Research Paper

Effect of urban green space changes on the role of rainwater runoff reduction in Beijing, China

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HIGHLIGHTS

- The green space area reduced by 199 km² and became fragmented from 2000 to 2010.
- The annual runoff reduction volume ranged from 132 million m³ to 198 million m³.
- The rainwater runoff reduction rate decreased by 6% with the land cover changes.
- The green space with larger LPI and AI is suitable for flooding risk reduction.

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ABSTRACT

The effects of urban green spaces on stormwater runoff have increasingly attracted attention because of climate change and rapid urbanization conditions. This study investigates the spatial–temporal changes of urban green spaces in Beijing and estimates their effects on rainwater runoff reduction based on an empirical model. Results indicate that green spaces in Beijing decreased by 199 km² from 2000 to 2010 and that landscape patches became increasingly isolated and fragmented. The volume of rainwater runoff controlled by urban green spaces first increased and then decreased with the increase in summer rainfall. The runoff reduction rate continuously decreased from 23% in 2000 to 17% in 2010, which is mainly attributed to the composition changes in urban green spaces. In addition, an immense regional difference that is closely related to the changes in the largest patch and aggregation indices of urban green spaces are observed in different regions. This study recommends an optimal landscape pattern of urban green spaces for the planning and management of green spaces in highly urbanized areas.

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1. Introduction

Rapid urbanization worldwide has become a critical issue in the 21st century (Grimm et al., 2008; Parrish & Zhu, 2009). The world urban population is expected to increase by 84% from 3.4 billion in 2009 to 6.3 billion in 2050 (United Nations, 2010). The number of megacities has significantly increased since 1970, with the newest ones emerging in developing countries (United Nations, 2012). Urban development involves the replacement of vegetated soils with impermeable surfaces; this process can exert profound influences on the biogeochemical cycle, hydrological process, climate change, and biodiversity in terrestrial ecosystems at multiple scales (Alberti, 2009; Kuang, Liu, Zhang, Lu, & Xiang, 2013; Pickett et al., 2011). The increase in summer flood risk in an urban environment is

a major concern in many regions of the world (Pitt, 2008; Wheeler & Evans, 2009). The United Nations (2012) reported that flooding has become the most frequent and significant hazard for 633 of the largest cities or urban agglomerations worldwide. Several highly urbanized areas in China, such as Beijing (Gu, Li, Zhou, & Wu, 2013; Li, 2012), Shanghai (Quan et al., 2010; Yin, Yin, Xu, & Wen, 2011), and Guangzhou (Guo & Deng, 2011; Zhang & Ouyang, 2011), have become increasingly prone to flooding in recent years as a result of short-term heavy rains. Thus, immense efforts are focused on improving conventional and innovative stormwater management practices to decrease the runoff volume associated with developed pervious and impervious land covers (Battiata, Collins, Hirschman, & Hoffmann, 2010).

The effects of vegetation on surface water runoff have been extensively studied (Armson, Stringer, & Ennos, 2013; City of Seattle, 2008; Inkiläinen, McHale, Blank, James, & Nikinmaa, 2013). The use of urban green space has been increasingly identified as a measure to reduce runoff and mitigate the negative effects of urbanization on the hydrology of urban areas (Bartens, Day, Harris,

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Dove, & Wynn, 2008; Mentens, Raes, & Hermy, 2006; Zhang, Xie, Zhang, & Zhang, 2012). Ellis, Leguédais, Hairsine, and Tongway (2006) demonstrated that tree belts can reduce runoff from an agricultural grassed slope by 32% to 68% in a 1-in-10-year storm event (24.5 mm in 30 min) and by 100% in a one-in-two-year storm event (48 mm/h for 13 mm). Clearing and planting five vegetated Northern Philadelphia vacant lots to retain stormwater decreased runoff by an average of 30%, with an average peak runoff reduction at nearly 24% from June 2005 to May 2006 (Yang & Myers, 2007). The trees and their associated tree pits in 9 m² Manchester plots reduced runoff from asphalt by as much as 62%, whereas grass almost totally eliminated surface runoff (Armson et al., 2013).

