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A new framework for modeling decentralized low impact developments using Soil and Water Assessment Tool

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ABSTRACT

Assessing the performance of LID practices at a catchment scale is important in managing urban watersheds. Few modeling tools exist that are capable of explicitly representing the hydrological mechanisms of LIDs while considering the diverse land uses of urban watersheds. In this paper, we propose computational modules that simulate the hydrological processes of LIDs including green roof, rain garden, cistern, and porous pavement. The applicability of the modules was evaluated using plot scale experimental monitoring data. The effectiveness of LIDs was investigated in a highly urbanized watershed located in Austin, TX. Results indicate that the performance of LIDs is sensitive to LID configurations, application areas, and storm event characteristics, suggesting the need for studies on spatial optimization of LIDs and critical storm events to maximize the utility of LIDs. The LID modules offer a comprehensive modeling framework that explicitly simulates the water quantity processes of the LIDs considering landscape heterogeneity.

1. Introduction

Low impact development (LID) practices are designed and implemented to reduce stormwater runoff at the source level, which subsequently leads to decreased velocity, prolonged travel time of downstream runoff, and then reduced pollutant loading to downstream areas. LIDs have been widely employed as measures to mitigate urbanization impacts on water quantity and quality (Dietz, 2007; Roy et al., 2008; Ahiablame et al., 2012). Estimating effectiveness of LIDs is a process necessary for developing stormwater management plans to improve urban water environment (Gilroy and McCuen, 2009). Although many studies reported effectiveness of LIDs with wide variations in reducing the amount of runoff and pollutants (Ahiablame et al., 2012; Li and Babcock, 2014), Only few research has been conducted on watershed-scale effects due in part to the lack of tools for simulating LIDs using process-based modeling techniques at this scale (Elliott and Trowsdale, 2007; Roy et al., 2008; Gilroy and McCuen, 2009). LID modeling tools are expected to be refined to better address the increasing complexity of urban landscape and stormwater infrastructure, let alone the growing popularity of LIDs implementation to control stormwater in urban watersheds (Brander et al., 2004; Elliott and Trowsdale, 2007; Hood et al., 2007; Freni et al., 2010; Ahiablame et al., 2013; Loperfido et al., 2014; Palla and Gnecco, 2015).

Mathematical models are critical and efficient tools that help better understand hydrological processes occurring at various spatial and temporal scales, and they have been commonly used to investigate effects of land use changes on watershed hydrology and water quality. Each model employs its own unique approaches and mechanisms to represent landscapes and simulate hydrological processes of a watershed, thus incorporating LID practices into the models would require different strategies. Technical Release 20/55 (TR-20/55) and Hydrologic Engineering Center – Hydrologic

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Modeling System (HEC-HMS) are event-based models developed for simulating surface runoff hydrographs of large storms without continuous soil water accounting (USDA, 1986; USACE, 2000). Since they represent the watershed landscape in a lumped way at a subwatershed level, it is not allowed to place LIDs in specific land uses. Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) is a screening model to assess the relative effectiveness of LIDs quickly by comparing watershed responses to land use change or LID scenarios represented using runoff curve numbers in a highly lumped way (USDA, 1986; Ahiablame et al., 2012).

Hydrologic Simulation Program – Fortran (HSPF) can consider various land use types in modeling, but it does not explicitly consider watershed-level runoff routing that is an important transport process controlling hydrological responses of a watershed to a storm event (Bicknell et al., 1996). Also, its lumped representation of watershed landscape restricts its capability to consider the spatial heterogeneity of the landscape in hydrological modeling. Storm Water Management Model (SWMM) is one of the most widely used models to simulate urban runoff and water quality of a small lot or block considering the sewer system (Rosa et al., 2015). However, a study area is represented with only two land types, pervious and impervious covers, and detailed hydrological processes are not explicitly incorporated in the model (Rossman, 2010; Burszta-Adamiak and Mrowiec, 2013). Thus, its capability of representing complicated urban watershed landscapes consisting of several levels of urbanizations would be greatly limited, and subsequently, it becomes difficult to show different hydrologic responses to the variety of urban land uses using the model. Simulation strategies of SWMM and HSPF were integrated into the simulation modules of System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN; Shoemaker et al., 2009). However, the oversimplified land use representation of SWMM was adopted in SUSTAIN without an improvement (Shoemaker et al., 2009). Useful reviews on current models for simulating LIDs can be found in the literature (Zoppou, 2001; Obropta and Kardos, 2007; Elliott and Trowsdale, 2007; Li and Babcock, 2014).

