Characteristics of impervious surface and its effect on direct runoff: a case study in a rapidly urbanized area
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ABSTRACT
In recent years, many cities have experienced serious urban flood and non-point pollution issues due to hydrological process changes in rapidly urbanizing areas. Understanding the relationship between impervious surface and direct runoff is important for urban planning to protect the urban hydrological system. In this study, we used a mixed spectral decomposition method to interpret the long-term series of impervious surface of Shenyang, China. Direct runoff was evaluated by an improved SCS-CN (Soil Conservation Service curve number) model, and the relative influences of five underlying surface factors on the direct runoff of each period were analyzed by boosted regression trees. The overall impervious area was significantly increased in both the study area and built-up area from 1984 to 2015. The impervious ratio showed a decreasing trend in the built-up area and increasing trend in the whole study area. The runoff coefficient of the built-up area showed a significantly decreasing trend. The runoff ratio of the built-up area to the whole study area was increased dramatically, reaching 0.26 by 2015. NDVI (normalized distribution vegetation index), vegetation, and impervious surface were the most important urban surface conditions in the study area for direct runoff generation. The relative influence of impervious surface showed a rapidly increasing trend and then gradually decreased from 2000.

Key words | boosted regression trees, direct runoff, hydrological response, impervious surface, urbanization

INTRODUCTION
The world is currently undergoing an unprecedented process of urbanization which has contributed to replacing existing natural green spaces with impervious surfaces (Zhang et al. 2012; Liu et al. 2014). Impervious surfaces, such as roofs, parking lots and paved roads, are unavoidable in built-up areas, which swallow up farmland, green space, and forest areas. Impervious surface increase caused by rapid urbanization could bring a range of environmental challenges for both the local, regional and wider environment as a direct result of the biochemical and physical changes to hydrological systems (Huang et al. 2008; Miller et al. 2014). Specifically, the rapid acceleration of impervious surfaces could result in loss of rainwater interception, storage, and infiltration and further lead to a concomitant increase in runoff generation in urban catchments (Mejía & Moglen 2010; Liu et al. 2013). Therefore, impervious surface has been recognized and widely adopted as a key indicator in urban environmental assessment (Ansari et al. 2016; Qiao et al. 2018).

Many previous studies focused on the impact of meteorological conditions on runoff, such as antecedent dry weather periods, rainfall duration, rainfall intensity, rainfall pattern, and magnitude. Rainfall events exhibit large fluctuations in local intensity and magnitude. Dunkerley (2012) found that uniform events of unvarying intensity yielded the lowest total runoff, the lowest peak runoff rate and
the lowest runoff ratio (Dunkerley 2012). Guan et al. (2016) reported that with the same magnitude, prolonged rainfall events with unvarying low intensity yield the smallest peak flow and the smallest total runoff, yet rainfall events with high peak intensity produce the largest runoff volume (Guan et al. 2016). The most significant effects of urbanization are the changes of underlying surface, especially the increase in impervious surface which could result in substantially increasing the production of runoff (Shuster et al. 2005). Therefore, there is a growing interest in exploring the relationship between long-term characteristics of impervious surface area and its impact on direct runoff.

The main objective of this article is to investigate the impact of impervious surface on hydrologic response. The spatial and temporal characteristics of impervious surface were investigated by comparing the changes of impervious surface area and path of the built-up area centroids. The hydrologic response of urbanization was illustrated by analyzing the changes in runoff during rapid urbanization from 1984 to 2015. We used the boost regression trees (BRT) method to analyze the relative influences of five underlying surface factors on direct runoff for each period in the whole study area.

**MATERIALS AND METHODS**

**Study area and data**

The study area focuses on Shenyang, the big city in northeast China. Landsat 5 TM images for the years 1984, 1989, 1995, 2000, 2006 and 2010, and a Landsat 8 OLI image for the year 2015 were chosen as the major sources for extracting time series of land-use types and built-up area. All images have small amounts of cloud cover, and were obtained from July to September in order to better distinguish the vegetation by remote sensing interpretation. The built-up area and non-built area from 1984 to 2015 were manually interpreted according to the distribution of constructed buildings using Landsat images. Daily rainfall data from May to October 2015 were used to simulate direct runoff in 1984, 1989, 1995, 2000, 2006, 2010, and 2015.

**Impervious surface interpretation**

Impervious area was interpreted by the linear spectral mixture analysis (LSMA) method, which has been widely used in surface estimation (Adams et al. 1995; Roberts et al. 1998). It assumes that the reflectance of a single pixel in each spectral band is a linear combination of the characteristic reflectance of each endmember and their respective abundances (Smith et al. 1990; Yang & He 2017). According to the vegetation-impervious surface-soil (V-I-S) theory presented by Ridd (1995), each pixel of urban land cover could be decomposed into vegetation, impervious surfaces, and soil.

