Environmental Modelling & Software 95 (2017) 143–155

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

An integrated assessment of urban flooding mitigation strategies for robust decision making

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ARTICLE INFO

Article history:
Received 10 July 2016
Received in revised form
12 May 2017
Accepted 16 June 2017

Keywords:
Drainage system
Hydrologic model
Low impact development
Urban flooding

ABSTRACT

In order to mitigate urban flooding, an integrated assessment has been proposed to identify the optimum drainage solution which implements the potential green infrastructure with the existing conventional gray infrastructure. The integrated evaluation framework which consists the data of remote sensing and geographic information system, and the assessments of 2D hydrologic simulation and life cycle cost has been applied into a developed area in Shanghai under nine design storms with different return periods and durations. The results showed that increasing the pipe diameter at this area could alleviate the node flooding and pipe hydraulic load under a short return period and rainfall duration. However, according to the integrated evaluation, the potential flooding risk under a longer rainfall duration could be well controlled by implementing a combination of low impact development practices of Rain Barrel (RB) + Pervious Concrete (PC) + Green Roof (GR).

1. Introduction

Urban flooding is a serious and growing development challenge, which causes widespread devastation, economic damages and loss of human lives (Shuster et al., 2005). The occurrence of floods is the most frequent among all natural disasters globally, which is mainly due to the climate change induced extended periods of high-intensity rainfall and rapid urbanization induced changes of watershed hydrology (Ahiablame and Shakya, 2016; Chen et al., 2015; Elliott and Trowsdale, 2007). Besides the global phenomenon of extreme rainfall event, considerable concern has been addressed to the increased proportional area of impervious surface which is the primary agent responsible for the catchment hydrologic changes associated with the urbanization process (Shuster et al., 2005). The increases in impervious surface cause a decrease in the infiltration of stormwater and an increase in the production of surface runoff which has indirect effects on downstream flooding.

In the context of urban flooding mitigation, conventional gray infrastructures included gutters, storm sewers, tunnels, culverts, detention basins, pipes and mechanical devices were used collectively in a system to capture and convey runoff (USEPA, 2016). Gray infrastructure is regarded as a typical approach to drain surface runoff from urban areas. The drainage capacity of gray infrastructures was increased relies on expanding and upgrading the existing systems. However, due to the pressures of climate change and urbanization, to increase the capacity of gray infrastructures has been increasingly proven to be unsustainable, costly and even impractical, especially for a developed urban area (Qin et al., 2013). Therefore, conventional gray infrastructures is experiencing

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http://dx.doi.org/10.1016/j.envsoft.2017.06.027
1364-8152/

difficulties in efficiently managing stormwater (Chen et al., 2015).

As an alternative to the traditional gray infrastructure, green infrastructure, also known as low impact development (LID), sustainable urban drainage systems (SUDS), water balance methodology (WBM), and water-sensitive urban design (WSUD), includes a variety of practices such as Green Roof, Bio-Retention Cell, Rain Barrel/Cistern, Vegetative Swale and Permeable Pavements (in this study they are operationally itemed as LID practices), is used to reduce runoff, minimize pollutant discharges, decrease erosion, and maintain base flows of receiving streams (USEPA, 2016).

The hydrological performance of LID practice has been studied on a laboratory and pilot scales as well as in-situ full scales (Liao et al., 2013; Qin et al., 2013). Studies have shown that LID practices offer significant environmental benefits over conventional stormwater management practices (USEPA, 2016). However, LID practices cannot completely substitute for the conventional gray infrastructures to control storm runoff (Damodaram et al., 2010). In order to provide control for an entire spectrum of storm events, an optimum strategy which incorporates green infrastructures into gray infrastructures is essentially needed (Casal-Campos et al., 2015; Qin et al., 2013).