Directly measuring how efficiently landscapes reduce runoff is costly in terms of field and laboratory time. Thus, computing models such as the stormwater management model (SWMM), SWAT, soil conservation service curve number (SCS-CN), and CITY-green have been widely used. Gill, Handley, Ennos, and Pauleit (2007) modeled the potential runoff reduction produced by trees in Manchester, United Kingdom; they determined that a 10% increase in tree cover in high density residential areas can lower surface runoff by 5.7% in a 28 mm event. Li, Li, Chen, Yuan, and Xu (2009) used the CITY-green model and determined that the annual surface runoff decreased by 30% from 1990 to 2005; the peak flow decreased by over 40% in Shenzhen, China. The aforementioned studies highlighted the value of urban green spaces in reducing rainwater runoff but failed to consider the effects of landscape patterns (i.e., size, shape, or spatial arrangement of vegetation patches) on the role of runoff reduction.

Landscape ecology and catchment hydrology are disciplines that deal with patterns, processes, interactions, and functional implications on different scales (Schröder, 2006). Many studies have shown that landscape structures are significant factors that affect surface runoff and spatial variety (Fiener, Auerswald, & Van Oost, 2011; Fohrer, Haverkamp, & Frede, 2005; Jencso et al., 2009; Lexartza-Artza & Wainwright, 2009; Nippgen, McGlynn, Marshall, & Emannuel, 2011; Ziegler et al., 2007). Investigating the relationships between vegetation structural attributes, soil surface properties, and hillslope hydrologic functions in a semi-arid Mediterranean landscape, Bautista, Mayor, Bourakhouadar, and Bellot (2007) found an inverse relationship between patch density and runoff and that both runoff and sediment yields increase as the spatial pattern of vegetation coarsens. With simulated rainfall experiments, Guo, Xu, and Lv (2007) concluded that the spatial structure of an urban underlying surface largely influences the rainfall infiltration rate. Liu, Wang, and Duan (2011) demonstrated that a clear relationship exists between landscape patterns and flood storage capacities in the Dongting Lake area in China. Thus, planning and designing the optimal landscape pattern of urban green spaces to facilitate positive runoff regulation are now urgent necessities for city managers.

The present study mainly focuses on the landscape pattern changes of urban green spaces (including landscape types and metrics) in Beijing as well as their effects on rainwater runoff reduction. We attempt to develop an empirical model for urban landscape pattern and rainwater runoff and to examine the effect of urban land cover changes on the role of rainwater runoff reduction at the local level. Using the inner city of Beijing from 2000 to 2010 as a case study, this study aims to achieve the following objectives: (1) to explore the temporal and spatial changes of urban green spaces in established areas in Beijing, (2) to estimate the amount and capacity of urban green spaces for rainwater runoff reduction, and (3) to analyze the regional differences in rainwater runoff reduction across different regions.

The rest of this paper is organized as follows. Section 2 provides a background of the study area and the assessment methods. Section

3 presents the results. Sections 4 and 5 provide the discussion and conclusions, respectively.

