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Modeling stormwater management at the city district level in response to changes in land use and low impact development

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ABSTRACT

Mitigating the impact of increasing impervious surfaces on stormwater runoff by low impact development (LID) is currently being widely promoted at site and local scales. In turn, the series of distributed LID implementations may produce cumulative effects and benefit stormwater management at larger, regional scales. However, the potential of multiple LID implementations to mitigate the broad-scale impacts of urban stormwater is not yet fully understood, particularly among different design strategies to reduce directly connected impervious areas (DCIA). In this study, the hydrological responses of stormwater runoff characteristics to four different land use conversion scenarios at the city scale were explored using GIS-based Stormwater Management Model (SWMM). Model simulation results confirmed the effectiveness of LID controls; however, they also indicated that even with the most beneficial scenarios hydrological performance of developed areas was still not yet up to the pre-development level, especially where there were pronounced changes from pervious to impervious land.

1. Introduction

The increase in the impervious surface areas as a result of urbanization has produced significant hydrological effects globally (Dietz, 2007; Choi and Deal, 2008; Ahiablame et al., 2012; Bell et al., 2016). It has been widely reported that such changes disrupt the natural water cycle, intensify the urban rain-island effect and the surface runoff, reduce water quality and diminish the groundwater supply (Pomeroy, 2007; Sheng and Wilson, 2009). Of these impacts, the most direct are significant increases in surface water runoff, flood peak frequency and volume, which intensify the risk, frequency, and extent of urban flood disasters (Pauleit et al., 2005) and threaten the safety and livelihoods of urban residents (Baxter et al., 2002; Dougherty et al., 2007). Recent increases in the intensity of precipitation events due to global climate change in various geographic locations further aggravate the impact of urbanization on the natural water system (Rosenberg et al., 2010; Hanak and Lund, 2012).

Traditional urban stormwater controls are mostly based on the grey infrastructure and involve measures such as increasing the drainage network and rainfall drainage pipe diameters to facilitate the rapid discharge of accumulated rainfall (USEPA, 2000; Cembrano et al., 2004). However, these measures directly affect generation of local water flow and associated conditions, increase the amount of stormwater, and complicate the task of urban flood prevention (Pomeroy, 2007), while also resulting in a substantial loss of urban water resources (Ahiablame et al., 2012). Therefore, it is important to develop new alternative urban stormwater management approaches globally.

Increasing infiltration has always been an important way to reduce stormwater runoff as well as to minimize its impacts (Huber and Cannon, 2002; Yao et al., 2016). Accordingly, a number of urban stormwater management strategies have been proposed and implemented in recent years, especially those controlling total impervious area (TIA) (Carter and Jackson, 2007; Roy and Shuster, 2009). Examples of these measures include water-sensitive urban design (WSUD) in Australia (Coffman, 2002; Zimmer et al., 2007), sustainable drainage systems (SuDS) in the UK (Scholz and Grabowiecki, 2007), and best management practices (BMPs) and Low Impact Development (LID) in the USA (USEPA, 2000; Ahiablame et al., 2012; Liu et al., 2016). Of these measures, LID is

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mentioned as an especially promising novel stormwater management strategy. It is mainly achieved by using green infrastructure, multilayer development and decentralized micro-scale control to create post-development hydrological conditions that mimic the pre-development natural hydrologic functions. LID has been widely applied for stormwater management in the USA, Australia, and several European countries (USEPA, 2000; Coffman, 2002; Adams et al., 2010; Pyke et al., 2011; Ahiablame et al., 2012; Yazdi and Neyshabouri, 2014). Numerous research studies and practical applications have demonstrated that natural drainage systems that are based on an LID concept and incorporate urban green space can effectively reduce surface runoff, decrease peak flow volumes, reduce soil erosion, and promote water quality (Hunt et al., 2006; Dietz, 2007; Gregoire and Clausen, 2011). In particular, the idea of LID-referenced "sponge" cities was developed in China, and a series of demonstration projections have been conducted in recent years (General Office of the State Council, 2015). However, most quantitative studies of LID scenarios to date have been limited to the lot or block scale. Currently, there are almost no comprehensive quantitative assessments of the hydrological effects of LID measures that go beyond this relatively small spatial scale. This limits the promotion and application of LID at the city or regional level (Dietz, 2007; Ahiablame et al., 2012).

Modeling LID impact at a larger scale of decision-making is necessary to generalize and provide guidance for stormwater management and LID practices (Lee et al., 2012). Hydrological models can be used to simulate the effects of LID application at various temporal-spatial scales in urban areas, thus enabling the potential multi-scale application of LID (Elliott et al., 2009; Ahiablame et al., 2012). Currently, various distributed hydrological models, including the SCS (Soil Conservation Service), SWAT (Soil-Water Assessment Tool), MOUSE (Model for Urban Sewers, Danish Hydraulic Institute, 1995), Hydro CAD, and the stormwater management model (SWMM) are available to manage urban runoff (Gironás et al., 2010; Mancipe-Munoz et al., 2014; Cunha et al., 2016). Bosley (2008) conducted a sensitivity analysis for the 19 most commonly used hydrological models or software programs by applying them to a representative area and found that SWMM was the most suitable hydrological model in the urban setting for various land-use scenarios and the application of LID simulation analysis.