Given the techniques available, the possible selection of green infrastructure practices are numerous at watershed scales because of complicated watershed features. In order to evaluate strategies which are effective and support decision-maker to optimally implement transitioning plan of drainage infrastructures, a systematic assessment of the possible strategy is necessary. First of all, the optimum drainage solution must be sufficiently resilient to handle urban flooding. Hydrologic model is a useful tool to estimate the performance of drainage solutions on urban flooding mitigation. Some of the modelling approaches, such as ILLUDAS (Terstriep and Stall, 1974), SWMM (Brown, 1976), TR-55 (Cronshey, 1986), HSPF (Bicknell et al., 2001), Inforworks (Koudelak and West, 2008), and STORM (Wiles and Levine, 2002) are proposed mainly for urban flood planning and management (Chen et al., 2015). The focus of these models are the underground pipeline water transportation, and have little or no function to calculate the surface runoff which is the main cause of urban flooding. To facilitate the surface runoff routing for urban flood mitigation, two-dimensional (2D) surface runoff routing was added to the hydrologic simulation in the latest modelling approach (Elliott and Trowsdale, 2007). In these models, the urban surface flow, river channel flow and underground pipeline flow are coupled, and the surface runoff routing could be calculated (Chen et al., 2015; Leandro and Martins, 2016). Therefore, in this study, a 2D hydrologic model (MIKE URBAN, DHI, www.mikepoweredbydhi.com) was employed to evaluate the performance of each drainage solution candidates on flood volume reduction under different rainfall characteristics, e.g. rainfall amounts, rainfall durations and locations of peak rainfall intensity.

Then, the optimum drainage solution must be also cost-effective. It has been reported that some LID practices can achieve stormwater management goals at a lower initial cost than conventional systems, since they require less pipe and underground infrastructure (Carter and Keeler, 2008; Santos and Ferreira, 2013). However, in some other cases, LID practices have higher initial costs than traditional approaches, but with lower maintenance and operating costs. Life cycle costs analysis (LCCA) is an useful framework that builds on the well-founded principles of economic analysis to evaluate the overall long-term economic efficiency between competing alternative investment options (Liao et al., 2014). It is recommended and used extensively to support project-level decisions (Carter and Keeler, 2008; David, 1997; O'Sullivan et al., 2015; Ossama et al., 2003). Therefore, in this study, the cost of each drainage solution candidate was subsequently accessed under a lifetime scale by LCCA approach.

Consequently, the primary purpose of this study is to propose a universal and practical framework for assessing which design alternative (LID or conventional) fulfils the performance requirements of a municipal land development project. The detailed focus were (i) identification of the potential to implement green infrastructure options in developed urban areas integrated with the existing conventional drainage systems, and (ii) identification of the optimal combination of existing conventional gray drainage systems and new green LID options that improves the performance at the lowest cost.

2. Materials and methods

The integrated assessment of urban flooding mitigation strategies consisted of a geographic information system (GIS) integrated urban water modelling software of MIKE URBAN (powered by DHI, www.mikepoweredbydhi.com) and a cost–benefit analysis estimated by the LCCA approach (Fig. 1). The modules of rainfall-runoff, pipe flow and 2D overland flow integrated into MIKE URBAN were used to simulate the flow dynamics between sewers and surface areas.

2.1. Urban flooding simulation

Rainfall-runoff module. The hydrological part of the rainfall-runoff module is governed by the values of runoff depths, hydrological reduction factor (φ), and rainfall initial loss (i). Runoff depths is frequently linear to the rainfall depths, whose values were them from literature (K. Arnbjerg-Nielsen, 1996; Lindberg and Jørgensen, 1986; Thorndahl et al., 2006). The hydrological reduction factor (φ) determining the part of the impervious area contributing to the runoff. The initial loss is the hydrological loss due to wetting loss and filling of terrain depressions in the beginning of a rainfall event. These two parameters were considered as global variables, i.e. the same value was implemented for every sub-catchment (Thorndahl et al., 2008). In addition, a Time/Area method was used to determine the runoff process through the computational time step. A more detailed description can be found elsewhere (Artina et al., 2007).

Pipe flow module. Saint-Venant function was used to represent the conduit as a conceptual link of defined length between two nodes, which is based on an expression similar to the Manning equation. The solution of the Saint-Venan equations are retained in pressurized flow by introducing a suitably narrow slot at the top of the closed conduit (Preissmann, 1961).

2D overland flow module. 2D shallowwater equations based on hydraulic wave model were employed to describe the overland flow process (Hunter et al., 2008). The gridded bathymetry data of the study area with a spatial resolution of 30 m was obtained and the values of the rest of elevation points were calculated by a linear interpolation between adjacent points, which was stored in the raster layer as a digital elevation model (DEM) and provided as an input to the 2D overland flow module. In addition, the bed resistance coefficient (C_b) (namely the roughness coefficient of surface) was considered as a global variable. The eddy viscosity was given by $E = 0.02 \cdot dx \cdot dy / dt$, where dx and dy are the model cell size; dt is the simulation time step. Then, the orifice equation was used for calculating the flow exchange between the pipe flow and 2D overland flow modules.

2.2. Classification of land use

The Environment for Visualizing Images (ENVI) software including ENVI 5.1 and ENVI classic were used to classify the land use. A supervised classification method of Support Vector Machines