2. Materials and methods

2.1. Study area

Beijing is located in Northern China at 39°38' to 41°05'N and occupies a total area of 16,807 km². The population was almost 16.95 million in 2010, the average population density was 1033 people/km², and the urbanization rate was 85.9% (Beijing Municipal Statistical Bureau, 2010). The road network in Beijing consists of ring roads and radials as arteries. The road around the Forbidden City is the first ring, and the ring roads beyond this area are the second, third, fourth, fifth, and sixth ones, which were termed as such relative to the radial distance of each road from the city center. Beijing underwent rapid urbanization with the implementation of the Reforms and Opening-up Policy. The urban area of Beijing increased from 183.84 km² in 1973 to 1209.97 km² in 2005; the built-up area has increased by 1026.13 km² over the past 32 years, with an annual expansion rate of 32.07 km² (Mu et al., 2007). Official statistics show that the built-up area of Beijing expanded from 109 km² in 1949 to 1350 km² in 2009 (National Bureau of Statistics of China, 2009). Considering that the high-density urban locale is the dominant landscape within the sixth ring road (Xiao, Ouyang, Cai, & Li, 2007), we adopted this region as the study area and divided it into five zones in accordance with the five ring roads (Fig. 1). The city has an average annual precipitation of 554.5 mm, nearly 80% of which is concentrated between June and September (Sun, Feng, Yang, & Wu, 2007). Beijing has suffered from a gradual decrease in annual precipitation from 1950 to present because of global climate change (Yue, 2007). In addition, extreme rainstorms frequently occur in urban centers (Zhong, Jia, & Li, 2013), thereby increasing flood risk sharply (Hu, Xuan, & Zhu, 2013). For example, the largest rainstorm in Beijing in the last 61 years occurred on July 21, 2012, and generated an average daily rainfall of 215 mm in the urban area, with the largest cumulative rainfall of 460 mm in Hebei village of Fangshan county. This rainstorm was referred to as the “7.21” catastrophic natural disaster because of its severe consequences (Li, 2012). Furthermore, 17 heavy rainstorms were experienced by Beijing during the recent 10-year period (Chen et al., 2011; Lan & Yang, 2009), including the “7.10” event in 2004 (the maximum 1 h precipitation exceeded 90 mm), “7.31” in 2006 (the maximum 1 h precipitation was 105 mm), and “6.23” in 2011 (the maximum 1 h precipitation reached 128 mm). Nineteen urban road water-logging events (road drainage systems cannot timely drain heavy or continuous rainfall resulted in urban traffic congestion or interruption) occurred in Beijing during the flood seasons (i.e., June, July, and August) from 2007 to 2010 (You, Shi, & Wu, 2001). These rainstorms resulted in dozens of deaths and immense losses in social welfare.

Vegetated areas present benefits, including water infiltration and storage in the soil, runoff reduction, nutrient and pollutant removal, and groundwater quality. The urban green space area in Beijing has decreased to 14.68% in the past 20 years because of rapid urbanization (Fu, 2012). However, the number and area of city parks increased substantially from 2000 to 2010, with the expansion of urban built-up area boundary. The urban center park area has increased by 5188.44 ha for the past 10 years with an expansion rate of 6.36% per year (Mao, Song, Yang, & Zhao, 2012). However, the green landscape distribution still remains uneven, the community structure is simple, and the landscape diversity index is low (Wang et al., 2010). In the past decade, city managers have focused greatly on the construction of drainage pipe networks given the lack of clear recognition of the positive roles of urban green spaces

Fig. 1. Regional location of the study area: (a) location of the study area in China; (b) location of the study area in Beijing; (c) five zones divided by ring roads in the study area: Zone 1 is encircled by the second ring road, Zone 2 is the area between the second and third ring roads, Zone 3 represents the area between the third and fourth ring roads, Zone 4 is the area between the fourth and fifth ring roads, and Zone 5 represents the area between the fifth and sixth ring roads.

in hydrological regulations (Li, 2012; Zhang et al., 2012). This condition has resulted in increased financial burden, decreased low flow, and diminished groundwater recharge. Therefore, a comprehensive understanding and assessment of land cover change effects on rainwater runoff is crucial to the planning, management, and sustainable development of urban green spaces.

2.2. Land cover area

Digital land cover maps (Fig. 2) were generated from a multi-temporal and multi-spectral dataset to serve as the bases for the hydrological impact evaluation of land cover changes. RapidEye images (with 2.5 m resolution) from 2000, 2005, 2008, and 2010 were used. Image pre-processing was completed with ERDAS Imagine 9.3 software. Satellite images were generated by applying coefficients for radiometric calibration, geometric rectification, and mosaic. First, we rectified these multispectral and panchromatic images with 20 ground control points through the nearest neighbor resampling algorithm and ascertained a less than 0.5 pixel root mean square error through image-to-image registration. After the rectification, a mosaic was created using the rectified images, which we re-sampled to a 5 m resolution and projected through the Universal Transverse Mercator zone 110E, WGS ellipsoid. Finally, the boundary of the sixth ring road was used to clip these images for the study area.

