Characteristics of impervious surface and its effect on direct runoff: a case study in a rapidly urbanized area

Chunlin Li, Miao Liu, Yuanman Hu, Min Zong, Minghua Zhao and M. Todd Walter

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

Chunlin Li
Miao Liu (corresponding author)
Yuanman Hu
Min Zong
CAS Key Laboratory of Forest Ecology and Management,
Institute of Applied Ecology, Chinese Academy of Sciences,
Shenyang 110016,
China
E-mail: *lium@iae.ac.cn*

Min Zong
University of Chinese Academy of Sciences,
Beijing 100049,
China

Minghua Zhao
Shandong Normal University,
Jinan 250358,
China

M. Todd Walter
Department of Biological and Environmental Engineering,
Cornell University,
New York 14853,
USA

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

doi: 10.2166/ws.2019.064

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

$$CN_C = S_I \times CN_I + S_V \times CN_V + S_S \times CN_S \quad (1)$$

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 km^2 to

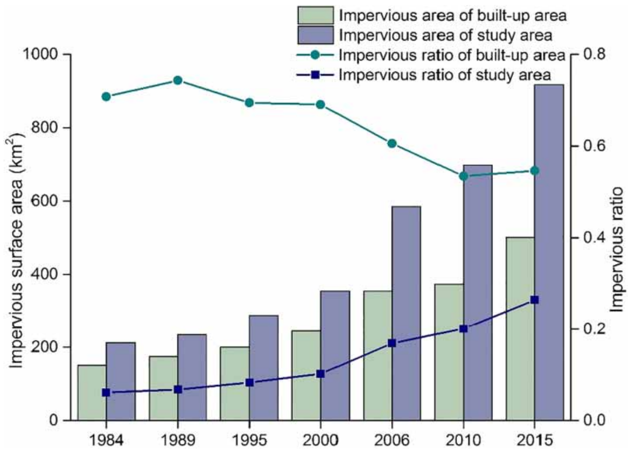

Figure 1 | Impervious surface changes of built-up and whole study areas from 1984 to 2015.

501.10 km^2 in built-up areas, and from 212.54 km^2 to 917.09 km^2 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

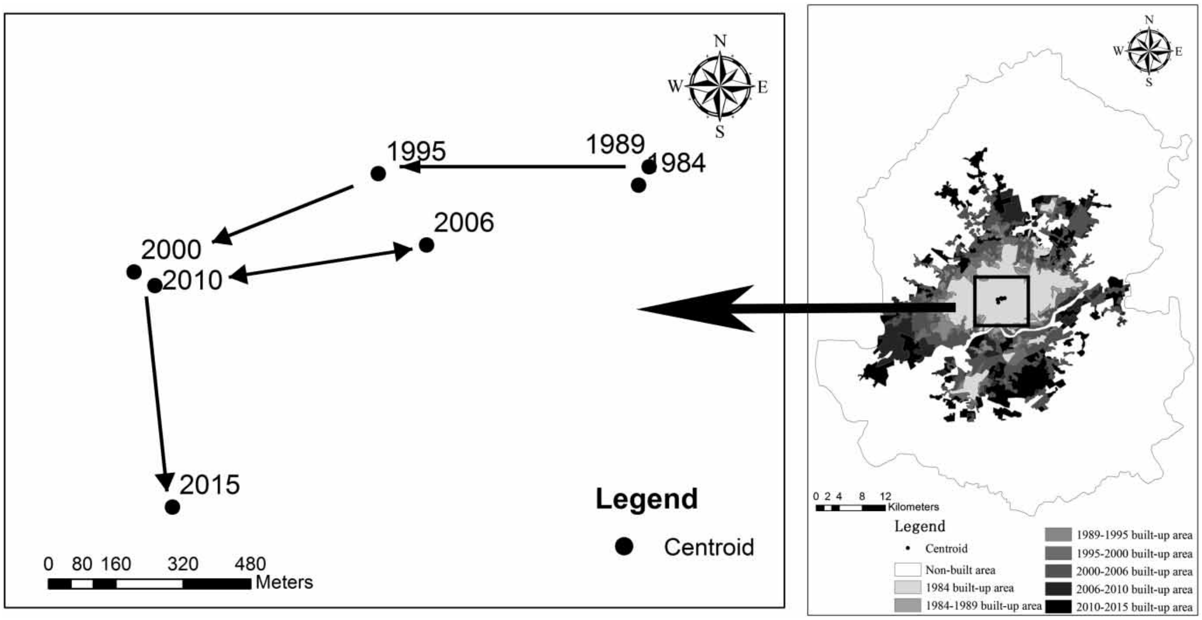

Figure 2 | Change path of the built-up area centroids from 1984 to 2015.