**Direct runoff evaluation**

Direct runoff was simulated by the Mishra and Singh (MS) model, which is a revised SCS-CN (Soil Conservation Service curve number) model considering the antecedent moisture condition (Mishra & Singh 2002). The MS model advantageously uses a separate expression based on antecedent 5-day rainfall to estimate antecedent moisture. This obviates sudden jumps in CN variation and, in turn, variation in retention capacity (Mishra & Singh 2002). And in this study, the CN values were calculated by an improved composite CN method (Fan et al. 2013; Li et al. 2018). According to the improved composite CN method, the CN value of each pixel was computed as the area-weighted average of CN values of impervious surface, vegetation, and soil. The composite CN calculation is via

\[
CN_{C} = S_{I} \times CN_{I} + S_{V} \times CN_{V} + S_{S} \times CN_{S}
\]  

(1)

where \(CN_{C}\) is the composite CN value; \(S_{I}\), \(S_{V}\), and \(S_{S}\) are fractions of impervious surface, vegetation and soil extracted by the LSMA, respectively; and \(CN_{I}\), \(CN_{V}\), and \(CN_{S}\) are the initial CN values of impervious surface, vegetation and soil, respectively.

The proportions of impervious surface, vegetation, and soil were interpreted by the LSMA method. \(CN_{I}\) under the dry antecedent moisture condition (AMC-I) was assigned a value of 98 according to the lookup table of Technical Release 55 (TR-55). The vegetation was classified by the NDVI (normalized distribution vegetation index), which
is calculated from a normalized transform of the near-infrared and red reflectance ratio (Sellers 1985), and soil was classified by the proportion of sand and clay. Thus, $CN_V$ and $CN_S$ were assigned values based on TR-55. The details of classification and CN values under AMC-I of the three components were described in our previous paper (Li et al. 2018).

**Boosted regression trees**

BRT was performed to analyze the relative influences of different factors affecting direct runoff from 1984 to 2015. BRT is an easy-to-use algorithm and freely available in the R environment (https://r-project.org/), and can be used to fit complex nonlinear relationships and automatically handle interaction effects between predictor variables (Elith et al. 2008; Segurado et al. 2018; Szymura et al. 2018). Our research focused on the effect of urban surface conditions on direct runoff generation. So the meteorological factors (precipitation, rainfall duration, rainfall patterns, antecedent dry period, and so on) were not taken into consideration in this study. The direct runoff depth of each pixel was selected as the response variable. Five important variables of direct runoff production were selected as independent variables, including NDVI, impervious surface ratio, vegetation ratio, sand ratio, and clay ratio of each pixel. NDVI was calculated from Landsat images based on spectral reflectance in the red and near-infrared regions (Gamon et al. 1995). Impervious surface and vegetation ratios were calculated by LSMA. Sand and clay ratios were derived from the soil texture map of Shenyang.

**RESULTS AND DISCUSSION**

**The spatial and temporal changes of impervious surface**

The impervious surface ratio of each pixel was interpreted by the LSMA method, and built-up area was manually extracted from Landsat images from 1984 to 2015. Figure 1 shows the impervious area and ratio changes of both built-up and whole study areas from 1984 to 2015. It can be seen from the histogram that the impervious surfaces constantly increased from 1984 to 2015, from 150.44 km² to 501.10 km² in built-up areas, and from 212.54 km² to 917.09 km² in the study areas, respectively. Impervious area increased slowly from 1984 to 2000, while it increased rapidly from 2000 to 2015. In addition, the impervious surface of the study area increased faster than that of the whole study area. The impervious ratio of the built-up area shows a decreasing trend, while the impervious ratio of the study area continues to increase from 1984 to 2015. The trends of impervious ratio were also slow from 1984 to 2000, and became faster from 2000 to 2015. These changes are mainly due to the Tiexi District transformation plan since 2002 and the urban renewal projects implemented from 2010 (Li et al. 2018). The policies formulated by the Shenyang government prompted a large number of industrial enterprises within the city to relocate from the central urban area to the periurban area, which resulted in the rapid urbanization and rapid increase in impervious surface from 2000 to 2015.

The centroid positions of the built-up area from 1984 to 2015 were calculated in ArcGIS (https://arcgis.com). It can be seen from the change path of the built-up area centroids that both the direction and distance of movement have changed a lot from 1984 to 2015 (Figure 2). From 1984 to 2000, the centroids of the built-up area had been moving westwards, indicating that the urban expansion direction had been expanding to the west of Shenyang during this period. From 2000 to 2010, the city had great expansion in both east and west directions. And from 2010 to 2015, the direction of urban expansion turned to southern Shenyang.
due to the establishment and development of the Hunnan new district.

**The effects of urbanization on runoff**

There are huge differences in runoff coefficient between the built-up area and study area (Figure 3). From 1984 to 2006, the runoff coefficient in the study area was relatively stable and concentrated around 0.11. After 2006, it decreased significantly, and decreased to 0.09 in 2015. Meanwhile, the runoff coefficient of the built-up area showed a considerably decreasing trend, from 0.32 in 1984 to 0.21 in 2015.