The supervised classification method with maximum likelihood clustering and digital elevation model (DEM) data was employed as a hybrid method to classify images and generate land cover maps. Post-classification analysis was performed to create the trend map of the land cover. Land cover categories were determined as farm, forest, grass, wasteland, impervious surface, and water. Pure pixels were selected as the training sample instead of mixed pixels. Mixed classes, such as forest and grass, were separated using the DEM data. The spatial mapping of urban green areas in 2010 from the

Beijing Municipal Bureau of Landscape and Forestry was performed to assist the image classification and validate the final results. Each image was classified through the same method.

The overall accuracy and kappa value (K_{ap}) were selected as the evaluation criteria for image classification. An error matrix was generated based on the test samples for each land cover map. The overall accuracy that ranged from 0 to 1 was computed by dividing the total number of correct pixels by the total number of pixels in the error matrix. Kappa analysis is a discrete multivariate technique used in accuracy assessment, and K_{ap} is between -1 and 1 . If test samples are in perfect agreement, the values of overall accuracy and K_{ap} are equal to 1 . The overall classification accuracy of each image in this study was over 92% with K_{ap} of more than 0.82 . The accuracy requirements were thus satisfied.

2.3. Volume of rainwater runoff reduction

Selecting effective methodologies for investigating the effects of land use changes on storm runoff generation remains an urgent problem. Recent proposals have largely focused on adopting computing models to address issues such as stormwater runoff generation and volume (Soulis, Valiantzas, Dercas, & Londra, 2009; Yang & Myers, 2007). However, the accuracy of runoff modeling is constrained by data availability, and the quantitative means to predict the storm runoff generated in a highly fragmented urban landscape are limited. The present study combines an empirical model with landscape metrics to estimate the volume of rainwater runoff generation from different land cover types.

Rainwater runoff is precipitation that does not sink into the ground upon landfall. Land cover, including forests, agricultural activities, and urban development, is the primary control in generating runoff (Fox et al., 2012). A soft ground of vegetated areas allows water to seep through as the vegetation absorbs water and releases it into the air through evapotranspiration (Bolund

Fig. 2. Land cover maps of the study area from 2000 to 2010: (a) the farmland clearly dominated the land cover areas in 2000; (b) the farmland area decreased, whereas the forest and grassland areas increased in 2005; minor changes in land cover were observed between 2008 (c) and 2010 (d).

& Hunhammar, 1999). Therefore, the increased creation of green areas has been proposed as a response to recent calls for ecological and green urbanization (Zhang et al., 2012). And in general, the rainwater runoff coefficient of green spaces in Beijing is viewed as 10%, whereas that of hard surfaces as 80% (Yin, 2009). In addition, a multitude of case studies have been conducted in Beijing to

investigate rainwater runoff with different land uses (Gao & Wang, 1993; Sun, Wu, Xiao, & Teng, 2009; Yu & Wang, 1999; Zhang et al., 2002). For example, Yang, Shi, Li, and Zhang (1994) measured actual rainwater runoff in six watersheds with the vegetation of a natural secondary shrubby forest in Xishan mountain (located in the western suburbs of Beijing, and approximately 20 km distant

Table 1
Rainwater runoff coefficients for different land cover types in Beijing.

Land cover	Underlying surface	Rainwater runoff coefficient	Case study
Forest	Conifer (Larch)	0.05	Gao and Wang (1993)
	Conifer (Platycladus)	0.25	Yu and Wang (1999)
	Broadleaf (Black Locust)	0.03–0.05	Gao and Wang (1993)
	Broadleaf (Birch)	0.21	Yu and Wang (1999)
	Mixed forest	0.03	Yu and Wang (1999)
	Shrub	0.06–0.08	Yang et al. (1994)
	Mean	0.1	
Grass	Natural grassland	0.04–0.19	Sun et al. (2009)
	Artificial grassland	0.03–0.07	Sun et al. (2009)
	Residential quarter	0.23–0.34	Zhang et al. (2002)
	Mean	0.17	
Farm	Corn	0.56	Sun et al. (2009)
	Corn	0.49	Huang et al. (2003)
	Mean	0.53	
Wasteland	Non-forest land	0.66	Yu and Wang (1999)
	Bare area	0.71	Huang et al. (2003)
	Bare field	0.63	Sun et al. (2009)
	Mean	0.67	
Impervious surface	Roof	0.80–0.98	Dong et al. (2008)
	Road	0.87–0.97	Dong et al. (2008)
	Mean	0.9	

Each land cover type is related to the runoff coefficients based on field measurements. The mean values were calculated from the runoff coefficients of different land cover types using an arithmetic method.

from the Forbidden City). Huang, Zhou, Zhang, and Zhang (2003) investigated the storm runoff from the agricultural field plots of the Guanting Watershed in Beijing under simulated rainfall conditions. The measured runoff coefficients in field studies have been collected at different sites and periods (Table 1), we derive the average value of the runoff coefficient for each land cover type, in order to simplify the calculation for runoff generation.

