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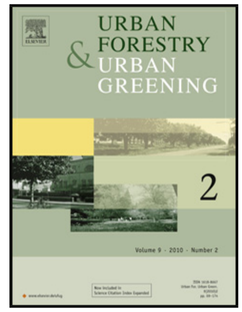

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Title

Assessing the hydrological behaviour of large-scale potential green roofs retrofitting scenarios in Beijing

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Highlights

- Beijing has a rich resources of the potential green roofs (PGRs), accounting for 19.6% of the study area.
- More than 10% of the runoff can be reduced by fully implementing of the PGRs in the north central downtown.
- 13 of the 20 flooding underpasses would not have happened in the 7.21 Rainstorm, if only 20% of the PGRs had been retrofitted in Beijing.

Abstract

Although the study of hydrological performance of green roofs is of great significance to urban water security and sustainable development, large-scale roofs greening within a city range has not received sufficient attention. In this study, a typical urban area of 675 km^2 within the fifth ring road of Beijing was chosen as a case study. The potential green roofs were defined before being identified from high resolution images. Under three retrofitting scenarios (100%, 50% and 20%) of extensive green roofs, the hydrological behaviour of potential green roofs was investigated at catchment units by employing the Soil Conservation Service Curve Number model. The behaviour was evaluated finally through two aspects of the runoff reduction effect and the flooding mitigation effect. According to this study, a 19.6% of the potential green roofs within the study area indicates a strong potential for the future greening. In the city scale, the average runoff reduction rates decrease from 9.38% to 6.13% with the increasing return period of rainfall events. Catchments in the core of northern city play key roles in reducing runoff, by more than 10% with the 100% implementation scenario. This study also showed that flooding in 13 of the 20 underpasses would have been avoided in the 7.21 Rainstorm if only 20% of the potential green roofs had been implemented. This study demonstrated a potentially positive hydrological behaviour contributed by roof greening in the future Beijing at a city scale, and effective runoff reduction can be achieved if only with a 50% greening of the potential green roofs. However, urban planners should take notice of the predicament that the deposit of high potential green roofs do not match spatially well to the severe flooding sites.

Keywords: Potential green roofs, Hydrological behaviour, Urban flooding, Remote sensing, Urbanization

1. Introduction

The urban population increased from 30% to 54% of the total world population between 1950 and 2014, and it is expected to reach 66% in 2050 (United Nations, 2014). This rapid urbanization has caused a large portion of natural surface transformed into imperviousness, which induces a dramatic decline of stormwater storage capacity in urban areas. Additionally, short-term but heavy rains are predicted definitely to become more frequent in the climate change context (IPCC, 2013; Du et al., 2012). Rainstorms are prone to cause serious flooding at many underpasses where storm runoff cannot be timely discharged in cities (Zhu et al., 2015). The dual impacts of urbanization and climate change make urban flooding to be more frequent and severe (Whitford et al., 2001; Grimm et al., 2008). In recent years, flooding disasters happened frequently in most cities of China, resulting enormous financial losses to those cities (Li, 2012).

Green infrastructure (GI) has been developed to mitigate excessive runoff and flooding. Green roof was one example of this strategy. In most metropolises, the amount of land available exclusively for GI is limited. So among them, green roof for being easily accomplished in existing built areas, becomes the most feasible one. In some cities, roof constitutes a significant proportion of the impermeable urban surface, approximately 40%-50% (Dunnett and Kingsbury, 2004). Unlike traditional roofs, green roofs are effective in reducing runoff and decreasing peak discharge (Razzaghmanesh and Beecham, 2014; Vijayaraghavan, 2016). Field experiments in Chongqing (China) showed that the annual retention volume by green roof could be 758.7 mm with a retention rate of 68% (Zhang et al., 2015). Feitosa and Wilkinson (2016) studied how green roofs with different substrate depths respond to the cumulative rainfall in a test bed of Auckland, using the HYDRUS-1D model. And it was shown that the retention rate is 28%-80% with substrates between 5 cm-160 cm. Karteris et al. (2016) found that by retrofitting all the potential green roof area, 45% of annual precipitation can be retained in Thessaloniki (Greece) in the context of averaging green roof retention data from literatures.

Palla and Gnecco (2015) used the Storm Water Management Model (SWMM) to study the hydrological behaviour of GI in a watershed of Genoa, Italy. Their research indicated that 7%-12% runoff reduction can be achieved if only 50% of roofs are greened and 16% of roads or parking lots are transformed into the permeable pavement. Their study also showed that noticeable runoff reduction effect demands for reducing at least 5% of effective imperious area in the watershed. Versini et al. (2015) integrated a conceptual model with SWMM to analyze the hydrological performance contributed by roof greening in the Châtillon basin (2.37 km^2), France. Their study indicated that a cover of 50% of potential green roof would reduce runoff by 12.4% and peak discharge by 18.3%, preventing urban flooding effectively.

