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How does imperviousness impact the urban rainfall-runoff process under various storm cases?

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ABSTRACT

Dramatic changes in imperviousness exert significant influence on the rainfall-runoff process in urban catchments. In urban rainwater management, imperviousness is generally adopted as an effective indicator for assessing potential runoff risk. However, the effects of imperviousness on rainfall-runoff at the scale of small urbanized drainage areas have not been fully determined, particularly when various storm characteristics are considered. In this paper, a model-based analysis is conducted in a typical urban residential catchment in Beijing, China, in which 69 subareas are delineated within the catchment as the basic drainage units. Two metrics, total impervious area (TIA) and directly connected impervious area (DCIA), are employed to quantify the spatial characteristics of imperviousness of the subareas. Three runoff variables within the delineated subareas including total runoff depth (Q_t), peak runoff depth (Q_p), and lag time (T_{lag}) are simulated by using the Storm Water Management Model (SWMM) to represent the specific rainfall-runoff characteristics. Moreover, model input storms are designated to several typical flood-induced rainfall events with varying amounts, locations of rainfall peak, and durations for holistic assessment of imperviousness. Regression analyses are conducted to explore the contributions and relative significances of impervious metrics in predicting runoff variables under various storm cases. The results indicate that the performances of imperviousness with fine spatial scale (<1 ha) and heavy rainfall conditions (>34 mm) may vary markedly according to storm conditions. Specifically, TIA rather than DCIA acts as a dominate factor affecting total runoff, and its significance maintains relatively stable with various storm conditions. In addition, the combined use of both TIA and DCIA are more effective for predicting peak runoff than that using a single impervious metric; however, rainfall amount, peak location, and duration alter the contribution gaps between TIA and DCIA and the overall performance of the regression model. Moreover, DCIA is more likely to affect runoff lag time without the contribution of TIA; however, an increase in rainfall peak ratio or duration will significantly limit its performance. These results can provide insight into the hydrologic performance of imperviousness, which is essential for landscape design and runoff regulation in small urban catchments.

1. Introduction

Impervious surfaces are defined as material with natural or anthropogenic sources that prevent the infiltration of surface water into underlying soils (Slonecker et al., 2001). The growth of impervious surfaces in urban areas is directly related to human activities and habitation through the construction of roofs, parking lots, roads, and other structures. Dramatic urbanization leads to the disturbance of natural landscapes and replacement of vegetation-covered surfaces with impervious surfaces. Specifically, increases in the number of impervious surfaces result in enhanced hydraulic efficiency and can cause substantially decreased capacity for rainwater infiltration in addition to a concomitant increase in runoff generation in urban catchments (Mejía and Moglen, 2010). Excess runoff can induce urban flooding and can result in traffic interruptions, economic losses, pollution, and health issues, which pose substantial threats to local residents and urban development. Thus, there is a growing interest in exploring the hydrologic performance of imperviousness for urban rainwater management.

As a simple, easily measured index, imperviousness has been recognized and widely adopted as a key predictor of urban impacts

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on rainfall-runoff processes (Arnold and Gibbons, 1996). Previous studies have documented that both the velocity and volume of surface runoff increase when impervious coverage is increased (Dunne and Leopold, 1978; Jacobson, 2011; Shuster et al., 2005). The most generally used imperviousness type in these studies is total impervious area (TIA), expressed as the whole fraction of impervious area in a catchment. Schueler (1994) reported that runoff volume can increase by orders of TIA. This quantity can also effectively reflect the magnitude of urbanization. However, TIA does not account for the relative proximity of impervious surfaces to the drainage system, which may lead to unexpected matching relationships between TIA and runoff parameters (Shuster et al., 2005). For example, rooftops often drain runoff onto lawns or other pervious areas and thus have less contribution than roadways, which typically drain runoff to the drainage system directly. Directly connected impervious area (DCIA), on the contrary, describes the part of TIA that is hydraulically connected to a drainage system, such as streets with gutters that are drained to an outfall. Lee and Heaney (2003) modeled the hydrologic performance of DCIA and reported that this type has the most pronounced effect on urban hydrology. Yang et al. (2011) and Burns et al. (2015) reported that DCIA is responsible for the majority of hydrologic alteration due to urbanization.