We have to consider land cover patterns in the runoff estimation when moving from single fields to large spatial scales. The effects of patchiness, spatial organization of patches, and linear structures on the surface runoff response are most visible on small headwater catchments (Fiener et al., 2011). A study in the Dongting Lake area (located in the south beach of the middle reaches of the Yangtze River, across Hunan and Hubei provinces) in China confirmed the relationship between landscape patterns and flood storage capacities (Liu et al., 2011). The results revealed that the correlations between the amount of flood retention and largest patch index (LPI) and aggregation index (AI) were the largest, with correlation values of 0.77 and 0.75, respectively. Therefore, we introduced LPI and AI as the revised coefficients in the empirical model.

$$PAI_i = LP_i \times AI_i \quad (1)$$

$$PARI_i = \frac{PAI_i - PAI_{\min}}{PAI_{\max} - PAI_{\min}} \quad (2)$$

where PAI_i is the aggregative index of the LPI and AI in the i th urban green space patch, $PARI_i$ is the revised coefficient of land cover patterns calculated from the normalization processing, and LPI_i and AI_i are the largest patch and aggregation indexes in the i th urban green space patch, respectively.

Nearly 80% of the annual precipitation in Beijing is concentrated between June and September. Summer rainfall (P) can be obtained from the sum of the monthly precipitation values between June and September. Therefore, the volume of rainwater runoff reduction (R) can be calculated using the runoff difference between the impervious surface (γ_h) and green spaces (γ_i) in Formula (3). The total amount of rainwater runoff reduction (TR) and the ratio of runoff reduction (RR) can be determined using Formulas (4) and (5), respectively.

$$R_i = P \times PARI_i \times (\gamma_h - \gamma_i) \times A_i \times 10^3 \quad (3)$$

$$TR = \sum_{i=1}^n R_i \quad (4)$$

$$RR = \frac{TR \times 100}{\sum_{i=1}^n (10^3 \times P \times A_i)} \quad (5)$$

where TR is the total volume of rainwater runoff reduction (m^3), R_i is the runoff volume controlled by the i th landscape patch (m^3), RR represents the ratio of runoff reduction (%), γ_i is the runoff coefficient of the i th landscape patch (Table 1), P is the summer rainfall (mm), A_i is the area of the i th landscape patch (m^2), and n is the number of land cover patches.

3. Results

3.1. Land cover changes

The spatial distribution of an urban land cover in Beijing (Fig. 2) shows that for all periods, the constructed part occupied the largest surface area at nearly 50–60% of the study area. As shown in Fig. 2, most of the land cover was concentrated in the core part of the city. Impervious lands occupied most of the area, followed by farmlands and forestlands. The largest net loss from 2000 to 2005 was

observed in the farmlands ($-295 km^2$), whereas the largest net gains were observed in the forestlands and grasslands. Most of these gains were from the farmlands (Table 2). The largest loss between 2005 and 2010 persisted in the farmlands. The surface area loss was approximately a quarter of the area from 2000 to 2005. The forest area also decreased substantially. Unlike the data from 2000 to 2005, the largest gain between 2005 and 2010 was observed in impervious surfaces with a net increase of $142 km^2$. Much of the urban growth in the earlier period was at the expense of the farmlands. However, urban land covers from farmlands and wastelands increased in the latter period. Overall, a large area of farmland and water was replaced by impervious surfaces from 2000 to 2010. These land cover changes mainly occurred in Zone 5 located between the fifth and sixth ring roads. Grass areas and forests benefited most from the farmland and wasteland losses (Fig. 2). Furthermore, a certain degree of swapping between forest, grass, and farmland was observed outside the fifth ring road, with virtually no growth in the other parts (Table 2).

