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A procedure for quantifying runoff response to spatial and temporal changes of impervious surface in Qinhuai River basin of southeastern China

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ABSTRACT

Quantitative assessment of the hydrological response to urbanization has been a major concern in hydrology and water resources management. In this study, a procedure combining different statistical methods and a hydrological model to quantify annual runoff response to spatial and temporal variations of impervious surface areas was proposed and applied to the Qinhuai River basin, an urbanized basin located in southeastern China, over the period from 1986 to 2013. The landscape indicators, such as impervious area and number of impervious patches were used to measure the spatial configuration of urbanization and quantify the runoff response to urbanization. Impervious area data were derived from the Landsat images using superior ensemble learning method of rotation forest. The Mann–Kendall test, Sen's estimator, Pettitt test and double mass curve method were applied to examine gradual trend and abrupt changes for hydro-meteorological data series. A hydrological model based on stepwise regression analysis was built and used to explore the relation among annual runoff and precipitation, potential evapotranspiration and landscape indicators. The results showed that annual runoff and runoff coefficient had significant increasing trends and an abrupt change after year 2001 when the watershed impervious area reached 8.6%. The average annual runoff increased by 60%, of which, urbanization was responsible for 59% of the increase, while precipitation changes were responsible for the remaining 1% in the study region. The annual runoff response to impervious area showed a nonlinear relationship, and was more sensitive in dry years than wet years. The changes of impervious area were more remarkable in connecting the existed impervious patches than in developing the new ones beginning in the early 2000s, which increased the watershed's drainage capacity and resulted in the abrupt change of runoff response. The study demonstrated that the proposed procedure was efficient to quantify the runoff responses to urbanization using landscape metrics of impervious surface.

1. Introduction

Urbanization, one of the most widespread land conversions by anthropogenic activities (Alberti, 1999), brings a range of physical and biochemical changes to hydrological system and processes (Fletcher et al., 2013; Jacobson, 2011).

The main characteristics of urbanization are the increase in impervious area and construction of artificial drainage systems, which reduce the infiltration into soils and replace natural drainage pathways. This combination increases hydraulic efficiency and decreases the capacity of moisture storing, leading to increase in surface runoff (Booth, 1991; Hsu et al., 2000; Zhou et al., 2013), and decrease in baseflow (Klein, 1979; Smakhtin, 2001). The flood characteristics also change with decreased lag time and increased peak flow from storm events (Dunne and Leopold, 1978; Stephan and Tsay, 1988; Kang et al., 1998; Beighley et al., 2003; Wang, 2006). However, some studies found no significant hydrologic response to urbanization and even opposite results (Chang, 2003; Ku et al., 1992; Brandes et al., 2005). The diverse results require further exploring the hydrological response to urbanization.

Impervious area has become a key indicator of watershed function and health over the past several decades (Arnold and Gibbons, 1996). Some studies related impervious area with hydrological and ecological responses to urbanization (Brun and Band, 2000; Alberti et al., 2007; Hamdi et al., 2011; Sun et al., 2014). Impervious area can be classified into total impervious area (IA) and effective impervious area (EIA).

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Shuster et al. (2005) defined EIA as the area that is hydraulically connected to a drainage system. Previous studies revealed that EAI has the most significant effects on watershed hydrology (Booth and Jackson, 1997; Lee and Heaney, 2003; Aichele and Andresen, 2013). EIA, at least conceptually, captures the hydrologic significance of imperviousness (Booth and Jackson, 1997). Unfortunately, connectedness of impervious area is difficult to quantify, making EIA mapping difficult. In order to interpret the hydrologic response to EIA, other EIA related indexes are substituted as surrogates such as number of road crossings (Alberti et al., 2007) and landscape metrics of impervious patches, etc. (Olivera and DeFee, 2007; Salavati et al., 2015).

One major concern that has been explored is whether there exists a threshold of impervious area above which the hydrological response of the basin is changed (Praskievicz and Chang, 2009). Hamdi et al. (2011) detected a change in the frequency of flood events and annual surface runoff as well as high flow for the Brussels Capital Region when IA exceeds 35%. Brun and Band (2000) found a threshold of IA (20%), above which the runoff ratio changed more significantly for upper Gwynns Falls watershed, Baltimore. Nirupama and Simonovic (2007) demonstrated that approximately 15% IA may be a threshold above which basin exhibits the typical urban hydrology of flashiness in London, Ontario. Olivera and DeFee (2007) found annual runoff depths and peak flows have increased by 159% and 146% respectively when the watershed reached a 10% IA in the Whiteoak Bayou watershed in Texas. Other studies found 3 to 8% IA as the threshold (Yeo and Guldmann, 2006; Booth and Jackson, 1997; Yang et al., 2010). However, Chang (2003) showed no significant increase (less than 2%) in annual runoff in a low-density suburban watershed in southeastern Pennsylvania. Chang (2007) also found no significant changes in peak runoff ratio and annual runoff ratio for an urban watershed and a mixed land-use watershed in the Portland Metropolitan Area of Oregon for the period from 1951 to 2000. These studies suggested that the threshold of impervious area varied significantly and are dependent on the time scale, the indices, watershed characteristics and climate conditions (Chang, 2007; Beighley and Moglen, 2002; Jones, 1997).