The runoff volume of the built-up area gradually increased, while the runoff of the study area showed a trend of increasing first and then decreasing from 1984 to 2015 (Figure 3). The total runoff volume in the study area in 2015 was $21.86 \times 10^6$ m$^3$ more than in 1984. We used runoff ratio to indicate the proportion of runoff volume of the built-up area to the total runoff of the study area. The runoff ratio has been constantly increasing. Before 2000, the runoff ratio was low, below 0.1, and growth was slow. From 2000 to 2015, the runoff ratio increased rapidly from 0.10 to 0.26. The change trend of runoff ratio is consistent with the trend of impervious area from 1984 to 2015.

The runoff coefficients were calculated for different periods, and the runoff coefficients of the area before being built-up were connected by dotted lines. Figure 4 shows the runoff coefficient changes of built-up areas from 1984 to 2015. From 1984 to 2015, the runoff coefficient is always higher in the old built-up area than in the newly built-up area. This may be because with the development of society, the newly built community tends to have more green areas and semi-permeable roads. The runoff coefficient of the 1984 built-up area showed a decreasing trend,
while other regions showed an increasing trend. When the land-use type is changed from non-urban land into built-up area, the runoff coefficient increases significantly.

**Relative influence analysis**

BRT was used to analyze the relative influence of the five factors on direct runoff of each period in the whole study area. The assessment results indicated that NDVI, vegetation, and impervious surface were the most important urban surface conditions in the study area for direct runoff generation from 1984 to 2015, while the relative influences of sand and clay were less than 1% (Figure 5). During urbanization from 1984 to 2015, the relative influences of NDVI, vegetation, and impervious surface were changed greatly. In 1984, the direct runoff was mainly affected by NDVI and vegetation, and the relative influences were 56.10% and 41.64%, respectively. However, impervious surface basically had little effect, and the relative influence was 1.78% in 1984. From 1984 to 2000, the relative influence of impervious surface increased dramatically, and the relative influence of NDVI and vegetation decreased rapidly. The relative influence of impervious surface exceeded that of NDVI and vegetation in 1995. By 2000, the relative influence of impervious surface reached its maximum of 52.42%, and the influences of NDVI and vegetation were 26.70% and 20.15% at that point. After 2000, the relative influence gradually decreased, and the difference of the relative influences of the three main factors gradually decreased. In 2015, the relative influences of impervious surface, NDVI, and vegetation were 36.99%, 33.62%, and 29.39%, respectively. With the process of urbanization, a large number of pervious surfaces have become impervious, changing the hydrologic cycle and reducing infiltration rates, making the relative influence of impervious surfaces rapidly increase (Suribabu & Bhaskar 2015; Qin et al. 2016; Angrill et al. 2017).

**CONCLUSIONS**

In this study, by using the impervious surface dataset derived from interpretation of Landsat images from 1984 to 2015 by the LSMA method, we analyzed the spatial and temporal changes of the impervious surface of Shenyang. The revised SCS-CN model and improved composite CN method were used to calculate the direct runoff. BRT was performed to analyze the relative influences of five underlying surface factors on direct runoff of each period in the whole study area. The following conclusions can be summarized:

(1) The impervious areas were significantly increased in both the study area and built-up area from 1984 to 2015. However, the impervious ratio of the built-up area was decreasing, while that of the entire study area was increasing. The centroids of built-up area have been changed significantly with the direction of urban development.
(2) The runoff coefficient of the built-up area shows a significantly decreasing trend. The runoff ratio of the built-up area to the whole study area increased dramatically, reaching 0.26 by 2015. The runoff coefficient was always higher in the old built-up area than in the newly built-up area. The runoff coefficient of the 1984 built-up area showed a decreasing trend, while other regions showed an increasing trend.

(3) NDVI, vegetation, and impervious surface were the most important urban surface conditions in the study area for direct runoff generation. From 1984 to 2015, the relative influence of impervious surface gradually increased to its maximum (52.42%) in 2000, and then gradually decreased.

The runoff data in this study was obtained from remote sensing combined with the SCS model. Due to the lack of measured data, it is impossible to verify the results. Therefore, we plan to select a few rainstorm events to monitor the urban flooding area and runoff depth in our future research. According to the results, we could find that the runoff ratio of the built-up area to whole area has increased rapidly. Meanwhile, the runoff coefficient of the old built-up area is always higher than that of the newly built-up area. This conclusion will provide the basis for location selection and adjustment of green infrastructures and guide the renewal of old urban areas of Shenyang.

ACKNOWLEDGEMENTS

Funding for this project was provided by the China National R&D Program (No. 2017YFC0505704) and National Natural Science Foundation of China (Nos 41871192, 41771200 and 31600372).

REFERENCES