SWMM developed in 1971 by the United States Environmental Protection Agency (USEPA, 2000) is a rainfall-runoff simulation model based on either a single rain event or a long-term rain series. This model can effectively simulate hydrology, hydraulics, and water quality using a series of sub-catchments that can accept rainfall as a source of runoff or as a pollutant (Hsu et al., 2000; Rossman, 2010; Cunha et al., 2016). Currently, SWMM is widely used in simulation, analysis, and design in areas such as urban storm runoff, drainage piping systems, catchment planning and, specially, runoff mitigation with LIDs (Peterson and Wicks, 2006; Elliott and Trowsdale, 2007; Lee et al., 2013). However, compared to other hydrological models, the insufficiently large scale of application for SWMM remains a challenge. To address this issue, a number of researchers have used GIS or the catchment discretization method to apply SWMM to large urban catchments (Barco et al., 2008; Rosa et al., 2015; Dietrich, 2015).

Total impervious area (TIA) has often been used to represent the land surface modified by urbanization (Shuster et al., 2005; Mejía and Moglen, 2010.); however, recent studies have suggested that TIA is not sufficient to explain the impact of urbanization on the local hydrology, for it does not reflect the impervious land connectivity pattern (Roy and Shuster, 2009; Beck et al., 2016). Alternatively, the metric of directly connected impervious area (DCIA), or the effective impervious area (EIA), has been proposed, representing the subset of impervious surfaces that route stormwater runoff directly to streams via stormwater pipes (Roy and Shuster, 2009; Jarden et al., 2016). DCIA not only provides an indicator of the watershed ecological condition (Urrutiaguer et al., 2012), but also has been found to strongly affect the surface runoff changes (Yao et al., 2016; Ebrahimian et al., 2016; Sohn et al., 2017) and hydrological responses at the catchment outlet (Mejía and Moglen, 2010). DCIA can be calculated based on the empirical relationships with TIA (Jacobson, 2011; Shuster and Rhea, 2013; Ebrahimian et al., 2016). However, such efforts usually lack an explicit consideration of the spatial pattern of land use and specific methods of stormwater flow management (Lee and Heaney, 2003; Sohn et al., 2017). The use of LID controls, and especially the spatial pattern of their implementation, can play a significant role in reducing DCIA. However, until now, little research has been conducted to optimize the spatial pattern of LID controls in order to reduce the DCIA (Roy and Shuster, 2009; Jacobson, 2011; Ebrahimian et al., 2016).

In the present research, a framework was developed to simulate stormwater runoff at the city scale under different development scenarios, using the GIS-based SWMM5.0 model to bring together urban planning data, geospatial and hydrological information. Focusing on a case study area in a new developing region west of Bazhong, Sichuan Province, China, the stormwater runoff characteristics of the four urban land use conversion scenarios were simulated under the same heavy rainfall condition. The aim of this study was to investigate: (1) how the hydrological responses to changes in land use in the near future vary among different scenarios with rapid urbanization; (2) how a growing city can integrate the LID-based design into urban planning to decrease the DCIA and more effectively manage stormwater; and (3) what potential hydrological effects result from LID implementation, and whether such effects can be evaluated by the GIS-based SWMM at a large urban region scale. The study presents new LID-based urban stormwater management models in a rapidly urbanizing region, and the results will provide an important decision-making basis for the future urban and land-use planning of the study area.

2. Study area

Bazhong is a city located in the Qinba mountains, northeastern Sichuan Province, China (106°20′–107°49′E, 31°15′–32°45′N) (Fig. 1). The city has a subtropical monsoon climate with four distinct seasons. The average annual rainfall is 1108.3 mm, approximately 80% of which falls from June to October. Excessive rainfall and rainstorms result in frequent flooding (Zhang et al., 2010). Bazhong is approximately 90% mountainous (Fig. 1b). Geological disasters, such as landslides and ground collapses, are common after the rainstorms.

Our study area is located west of downtown Bazhong with a total area of about 838 ha (Fig. 1b). At the time of this research, this area was still a predominantly rural landscape covered by farmland (49.2%) and forest (42.0%) with the remaining 3% of land occupied by housing, roads, and water bodies. The TIA is about 5.8% of the total study area. During the rainy season, management of stormwater is mainly achieved by relying on the river networks in the study area (Fig. 1b, c and d).

However, the 2013–2030 urban development plan for this study area indicates that the land use pattern will change significantly, and the region will likely become more intensively developed by 2030. Specifically, the impervious land is expected to increase