Although TIA and DCIA have both proved to be effective for predicting urban runoff, most previous research focuses on the fluvial runoff feedback in urbanized watersheds combined with mixed land cover (e.g., developed, rural, and natural surfaces) at various spatial scales of several hectares (Arnell, 1982; Boyd et al., 1993, 1994; Sillanpää and Koivusalo, 2014) to hundreds of square kilometers (Mejía and Moglen, 2009; Sheeder et al., 2002; Yang et al., 2011). In the urban built-up regions, previous studies tend to focus on relatively small and integrated drainage basins (e.g., residential sites) that usually cover less than 1 km^2 and incur severe pluvial risks (Dietz and Clausen, 2008; Lee and Heaney, 2003). Such studies also reveal significant relationships between imperviousness and rainfall-runoff. These findings are based mainly on the entire catchment scale, where the runoff responses can be significantly altered by the various drainage network structures such as the drainage density and width function (Meierdiercks et al., 2010). However, insufficient attention has been paid to the sub-basins within these urbanized catchments, which account for small areas that function as elementary drainage units in which the rainfall-runoff processes are not affected by the drainage system (Gilroy and McCuen, 2009; Krebs et al., 2014; Versini et al., 2015). With the same drainage condition, different impervious distribution within the catchment may alter the final runoff hydrograph at the catchment outlet, particularly for peak discharge (Meierdiercks et al., 2010). Similar findings were obtained by Hood et al. (2007) and Guan et al. (2015b), who reported that the modifications in imperviousness with different development strategies at small catchments result in significant flow changes. Therefore, establishing a quantitative relationship between imperviousness and rainfall-runoff in finer scales such as a neighborhood, parcel, or even smaller area may contribute to urban flood management assigned with more scientific guidance for landscape/imperviousness designs in urban regions. In large urban watersheds, however, the sizes and complexities of landscape patches are always greater than that in small catchments, resulting in different runoff discharges and travel times (Walsh et al., 2009; Yang et al., 2011). Thus, imperviousness may present different hydrologic contributions at different spatial scales. Consequently, established causality relationships between imperviousness and rainfall-runoff in large watersheds cannot be directly applied in these fine-scaled areas. Event-based analysis is also important in realistic short-term prediction when applying flood regulations in urbanized catchments. The contributing surface area for runoff generation has been reported as variable and dependent on the given rainfall event (Ramier et al., 2011). Qin et al. (2013) demonstrated that rainfall characteristics such as rainfall amount, duration, and peak location have significant effects on urban runoff in small urbanized catchment. Guan et al. (2015a) reported that rainfall patterns have a certain influence on runoff generation in a developing residential catchment of 12.5 ha, where higher rainfall peak intensity led to increased urban runoff. However, the hydrologic performances of TIA and DCIA under a variety of rainfall amounts, rainfall durations, and locations of peak rainfall intensity in fine-scaled urbanized catchments remain unclear. It is necessary to determine the hydrologic performances of imperviousness under various rainfall conditions in order to expand the current knowledge on urbanization and its runoff responses and target urban design with stratified flood protection.

The objective of this study is to provide effective indicators for runoff management of small urbanized catchments in cities. A highly urbanized residential site is selected as a case study, and several fine-scaled subareas are delineated as basic sub-basins for rainwater drainage. This study focuses on revealing whether and how TIA and DICA function on predicting the rainfall-runoff process in these subareas. Three pivotal parameters including runoff depth, peak discharge, and lag time are simulated by using a hydrological model to describe the integrated runoff hydrograph, and the quantitative relationships among TIA/DCIA and all these runoff variables are established by using regression analysis. Moreover, this study investigates the manner in which runoff contributions from imperviousness change according to the type of flood-induced storm case, considering the differences in storm depth, shape, and duration.

2. Materials and methods

2.1. Study site and monitored data

The study catchment, Wangchunyuan (WCY), is located in the northern part of Beijing in a built-up region (Fig. 1). WCY belongs to a temperate monsoon climate with an average temperature of 12 °C and mean precipitation of 543 mm/year (Beijing Statistical Bureau, 2012). The annual rainfall distribution is quite uneven, and >80% of the annual rainfall is concentrated in summer in June, July, and August.

WCY covers nearly 11 ha of drainage area and is one of the largest residential zones in Beijing dominated by high-rise buildings. The soil type in WCY is mainly silt loam. Land cover, identified by visual interpretation from 0.6-m satellite image, consists of asphalt roads, concrete pavers, concrete roofs, brick alleyways, lawns, trees, and landscape ponds (Fig. 1). Asphalt roads, concrete pavers and roofs, and brick alleyways are classified as impervious surfaces, accounting for nearly 48% of the total area in WCY, whereas lawns and trees are pervious surfaces covering nearly 47%. Landscape ponds were not included in this study because their concave design does not contribute to rainfall-runoff. Among all of the compositions of impervious surfaces, concrete roofs cover 2.37 ha, followed by brick alleyways, asphalt roads, and concrete pavers at 1.71 ha, 0.84 ha, and 0.30 ha, respectively. For pervious surfaces, lawns and trees cover 3.65 ha and 1.86 ha, respectively.

As shown in Fig. 2, WCY is drained into four catchments through separate rainwater networks of circular pipes. Rainfall-runoff data for model calibration and validation were recorded at 5-min intervals in 2013. An automatic area-velocity flow meter sensor (ISCO 750) was installed at the outlet of the southern catchment in WCY, covering 1.69 ha (Fig. 2). The sensor on the ISCO 750 uses Doppler technology to directly measure average flow velocity in a pipe system. An integral pressure transducer was used to measure flow depth to determine the flow area. The flow rate was calculated by multiplying the area of the flow by its average velocity with ±2% reading error. Three effective runoff events were recorded on