on magnitudes of generated surface runoffs and may leads to erroneous results (e.g. see AghaKouchak et al., 2010; Golian et al., 2011). Nevertheless, these spatial uncertainties have not been considered so far in optimization of cost-effective designs of floodplain systems, likely due to the difficulty and complexity of generating joint probability distributions for rainfall variables. In this paper, spatial variability of rainfalls along their dependence structures are addressed through joint cumulative distribution functions (CDFs) derived by copula functions within a Monte Carlo (MC) framework. A major advantage of copula method for generating CDFs is that marginal distributions of individual variables can be of any form and the variables can be correlated (Favre et al., 2004). This represents a significant advantage compared to conventional multivariate analysis as many variables from hydrological phenomena cannot be described using the same type of probability distributions (Fu and Butler, 2013).

Besides the inherent uncertainties, epistemic uncertainties, stemmed from incomplete knowledge or imprecise information about a physical system, also play an important role in flood risk management. In optimal design of flood mitigation measures, the performance of LID strategies is often considered through updating the curve numbers (CNs). CN modifications however are subject to a great deal of epistemic uncertainties, arising from the lack of knowledge and existing ambiguity in the curve number of practices and land use changes in the future plans. Less attention however has been paid to these parameter uncertainties in representing cost-effective LIDs. To cover this gap, fuzzy approach is addressed throughout this paper which is able to characterize curve number uncertainties into the system design.

Generally, in flood risk management, sparse efforts have been spent to develop methodologies that can propagate both types of uncertainties simultaneously through the modeling process. Fu and Kapelan (2011) employed a random set based method to bridge the gap between probability and fuzzy set for sewer flooding estimation. Their method however is not able to handle spatial uncertainties of floods while these uncertainties are of great importance in flood risk assessment when studies are carried out in watershed scale.

The work described here represents an innovative methodology which integrates inherent and epistemic uncertainties in a unified framework for identifying the optimal flood risk management strategies, offering a flexible facility to handle both types of uncertainty. Multivariate joint distribution of observed extreme rainfalls is constructed for considering temporal and spatial flood uncertainties within a MC procedure. On the other hand, epistemic uncertainties of curve numbers are characterized through the fuzzy membership functions and α-cut concept in order to propagate curve number uncertainties into the flood damage fuzzy membership functions. Both approaches are aggregated with NSGA-II optimization model to represent optimal land use strategies as LID measures. Details of the methodology are represented in continued sections.

Hereafter throughout this paper, the terms “LID strategies”, and “land use change strategies” are used interchangeably.

2. The analysis of extreme rainfall data

Flood rainfalls/discharges are naturally uncertain i.e. their values constantly fluctuate with random patterns. These uncertainties are a property of the system and cannot be reduced due to their inherent nature. Henceforth, they are so called as inherent uncertainties. Inherent uncertainties are traditionally represented by probability theory in which the value of uncertain variables is described by probability density functions (PDFs). The probabilistic approach has been extensively used in practice for considering flood uncertainties on optimal design of hydro-systems (e.g. Afshar and Marino, 1990; Tung and Bao, 1990; Kort and Booij, 2007; Karamouz et al., 2008; Afshar et al., 2009; Qi and Altinakar, 2011; Delelegn et al., 2011; Sun et al., 2011; Yazdi and Salehi Neyshabouri, 2012). The methodology represented by US Army Corp of Engineers (1996) is commonly used to address the hydrologic (flood-frequency analysis), hydraulic (rating-curve development), and economic uncertainties (stage-damage analysis) in flood risk management, particularly for floodplain systems. Despite extensive application, there are still some challenges when this probabilistic approach is used on a watershed scale for selecting the best flood risk mitigation measures which have not been reported yet through other research works. Flood magnitudes are not the same at different parts of the watershed (Fig. 1) and this means in addition to temporal uncertainties, floods have considerable variations on spatial scales.

Thus, a multi-site sampling approach is required for rainfall generation from the PDFs of extreme rainfalls at monitoring rain gauges of the watershed. Multi-variate sampling however is a

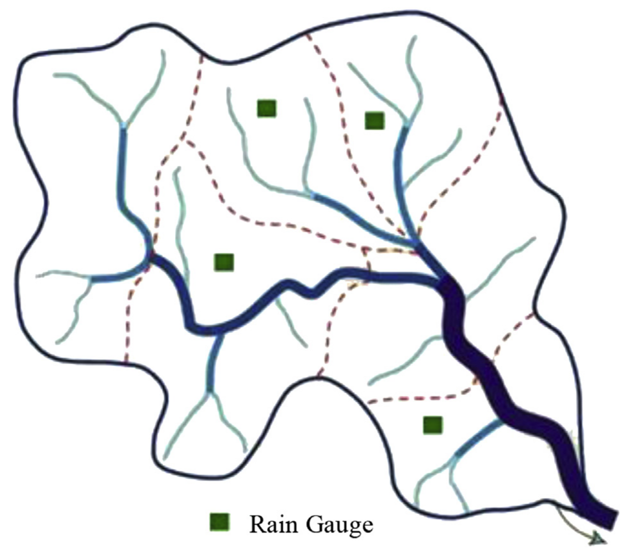

Fig. 1. A schematic view of a watershed and scattered rain gauges.