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Research article

Integrated design workflow and a new tool for urban rainwater management

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ABSTRACT

Low Impact Development (LID) practices provide more sustainable solutions than traditional piping and storm ponds in stormwater management. However, architects are not equipped with the knowledge to perform runoff calculations at early design stage. In response to this dilemma, we have developed an open-source stormwater runoff evaluation and management tool, Rainwater+. It is seamlessly integrated into computer-aided design (CAD) software to receive instant estimate on the stormwater runoff volume of architecture and landscape designs. Designers can thereby develop appropriate rainwater management strategies based on local precipitation data, specific standards, site conditions and economic considerations. We employed Rainwater+ to conduct two case studies illustrating the importance of considering stormwater runoff in the early design stage. The first case study showed that integrating rainwater management into design modeling is critical for determining LID practice at any specific site. The second case study demonstrated the need of visualizing runoff flow direction in assisting the placement of LID practices at proper locations when the terrain is of great complexity.

1. Introduction

With the rapid progress of urbanization, environmental deterioration and ecological destruction in urban areas are becoming the bottleneck of sustainable urban growth (Cohen, 2006; Grimmond, 2007; Hubacek et al., 2009; Tong et al., 2015, 2016a, 2016b). The increased impervious surfaces associated with city development have consistently shown to result in degraded aquatic ecosystems (Carter and Jackson, 2007; Hsieh and Davis, 2005; Lee and Bang, 2000; Miltner et al., 2004). The replacement of vegetated areas that provide rainwater interception and storage often results in an increase in the rate and volume of stormwater runoff (Kim et al., 2003; Mansell, 2003; Whitford et al., 2001). The subsequent urban flooding with increased frequency and severity is exacerbated by the climate change, which causes amplified magnitude of rainfall intensity in some parts of the world (Dore, 2005; Villarreal et al., 2004). The resultant urban flooding causes exceptionally severe damage where massive, rapid urbanization is occurring due to poorly engineered infrastructure (Huong and Pathirana, 2011; Liu, 2009; Wang, 2001). To address this urgent concern, it is crucial for architects and landscape designers to have a greater understanding and modeling capability of stormwater runoff to face the increasing risks in the future.

In regard to strategies for reducing high runoff and harvesting of rainwater as an alternative water supply source, the conventional strategy—using piping to partially offset the environmental damage of impervious surfaces—is becoming obsolete because of its limited effect on drainage capacity and pollution control, as well as the high costs and disturbance to local neighborhoods (EPA, 2000). As a result, Low Impact Development (LID) practices have been suggested as a viable solution (Burns et al., 2012; Chang, 2010; Dietz, 2007; Maniquiz-Redillas and Kim, 2016; Qin et al., 2013; Tong et al., 2016c). LID practices increase sustainability by using porous pavement, bioretention, green roofs, rainwater harvesting and other strategies that manage rainwater as close to its source as possible. In particular, bioretention is effective in retaining large volumes of runoff. As well, porous pavement is effective in infiltrating stormwater runoff (Niu et al., 2015), and green roofs can retain a large percentage of rainfall in a variety of climates (Dietz, 2007). These approaches increase groundwater replenishment, rainwater reuse, and on-site water balance, while mitigating downstream flooding (Pyke et al., 2011).

In the U.S., the rainwater runoff of a development project is

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calculated by hydrology engineers who are usually engaged during the design development phase or perhaps even later. In addition, for the sizing of conventional runoff management such as retention ponds or drainage pipes, hydrology engineers could conduct the task with little participation by the architectural team. Unfortunately, overlooking the site hydrology in the early design stage can lead to many challenges when incorporating LID strategies. This is because many LID practices must be integrated with other design elements or, to some extent, are parts of the design itself. Architects and landscape designers must be able to develop preliminary on-site stormwater management strategies in harmony with early architectural, structural and landscape design. Addressing the problem later in the process may limit one's options for selection, location or sizing of systems. Moreover, since local regulations, environmental standards such as LEED (USGBC, 2013) and design best practices increasingly mandate rainwater management targets, project teams need to consider runoff issues as an integrated part of the early design to guarantee the fulfillment of their goals. The team should be able to conduct quick compliance checks, and if the design falls short, adjust their strategies accordingly.