The total area of the urban green spaces in Beijing continuously decreased in the 2000–2010 period (Fig. 3), resulted in a continual decrease from $1041 m^3$ in 2000 to $842 km^2$ in 2010. Almost $20 km^2$ of the urban green spaces were replaced by impervious surfaces annually. The landscape metrics on the patch level were calculated using FRAGSTATS (Version 3.3). The class-specific AI is independent of landscape composition and provides a quantitative basis for correlating the spatial pattern of each class with a specific process (He, DeZonia, & Mladenoff, 2000). In this study, the AI of the urban green spaces constantly decreased through time from 92 in 2000 to 88 in 2010. The LPI, which quantifies landscape composition through the percentage of total landscape area encompassed by the largest patch, is widely used as an indicator of landscape fragmentation as well. The LPI of the urban green spaces in this study decreased substantially from 7.5 to 5.2 in the 2000–2005 period, whereas a gradually descending trend was observed from 2005 to 2010. Therefore, the landscape patches of the urban green spaces in Beijing were increasingly isolated and fragmented over the 11 year span.

3.2. Rainwater runoff reduction across different years

Many studies have confirmed that urban green spaces can play a positive role in reducing rainwater runoff. The spatial-temporal patterns in urban green spaces significantly influence surface runoff generation as well. We obtained summer rainfall data from 2000 to 2010 (Fig. 4) using the monthly rainfall data published on the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>).

The urban green spaces could reduce rainwater runoff by $132\text{--}198$ million m^3 . The urban green spaces provided the largest stormwater runoff reduction in 2008 and controlled the lowest runoff in 2000. The urban green spaces reduced storm runoff by 159 million m^3 in 2005 and by 146 million m^3 in 2010. The increased built-up areas resulted in decreased urban green spaces, whereas the summer precipitation clearly showed an increasing trend. The estimated runoff reduction volume increased by 66 million m^3 and decreased by 52 million m^3 based on the land cover distribution pattern between 2000 and 2010. We also adopted the runoff reduction rate (i.e., the percentage of the runoff reduction amount of the annual summer rainfall) to analyze the capacity of urban green spaces for runoff regulation. The green spaces in 2000 indicated the highest runoff reduction rate at 23.43%. The next factors were the urban green spaces in 2005 and 2008, which were measured at 22.59% and 19.15%, respectively. The minimum runoff reduction rate was 16.89% in 2010.

Table 2Changes in urban land cover areas in Beijing from 2000 to 2010 (km²).

Year	Land cover						
	Forest	Grass	Farm	Wasteland	Water	Impervious surface	Green space
2000–2005	135.20	91.96	–295.09	2.13	–11.56	77.37	–65.80
2005–2010	–73.40	31.29	–76.34	–14.23	–3.88	141.83	–77.28
2000–2010	61.81	123.25	–371.44	–12.10	–20.71	219.19	–198.49

Fig. 3. Changes in the area and landscape metrics of the urban green spaces in Beijing. The green space areas in Beijing continuously decreased from 2000 to 2010. Landscape metrics (i.e., LPI and AI) also showed descending trends.

The changes in urban green spaces and their capacity for runoff reduction (Figs. 3 and 4, respectively) indicate the changing trends of the urban green space area in Beijing and the role of rainwater runoff reduction. The magnitude of rainwater runoff reduction first increased and then decreased. This condition is mainly correlated with the changes in summer rainfall. However, the reduction ratio of rainwater runoff decreased from 23% to 17%. This variation is primarily attributed to the changes in the types and areas of urban green spaces. In 2000, a majority of the urban green spaces were occupied by farmlands, which accounted for larger runoff coefficients compared with forests and grasslands. Low levels of farmland areas were maintained, and the area percentages

of forests and grasses increased in the following period. Thus, the changes in the runoff reduction capacity resulted primarily from agricultural lands, which were partly compensated by the increase in grass areas.