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.

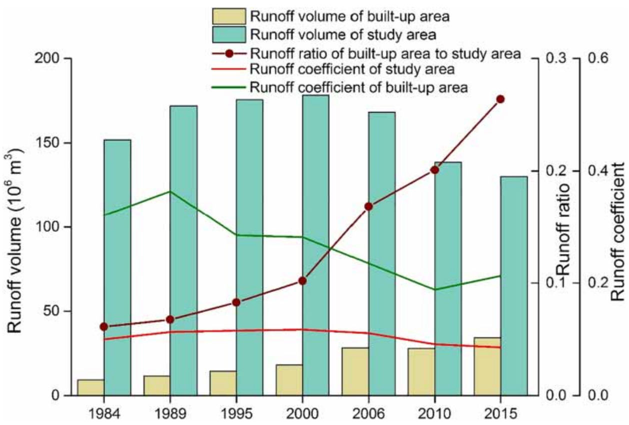

Figure 3 | Runoff volume, ratio and coefficient changes from 1984 to 2015.

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 21.86×10^6 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,

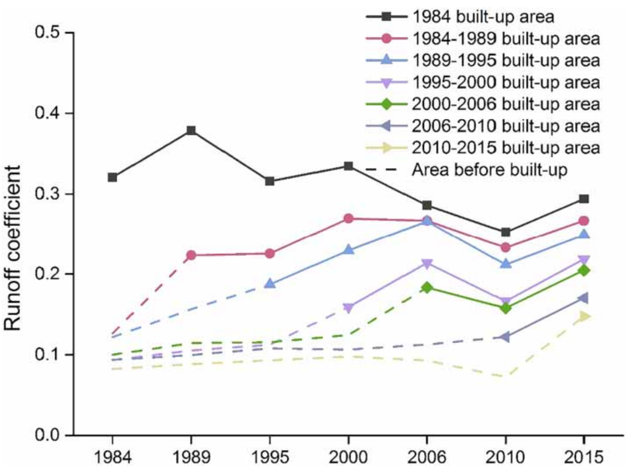

Figure 4 | Runoff coefficient changes of built-up areas from 1984 to 2015.

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,

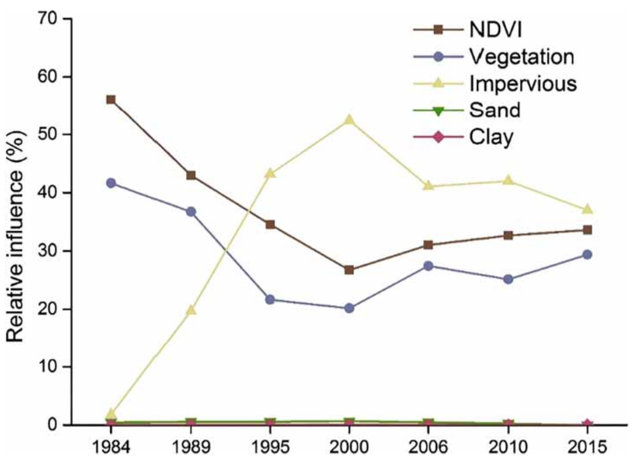

Figure 5 | Relative influence of different factors on direct runoff from 1984 to 2015 in the study area.

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

Adams, J. B., Sabol, D. E., Kapos, V., Filho, A. R., Roberts, D. A., Smith, M. O. & Gillespie, A. R. 1995 Classification of multispectral images based on fractions of endmembers: application to landcover change in the Brazilian Amazon. *Remote Sensing of Environment* **52** (2), 137–154.

Angrill, S., Petit-Boix, A., Morales-Pinzón, T., Josa, A., Rieradevall, J. & Gabarrell, X. 2017 Urban rainwater runoff quantity and quality – a potential endogenous resource in cities? *Journal of Environmental Management* **189**, 14–21.

Ansari, T. A., Katpatal, Y. B. & Vasudeo, A. D. 2016 Spatial evaluation of impacts of increase in impervious surface area on SCS-CN and runoff in Nagpur urban watersheds, India. *Arabian Journal of Geosciences* **9** (18), 702.

Dunkerley, D. 2012 Effects of rainfall intensity fluctuations on infiltration and runoff: rainfall simulation on dryland soils, Fowlers Gap, Australia. *Hydrological Processes* **26** (15), 2211–2224.

Elith, J., Leathwick, J. R. & Hastie, T. 2008 A working guide to boosted regression trees. *Journal of Animal Ecology* **77** (4), 802–813.

Fan, F., Deng, Y., Hu, X. & Weng, Q. 2013 Estimating composite curve number using an improved SCS-CN method with remotely sensed variables in Guangzhou, China. *Remote Sensing* **5** (3), 1425–1438.