To address the issues discussed earlier in the paper, there is a need for developing a stormwater runoff model that provides quantitative visualization and estimation that incorporates site geometries. There are only few models in the market for stormwater runoff calculation that can benefit landscape design. The most advanced tool is EPA's Storm Water Management Model (SWMM) (Huber et al., 2005). It is a rainfall-runoff simulation model that predicts runoff quantity and quality from primarily urban areas. It is not friendly to landscape designers for the following reasons. First, the model does not support direct import of complex computer-aided design (CAD) geometries. Second, the model simplifies terrain to two dimensions, which does not indicate runoff flow directions. HydroCAD is another application developed by HydroCAD Software Solutions, LLC (Koo, 1989). Its function is limited to water conveyance and pond design (including storage chamber), and this model has no capacity for other runoff management practices such as green roofs, permeable pavement or rainwater harvesting. The model presented in the paper is the first one to our knowledge that offers 1) graphical visualization of buildings and landscape; 2) prediction of runoff flow directions; and 3) user-friendly interface for architect and landscape designers. With these tailored features, Rainwater+ is an intuitive tool for runoff evaluation and management that can enables designers to integrate rainwater considerations into their design workflow.

In Table 1, four softwares listed are positioned to solve different problems although they all belong to the general category of "stormwater runoff estimation". SWMM and HydroCAD are comprehensive packages with dynamic modeling capacity for peak flow and water quality prediction, whereas the National Stormwater Calculator (NSC) and Rainwater+ only concern about runoff volume. The former two can be used for water conveyance (e.g. pipe design) in the Construction Documents phase, while the latter two, used in the Schematic Design phase, can provide general reference for the compliance of the "runoff management" requirements in the vast majority of sustainable rating systems or state codes. Unlike SWMM and HydroCAD whose target users are civil engineers and researchers, Rainwater+ and NSC are tools tailored for "less-professional" users such as architects and landscape designers. Their user interfaces are designed to be much simpler. In contrast with NSC, Rainwater+ provides features (system sizing and flow visualization) that can greatly assist the LID design process. In addition, the integration of Rainwater+ into CAD platform (e.g., Rhino) allows the possibility to accommodate the need of frequent design changes in the early design stage while achieving the same accuracy of calculation. The streamlined process of Rainwater+ eliminates the uncertainties associated with redrawing and simplifying geometries in other platforms for runoff calculation.

This paper is organized as follows: We start with a detailed description of our numerical model, Rainwater+. Next, we share two case studies that employed the Rainwater+ software to illustrate the importance of considering stormwater runoff in the early design stage. Finally, we provide design recommendations based on the results of our analysis.

2. Model description

Rainwater+ presented in this paper is an intuitive and interactive tool for the use in the early design process, which was designed to better serve architects, landscape designers and ultimately the hydrological engineers who work with them. Rainwater+ is an open source model available for download from the website, www.rainwaterplus.com.

Rainwater+ is built upon the software platforms Rhinoceros and Grasshopper, developed by Robert McNeel & Associates. Rhinoceros is one of the fastest-growing, three-dimensional modeling tools for architects and landscape designers. As many designers are already familiar with Rhinoceros, Rainwater+ allows them to consider stormwater runoff based on existing geometries without interrupting their workflow by having to engage a separate tool. Rainwater+ is developed with Grasshopper, a graphical programming platform integrated with Rhinoceros's 3D modeling tools. The general workflow of Rainwater+ is displayed in Fig. 2. Using this platform, Rainwater+ is able to provide instant feedback based on CAD models throughout the entire design process. Rainwater+ is positioned to address rainwater management issues of site less than 1 km^2 – the relatively small and integrated drainage basins in highly developed urban regions that are vulnerable to severe urban flood risks (Lee and Heaney, 2003; Dietz and Clausen, 2008).

2.1. Model features

Rainwater+ can be used for design evaluation, decision-making, compliance checking, and rough cost estimation. It is comprised of four major process components that will be discussed in greater detail: 1) a built-in precipitation database; 2) a terrain analysis tool; 3) a runoff volume calculator; and 4) a library of LID practices and sizing components. The interface integrates directly with the

Table 1
A comparison of four stormwater runoff estimation softwares in terms of their features and target users.

Tool	Runoff volume estimation	Flow rate estimation	Water quality prediction	LID design	System sizing	Graphic inter-connection	Flow visualization	Targeted user
SWMM	✓	✓	✓	✓	✓	Limited	N/A	Civil engineers, Scientific researchers
HydroCAD	✓	✓	Limited	Limited	Limited	Limited	N/A	Civil engineers
National Stormwater Calculator (NSC)	✓	N/A	N/A	✓	N/A	N/A	N/A	Developer, Landscape architects, Urban planners, Homeowner
Rainwater+	✓	N/A	N/A	✓	✓	✓	✓	Architects, Landscape architects