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Effects of urbanization on direct runoff characteristics in urban functional zones

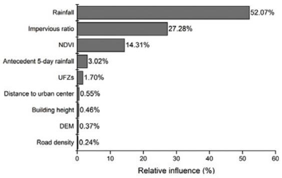
Chunlin Li [a], Miao Liu [a,*], Yuanman Hu [a], Tuo Shi [a,b], Xiuqi Qu [a,b], M. Todd Walter [c]

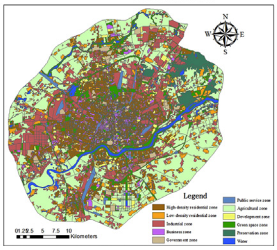
[a] CAS Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Department of Biological and Environmental Engineering, Cornell University, 62 Riley-Robb Hall, Ithaca, NY 14853, USA

HIGHLIGHTS

- An improved method to evaluate direct runoff in urban areas is proposed.
- Urbanization affected the direct runoff increments and flooding hazard distribution.
- The direct runoff has significant positive spatial autocorrelation.
- Urbanization factors have less impact than environmental and meteorological factors.

GRAPHICAL ABSTRACT





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ABSTRACT

As urbanization processes, the increasing direct runoff caused by land use change has become a major challenge for urban hydrological system. In this study, the impact of urbanization on direct runoff in the Shenyang urban area was investigated using a modified Soil Conservation Service Curve Number model combined with remote sensing. Urban functional zone (UFZ) was used as the basic unit for hydrological analysis. The hydrological changes in runoff were analyzed by calculating the runoff difference between the current condition and the pre-urbanization condition. Moran's I was used to estimate the spatial autocorrelation of the entire area. Then we assessed the relative influence and marginal effects of factors affecting direct runoff using boosted regression trees (BRT). Our results showed that direct runoff was significantly related to urbanization. Under current conditions, direct runoff increment depth affected by urbanization in the study area was 68.02 mm. For different UFZs, high-density residential, business and industrial zones tended to have large runoff volumes and high runoff coefficients. Through flooding hazard analysis, we found about 6.53% of the study area fell into a significant hazard category. The industrial zone had largest area of significant hazard land (40.97 km^2) and the business zone had the largest significant hazard percentage (21.19%). Moran's I results illustrated that the high-high clusters in Shenyang were mainly concentrated in the urban center. BRT analysis indicated that runoff had the strongest correlation with rainfall (52.07%), followed by impervious ratio (27.28%), normalized difference vegetation index (14.31%), antecedent 5-day rainfall (3.02%), and UFZs (1.70%). The industrial zone, business zone and high-density residential zone tend to have greater influence on runoff. Our study could present method for recognizing

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* Corresponding author.
E-mail address: lium@iae.ac.cn (M. Liu).

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hotspots of direct runoff in large city, and may provide potential implications for green infrastructure selection and urban planning.

1. Introduction

Urbanization is a worldwide phenomenon, with population density continuing to grow and urban area to expand. By 2030, urban land cover will increase by 1.2 million km^2, nearly tripling the global urban land area circa 2000 (Seto et al., 2012). The increase of urbanization associated with population growth is one of the major changes affecting land use in big cities (Jacqueminet et al., 2013). Urban sprawl inevitably leads to non-urban land being converted to built-up areas, resulting in a significant increase in the proportion of impervious surfaces from roads, rooftops, parking lots and other urban surfaces (Braud et al., 2013b; Mejia and Moglen, 2010b). The process of urbanization can alter urban hydrological responses and negatively impact surface and downstream waters owing to the introduction of impervious surfaces (Zampella et al., 2007), removal of deep rooted vegetation and alterations (Hibbs and Sharp, 2012) to the natural drainage network (Zhou et al., 2013). These can result in losses of infiltration, increased surface runoff (Angrill et al., 2017; Fletcher et al., 2013; Weng, 2001), and the potential to produce huge floods (Huang et al., 2008; Olang and Furst, 2011; Quan et al., 2010; Richert et al., 2011; Yao et al., 2017). Several studies have demonstrated that the flooding hazard in an urban area can be partly attributed to the rapid replacement of natural ecosystems by impervious urban surfaces (Hu, 2016; Kvočka et al., 2016; Shepherd, 2006; Zhang et al., 2015).