SWAT was developed to simulate the impacts of land use management practices on hydrology and water quality processes, initially for an agricultural watershed (Arnold et al., 1998; Gassman et al., 2007). The model is capable of simulating hydrological processes at multiple spatial scales, from HRUs to subwatersheds and watersheds, which allows detailed descriptions of heterogeneous watershed landscape and processes and placements of LIDs at the HRU level (Her et al., 2015). In addition, SWAT allows continuous simulation of watershed hydrology by accounting soil water with consideration of infiltration, evapotranspiration, and percolation between storm events (Arnold et al., 1998; Neitsch et al., 2011). Recent enhancements for sub-hourly simulation expanded its utility to urban stormwater modeling (Jeong et al., 2010, 2011, 2013; Kannan et al., 2014), and the model has become a good alternative to other models in assessing long-term urban watershed processes in a distributed and process-based manner. Thus, it would be encouraged to take a benefit of the utilities and strengths of SWAT in developing modeling tools for spatial and temporal analysis of urban watershed hydrology.

The objectives of this study are to develop algorithms for (1) simulating hydrological processes of spatially distributed LIDs such as green roof, rain garden, cistern, and porous pavement and (2) assessing their effectiveness in reducing stormwater discharge volume and rate at the field and watershed scales. Runoff hydrographs simulated using the LID modules and observed from field experiments were compared to assess the validity of the LID modules. Also, the sensitivity of simulated discharge to LID parameters was investigated to assess the hydrological behavior of the modules. Twenty-six LID implementation scenarios were developed and evaluated to find a correlation between the watershed-scale effectiveness of LIDs and their application areas.

2. Methods and materials

2.1. Study watershed and input data preparation

A SWAT model was prepared to simulate the dynamic runoff hydrographs in the Brentwood watershed, which is a highly urbanized catchment (149.8 ha) in Austin, TX (Fig. 1). Austin is the capital city of Texas, which has recently been growing as fast as any other cities in the United States. The city of Austin is keen on protecting the environment and mitigating flood risks in populated urban areas. The watershed has ten land uses based on an in-house database ("LANDUSE 12": City of Austin, 2012) of the City of Austin (Table 1). A fraction of each land cover directly connected to the impervious area was calculated using citywide sampling data for the total impervious area (TIA) of each land use type and using the method Sutherland (2000) proposed to estimate effective impervious areas (EIA) from TIA (Table 1). Soil properties were obtained from the SSURGO database (USDA, 2015). Streamflow has been monitored by the City of Austin, where they installed two

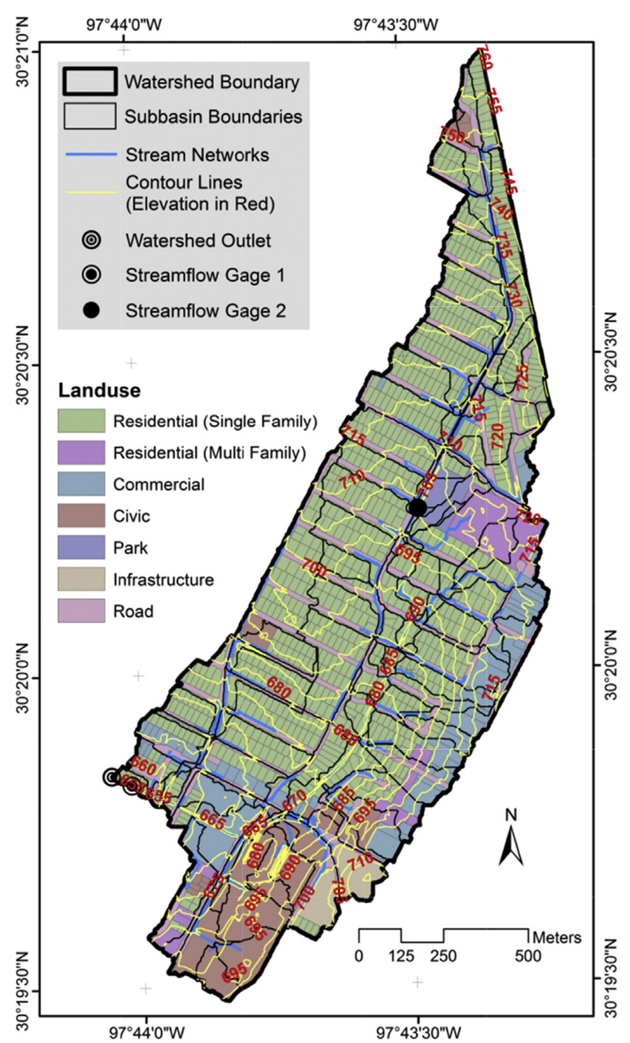

Fig. 1. Land uses elevation, channel networks, and SWAT subbasins of the study watershed.