There are mainly two approaches adopted in the study of hydrological response to urbanization. One approach is to apply a hydrological model and examine changes of runoff characteristics with different urbanization scenarios (e.g., Bhaduri et al., 2001; Tu, 2009; Zhou et al., 2013; Zhu and Li, 2014; Yan et al., 2016; Yang et al., 2016). This approach enables one to distinguish hydrological effects of urbanization by controlling other variables, but it is subject to modeling accuracy and uncertainty (Choi et al., 2016). Another approach is to use statistical methods to examine long-term trends of runoff characteristics between different periods in a catchment or catchments with different degrees of urbanization (e.g., Huo et al., 2008; Rougé and Cai, 2014; Choi et al., 2016). The nonparametric Mann–Kendall test for gradual trend analysis (Mann, 1945; Kendall, 1975) and Pettitt test for abrupt change detection (Pettitt, 1979) are frequently adopted. This approach is more effective in determining whether hydro-climatic variables changed significantly over time, than in attributing the changes to particular causes (Choi et al., 2016). The approach also requires long time series of hydro-climatic data. In this study, to take advantages of both approaches, a procedure is proposed to explore the annual runoff response to impervious surface area changes in the Qinhuai River basin, an urbanized basin located in southeast China with monsoon climate (humid subtropical climate). In addition, most studies used impervious area as a metric of urbanization to explore the relation between hydrological response and urbanization (Bhaduri et al., 2001; DeWalle et al., 2000; Zhu and Li, 2014; Sun et al., 2014). In this study, in addition to impervious area, the number of impervious patches was also used to capture the hydrological conveyances of urbanization and interpret the hydrological response.

The specific objectives of the study are: (a) to test the possibility of characterizing the spatiotemporal changes of impervious surface by using landscape metrics; (b) to determine whether there exists a threshold of IA below which the annual runoff response of the basin is unchanged; (c) to explain runoff changes based on landscape metrics of impervious areas if a threshold exists; and (d) to explore the relationship between annual runoff changes and percent impervious area under various hydrological conditions. The objectives were achieved by a procedure consisting of the following steps: change detection methods (Mann–Kendall test, Sen's estimator, Pettitt test, double mass curve method) were used to examine the temporal changes in the long-term hydro-climatic data series; an annual rainfall-runoff model was built by using stepwise regression method to simulate runoff process and separate contributions of urbanization and climate variability to runoff response; and the relation between runoff response and urbanization degree (landscape metrics) under varied climate conditions was investigated using the annual rainfall-runoff model.

2. Materials and methods

2.1. Study area and data

Qinhuai River, located in the southwest of Jiangsu province, is one of the tributaries of lower Yangtze River. The basin area is 2631 km^2, ranging from 118°39′ to 119°19′ E, and 31°34′ to 32°10′ N. As a typical watershed in the Yangtze delta plain, the Qinhuai River basin abounds with paddy rice and freshwater fish and supports advanced industrial economies. With marked advancement of urbanization since the beginning of the 21st century, significant land use changes have occurred in the Qinhuai River basin. It is hypothesized that the hydrologic cycle, even the whole ecological system has changed accordingly. Therefore, it is of profound significance to quantify the impervious area changes and hydrological responses of land use pattern.

The annual mean air temperature is 15.4 °C, average annual precipitation is 1116 mm (1986–2013), and the rainy season is from April to October. The measured annual runoff, which mainly occurs during June to August, is about 430 mm. (Hao et al., 2015).

There are 5 types of land use in Qinhuai River basin: paddy land, dry farmland, woodland, impervious surface and water. Paddy land and dry farmland are the dominant land use types.

The basin location, elevation, network, and the distribution of the two hydrological stations and seven rain- gauge stations are shown in Fig. 1.

The 28-year (1986–2013) daily rainfall data for the seven rain-gauge stations and the daily discharge data of the Inner Qinhuai and Wudingmen stations were obtained from the local hydrological bureau. Both of the two runoff gauging stations are located at the outlets of the research river. Potential evapotranspiration (PET) estimates were obtained from Hao et al. (2015) for the period of 1986–2013. Seven cloud-free Landsat images were chosen as the major sources for extracting time series of impervious areas, which were used to estimate the urbanization level and quantify the changes of land use pattern in the study area (Table 1).

2.2. The extraction of impervious surface

The preprocessing procedure of remote sensing images included atmospheric correction and band synthesis. After preprocessing, Rotation Forest, a new classifier ensemble system proposed by Rodriguez et al. (2006) was used to extract the impervious surface. It is based on a decision tree and combines the accuracy of individual classifiers and the diversity between different classifiers. The bootstrap samples of the original training set are used to construct a new training set. Then the feature set is split to K random subsets and Principal Component Analysis (PCA) is performed on them. As a result, by combining all the principle components, the feature subset is rebuilt. For the reason that a completely different decision tree can be built through a small rotation of axes, the diversity between the base