Research and practice in the last decades has shown that the impacts of urbanization on the hydrological cycle are strongly related to impervious surfaces (Mejia and Moglen, 2010a). However, the rainfall–runoff relationship is highly nonlinear and complex, and is dependent on numerous factors such as antecedent soil moisture, evaporation, infiltration and rainfall duration (Guan et al., 2016; Isik et al., 2013; Sajjad et al., 2015; Zhang et al., 2012). Many studies have investigated the hydrological impact of urbanization based on field data (Choi et al., 2016; Zhang et al., 2013). Gallo et al. (2013) assessed the effect of urban land cover on hydrological responses using summer runoff data from five catchments dominated by distinct urban land uses and found it was tightly coupled to the magnitude of rainfall (Gallo et al., 2013). Braud et al. (2013a) and Braud et al. (2013b) explored several indicators to demonstrate the impact of urbanization on discharge series, and the results showed a decrease of specific discharge from upstream to downstream corresponding to an increase in artificial areas, except during high flows (Braud et al., 2013a). Putro et al. (2016) used historical data to identify the impact of climate and urbanization on selected water quantity and quality indicators, and results indicated an upward trend in runoff totals in urban catchments but not in rural catchments (Putro et al., 2016). Many studies assessing the hydrological impacts and storm water management activities of urbanization have applied hydrological models (Choi et al., 2003; Li et al., 2016; Qin et al., 2016), such as full distributed process-based models (e.g. MIKE SHE, RHESSys, TOPLATS, and WASIM), physically-based semi-distributed models (e.g. SWAT, SWMM, and HYLUC), and conceptual lumped models (e.g. IHACRES and NAM). The Soil Conservation Service Curve Number (SCS-CN) model, developed by the U.S. Department of Agriculture in 1954, is one of the most widely used empirical hydrological models for computing the volume of direct surface runoff (Jiao et al., 2015). It is also an effective tool for assessing direct runoff in large urban areas which lack observed data (Ansari et al., 2016; Bartlett et al., 2016; Sahu et al., 2012; Singh et al., 2013; Tsihrintzis and Hamid, 1997).

Owing to clustered and unplanned development of urban areas, urban resources (population, impervious surface, building density, green area, and so on) are disproportionately distributed within urban areas (Yao et al., 2015). To analyze the quality and distribution patterns of direct runoff caused by urbanization, we used urban functional zones (UFZs) as the spatial scale (Sanders, 1986). UFZs are the spatial patterns of a city related to its urban functions (Tian et al., 2010). Each type of UFZ comprises many zones with both similar structural characteristics and similar socioeconomic functions. Each zone is organized by a cluster of land uses, and its function is determined by the dominant land use. Similar urban spatial structures, human activity types and urban functions of same UFZ result in similar hydrological characteristics, which makes the UFZ a suitable scale for evaluating the hydrological impact of urbanization.

In this study, a modified SCS-CN model combined with remote sensing was used to estimate the effect of urbanization on direct runoff variation in the Shenyang urban area. There were two major goals for this paper: (1) to evaluate the hazard and spatial autocorrelation of direct runoff, and (2) to identify the main factors affecting runoff and analyze the changes of marginal effects.

2. Materials and methods

2.1. Study area and data

Shenyang is the largest and most important industrial city in Northeast China (41°11′51″–43°02′13″N, 122°25′09″–123°48′24″E). Mean annual precipitation is 510–680 mm, most of which falls from June to August. The urban sprawl of Shenyang has gradually expanded from the central to suburban areas, and a four-ring road network was created during the last 30 years. The entire urban area of Shenyang (called the four-ring area) can be divided into four areas (zones 1–4) according to the four-ring roads (Fig. 1). The stages of urbanization are represented from the first to the fourth ring areas. Our study covered the whole four-ring area. The area of water was excluded because it did not provide direct runoff. The four-ring area is the fastest growing urbanization section with most of the population and built-up areas.

UFZs are the largest elements of landscape planning related directly to functions such as dwellings, education, industry and commerce (Sun et al., 2013). QuickBird satellite images from 2015 were used to manually interpret the UFZs of the Shenyang four-ring area. First, we used the main roads to divide the entire area into blocks, and assumed each block had the same urban function, forming one UFZ. Second, we determined the main functions of these UFZs by looking up the buildings in the block on Google Maps, and eventually classified 9278 UFZs. Finally, referring to the definitions of UFZs by other researchers (Sun et al., 2013; Yao et al., 2015), we grouped the study area into 11 types of UFZs. The area and description of UFZs are shown in Table 1. Field verifications were conducted for indeterminate UFZs. Because the WTR area cannot produce direct runoff, we did not include the WTR zones in our study.

2.2. Direct runoff evaluation

In this study, direct runoff was simulated with the Mishra and Singh (MS) model which is a revised SCS-CN model using a separate expression based on antecedent 5-day rainfall to estimate antecedent moisture (Mishra et al., 2002). The MS model equations are as follows:

$$Q = \begin{cases} \dfrac{(P-I_a)(P-I_a+M)}{P-I_a+M+S}, P>I_a \\ 0, P\leq I_a \end{cases} \qquad (1)$$