3.3. Rainwater runoff reduction across different regions

The capacities for rainwater runoff reduction across different districts (Fig. 5) show that, the urban green space in Zone 5 (between the fifth and sixth ring roads) recorded the maximum runoff reduction ratio (average of 28%). The next area was Zone 1 (inner part of the second ring road), followed by Zone 4 (between

Fig. 4. Summer rainfall and the role of rainwater runoff reduction from 2000 to 2010. The summer rainfall volume constantly increased from 2000 (294.4 mm) to 2008 (455.6 mm) but decreased in 2010 (381.3 mm). The rainwater runoff volume controlled by the urban green spaces first increased and then decreased with the increase in summer rainfall. Meanwhile, the runoff reduction rate continuously decreased from 23% in 2000 to 17% in 2010.

Fig. 5. Ratios of rainwater runoff reduction across different regions. The largest runoff reduction capacity was in Zone 5, followed by Zones 4, 1, 3, and 2.

the fourth and fifth ring roads) and Zone 3 (between the third and fourth ring roads), which recorded mean runoff reduction capacities of 6%, 3%, and 1.5%, respectively. The minimum stormwater runoff reduction was 0.5% in Zone 2 (between the second and third ring roads). These differences depended on the green space areas in each zone and landscape patterns of the urban green spaces. From the perspective of dynamic change, the rainwater runoff reduction ratios in Zones 1 and 2 indicated minimal changes from 2000 to 2010, whereas the runoff reduction capacity in Zone 5 clearly exhibited a decreasing trend in the 2000–2010 period. By contrast, a large variation in Zones 3 and 4 were observed, with the runoff reduction capacity initially increasing and then decreasing.

The patchiness of the urban green space landscape has important implications for surface runoff generation. Patchiness is largely due to the differences in the landscape patterns of urban green spaces. In this study, a strong positive correlation was noted between runoff reduction capacity, LPI, and AI. Thus, an increase in the LPI or AI expands the role of rainwater runoff reduction facilitated by urban green spaces. The urban green spaces in Zone 5 recorded large LPI and AI values, which led to high connectivity such that the rainwater runoff tended to be minimal. The landscape metrics for all periods significantly decreased. This result can be associated with the diminished magnitude and capacity for runoff reduction in the urbanization of the study area. The comparative analysis of the type, area, and landscape metrics between Zones 1 and 2 is presented in Table 3. The green space in Zone 1 was composed primarily of grass and forest and had large LPI and AI, thus promoting the role of rainwater runoff reduction. By contrast, the green space in Zone 2 consisted of grass, forest, farmland, and wasteland, thereby accounting for large runoff coefficients. The landscape metrics of the LPI and AI were relatively small, resulting in the poor role of rainwater runoff reduction. Therefore, the landscape patterns of the urban green space in Zone 1 should be recommended for rapidly developing urban areas such as Beijing.

4. Discussion

Given the conditions of global climate change and rapid urbanization, clear guidance is necessary for the local authorities and public to formulate the best plan for urban green space management. Beijing was subject to major land cover changes at the

beginning of the 21st century. Housing and agricultural activities, as well as forest, river, and other land uses, shifted as a result of urbanization. Land cover underwent significant changes in Beijing in the 2000–2010 period. This observation is consistent with most of the land use changes studied or scenarios that highlighted significant decreases in the areas and landscape metrics of urban green spaces (Fu, 2006; Mao et al., 2012; Wang et al., 2010). Land use changes modify hydrological processes over a range of temporal and spatial scales (Ali, Khan, Aslam, & Khan, 2011). On July 21, 2012, Beijing suffered the heaviest rain and overall reached the torrential level since 1951. The disaster affected 1.9 million populations and had aroused wide concerns in China. Several studies have demonstrated that the risk change of storm flooding in an urban center can be partly attributed to the rapid replacement of natural ecosystems by impervious urban surfaces (Hu et al., 2013; Liu, 2009; Shepherd, 2006; Zhong et al., 2013). A combination of a land use scenario and a hydrological model has been considered as an appropriate approach to quantify this effect (Ali et al., 2011). Defining a critical green space threshold for runoff reduction is a complex task because of the effects of land cover changes relative to several factors, such as magnitude, type, spatial location, and climatic effects (Fox et al., 2012). The present study assumed climatic and soil factors as constant and concluded with rainwater runoff reduction rates ranging from 17% to 23% across different years. This finding is similar to the results of previous studies. Li et al. (2009) employed the CITY-green model and reported that urban green spaces in Shenzhen, China, reduce annual surface runoff by 30% and peak flows by over 40%. Given the higher rainfall amount and frequency in the southern region than in the northern region of China, the role of runoff reduction provided by urban green spaces in Shenzhen should be superior to that in Beijing.