Gamon, J. A., Field, C. B., Goulden, M. L., Griffin, K. L., Hartley, A. E., Joel, G., Penuelas, J. & Valentini, R. 1995 Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. *Ecological Applications* **5** (1), 28–41.

Guan, M., Sillanpää, N. & Koivusalo, H. 2016 Storm runoff response to rainfall pattern, magnitude and urbanization in a developing urban catchment. *Hydrological Processes* **30** (4), 543–557.

Huang, H. J., Cheng, S. J., Wen, J. C. & Lee, J. H. 2008 Effect of growing watershed imperviousness on hydrograph parameters and peak discharge. *Hydrological Processes* **22** (13), 2075–2085.

Li, C., Liu, M., Hu, Y., Shi, T., Zong, M. & Walter, M. T. 2018 Assessing the impact of urbanization on direct runoff using improved composite CN method in a large urban area. *International Journal of Environmental Research and Public Health* **15** (4), 775.

Liu, Z., Wang, Y., Li, Z. & Peng, J. 2013 Impervious surface impact on water quality in the process of rapid urbanization in Shenzhen, China. *Environmental Earth Sciences* **68** (8), 2365–2373.

Liu, M., Xu, Y., Hu, Y., Li, C., Sun, F. & Chen, T. 2014 A century of the evolution of the urban area in Shenyang, China. *PLoS ONE* **9** (6), e98847.

Mejía, A. I. & Moglen, G. E. 2010 Spatial distribution of imperviousness and the space–time variability of rainfall, runoff generation, and routing. *Water Resources Research* **46**, W07509.

Miller, J. D., Kim, H., Kjeldsen, T. R., Packman, J., Grebby, S. & Dearden, R. 2014 Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology* **515**, 59–70.

Mishra, S. K. & Singh, V. P. 2002 SCS-CN-based hydrologic simulation package. In: *Mathematical Models in Small Watershed Hydrology and Applications* (V. P. Singh &

D. K. Frevert, eds). Water Resources Publications, Littleton, CO, USA, pp. 391–464.

Qiao, K., Zhu, W., Hu, D., Hao, M., Chen, S. & Cao, S. 2018 Examining the distribution and dynamics of impervious surface in different function zones in Beijing. *Journal of Geographical Sciences* **28** (5), 669–684.

Qin, H.-p., He, K.-m. & Fu, G. 2016 Modeling middle and final flush effects of urban runoff pollution in an urbanizing catchment. *Journal of Hydrology* **534**, 638–647.

Ridd, M. K. 1995 Exploring a V-I-S (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities. *International Journal of Remote Sensing* **16** (12), 2165–2185.

Roberts, D. A., Gardner, M., Church, R., Ustin, S., Scheer, G. & Green, R. O. 1998 Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. *Remote Sensing of Environment* **65** (3), 267–279.

Segurado, P., Almeida, C., Neves, R., Ferreira, M. T. & Branco, P. 2018 Understanding multiple stressors in a Mediterranean basin: combined effects of land use, water scarcity and nutrient enrichment. *Science of The Total Environment* **624**, 1221–1233.

Sellers, P. J. 1985 Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing* **6** (8), 1335–1372.

Shuster, W. D., Bonta, J., Thurston, H., Warnemuende, E. & Smith, D. R. 2005 Impacts of impervious surface on watershed hydrology: a review. *Urban Water Journal* **2** (4), 263–275.

Smith, M. O., Ustin, S. L., Adams, J. B. & Gillespie, A. R. 1990 Vegetation in deserts: I. A regional measure of abundance from multispectral images. *Remote Sensing of Environment* **31** (1), 1–26.

Suribabu, C. R. & Bhaskar, J. 2015 Evaluation of urban growth effects on surface runoff using SCS-CN method and Green-Ampt infiltration model. *Earth Science Informatics* **8** (3), 609–626.

Szymura, T. H., Szymura, M., Zając, M. & Zając, A. 2018 Effect of anthropogenic factors, landscape structure, land relief, soil and climate on risk of alien plant invasion at regional scale. *Science of The Total Environment* **626**, 1373–1381.

Yang, J. & He, Y. 2017 Automated mapping of impervious surfaces in urban and suburban areas: linear spectral unmixing of high spatial resolution imagery. *International Journal of Applied Earth Observation and Geoinformation* **54**, 53–64.

Zhang, B. A., Xie, G. D., Zhang, C. Q. & Zhang, J. 2012 The economic benefits of rainwater-runoff reduction by urban green spaces: a case study in Beijing, China. *Journal of Environmental Management* **100**, 65–71.

First received 6 November 2018; accepted in revised form 2 April 2019. Available online 17 April 2019