However, the present study has several limitations. The spatial variation of storm rainfall in the summer was excluded. In addition to land cover, other factors (i.e., soil properties) can contribute to runoff generation. Although the integrated models such as SWMM and SCS-CN can accurately assess hydrological responses relative to land use change, applications remain difficult because of data scarcity. The runoff parameters from the field observations were averaged and kept constant in all of the processes. However, the runoff coefficients during floods would be very different from the long term averages. The proportion of an extreme rainfall that is

Table 3

Comparison of type, area, and landscape metrics of urban green spaces between Zones 1 and 2.

Year	Type		Area		LPI		AI	
	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2
2000	Grass and forest	All	4.35	5.39	2.59	0.77	80.36	69.35
2005	Grass and forest	All	4.89	6.74	2.79	0.87	79.51	71.93
2008	Grass and forest	All	4.93	6.24	2.74	0.87	78.85	70.49
2010	Grass and forest	All	4.86	6.14	2.74	0.87	78.80	70.27

"All" represents grass, forest, farmland, and wasteland.

reduced by green space is usually much less the average proportion expressed by the average type of coefficients in this study. We must remember that in such extreme events as "7.21 event" in 2012, the surfaces get so wet after a certain amount of rain that every drop more rain immediately runs off concrete, grass and trees at virtually the same rate. Therefore, further research should be conducted to determine the role of runoff reduction within the urban green spaces of urbanized areas.

Despite these limitations, our study provides a reference point for public and government organizations to maximize benefits while controlling costs. Climate change and urban sprawl present threats and opportunities for urban green spaces. This study highlights the significant potential of the use of sustainable urban green spaces to reduce surface runoff particularly at the local level. Excess rainwater can be stored and used to irrigate green spaces in drought periods. The annual economic benefit for rainwater runoff reduction provided by urban green spaces in Beijing was approximately 1.34 billion RMB, which was equivalent to three-quarters of the maintenance cost of Beijing's green spaces (Zhang et al., 2012). In addition, the green spaces in Beijing could absorb 3.33×10^{12} kJ of heat via evapotranspiration during the entire summer. The cooling effect largely reduced air conditioning demand and CO₂ emission (Zhang, Xie, Gao, & Yang, 2014). However, the functionality of the green spaces depends on their location and structure (Gill et al., 2007). Thus, opportunities to enhance a green cover requires going to where structural changes occur. Green space also assists in reducing runoff through engineered sustainable drainage systems, except such things as grassed waterways and flood detention ponds, as well as keeping flood plains for floods. In addition, specific knowledge on rainwater runoff reduction within urban green spaces across different regions can contribute to the policy design for urban environmental management.

5. Conclusions

This study investigated land cover changes in Beijing in the context of rapid urbanization and estimated the role of urban green spaces in reducing stormwater runoff between 2000 and 2010. The green spaces in Beijing were rapidly decreased by 199 km² from 2000 to 2010 at the expense of agricultural lands. Green landscapes became considerably isolated and fragmented as well. These changes occurred mainly in the areas between the fifth and sixth ring roads. Unlike impervious surfaces, the urban green spaces in Beijing could control 17% to 23% of the rainwater runoff annually. Thus, runoff reduction capacity varies with the dominant type and landscape pattern of urban green spaces, under similar rainfall conditions. This variation indicates a potential for water-logging risk reduction through urban green space management in Beijing. The findings of this study provide several references for many highly urbanized areas that suffer from water-logging risk. The optimal landscape patterns should be recommended as urban green space arrangements within the second ring road. In this way, policies can be employed to encourage the optimal structure and composition of urban green spaces through green space strategies. City managers should focus greatly on the role of urban green spaces in

rainwater regulation and on the scientific management of urban green spaces.

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