Extensive studies have been reported concerning the effectiveness of green roofs on reducing runoff and decreasing peak discharge (Brudermann and Sangkakool, 2016; Stovin et al., 2013; Carter and Jackson, 2007), but most studies focused on the retention of varied configurations of green roof itself (Stovin et al, 2015; Eksi and Rowe, 2016). Although the process-based hydrological model like SWMM has achieved progress recently, the hydrological performance of green roof is constrained in small sized communities or catchments due to the high cost and availability to retrieve the hydrological parameters for cities larger than 10 km^2. The lack of researches within a large city range obviously hinders the development of scientific green roof strategies at an entire city scale.

The hydrological behaviour of green roofs was conducted by integrating GIS and remote sensing with a hydrological model in this study, selecting a large-scale urban area within the fifth ring road of Beijing, China as the study area. Three research goals were developed as follows. The first is to investigate the spatial distribution of potential green roofs (PGRs), which was defined and extracted based on high resolution remote sensing images. The second is to analyze the runoff reduction effectiveness contributed by green roofs based on the four synthetic rainfall events of different return periods. The third is to investigate the flooding mitigation contributed by green roofs based on the comparation between the storage volume by green roofs and the flood water volume of a historical severe rainstorm.

2. Materials and methods

2.1 Study domain and data sources

Beijing is characterized by a temperate monsoon climate, with rainfall mainly concentrated in summer. It has an average precipitation of 542.6 mm/year. As China's capital, Beijing has been highly urbanized. In 2014, the permanent resident population of Beijing was 21.516 million, with a density of 1,311 persons/km^2 (Beijing Statistical Bureau, 2015). The impervious surface accounts for more than 68% of the urban area within the fifth ring road of Beijing (Peng et al., 2016). Beijing met very frequent flooding in recent years. For example, the largest rainstorm of the last 61 years occurred on July 21, 2012, known as 7.21 Rainstorm. During this flooding event, 77 people lost their lives and total 1.60 million residents were under attack with 1 billion Yuan economic losses. Because of Beijing's severe flooding situation and the pressures of increasing population, it has become urgent to implement the large-scale construction of green roofs in order to reduce waterlogging and mitigate urban flooding. Therefore, the study chose the area within the fifth ring road of Beijing to investigate the hydrological impacts by retrofitting green roofs. The study area occupies a total of 675 km^2 which covers seven districts, the whole area of Xicheng and Dongcheng districts, about half of Chaoyang, Haidian and Fengtai districts, and a small portion of Daxing and Shijingshan districts (Fig. 1).

In this study, the 2.1 m panchromatic and 5.8 m multi-spectral (four wavebands of red, green, blue, and near infrared) images of the ZY-3 satellite were used. The images were captured on June 2, 2015. They were georeferenced, and then processed for a higher spatial resolution. The 5.8 m spectral bands image was pan-sharpened to the 2.1 m image through a Gram Schmidt spectral sharpening method. The vector data of roads was acquired from OpenStreetMap (http://www.openstreetmap.org/#map=12/39.9045/116.4812) as lines. The polygon data of roads was derived from lines after matching the road to the ground transportation lines of the image, inspecting and editing in geographic information system software (ArcGIS). And it was prepared to segment the image.

Catchments with area below 30 km^2 were digitized based on a 1:450,000 map of the small basins in Beijing, provided by the Beijing Hydrological Station. The delineation of catchments was carried out by combining multi-source data, the 1:10,000 DEM, the urban drainage pipelines data, sewage outlets and water dams, with the drainage direction investigated by field observation. That resulted in independent and closed drainage areas, and ensured that the catchments do not cross basins and villages. The study area was divided into 77 catchments. In addition, the flooding information of Beijing's underpasses during the 7.21 Rainstorm was obtained through field investigations and a collection of the recording materials provided by the traffic office.

2.2 Overview of the methodology

The Geographic Object Based Image Analysis (GOBIA) was adopted to extract land cover information and PGRs from the high resolution images, along with a definition of PGRs. The SCS-CN model was employed to calculate the runoff generation at catchment scale. PGRs and land cover were then generalized at each catchment where CN values of the reference and retrofitting scenarios were computed. The reduction rate was calculated under four synthetic rainfall events, indicating the runoff reduction effect. The storage volume was computed under 7.21 Rainstorm and was compared with the flood water volume, demonstrating the flooding mitigation effect (Fig. 2). All the information extraction was processed on the Ecognition Trimble 8.9 platform, and the spatial analysis was processed on the ArcGIS 10.1 platform.

The GOBIA method becomes prevalent with the development of high resolution images (Cheng and Han, 2016; Yao et al., 2015; Sebari and He, 2013). By considering objects as the basic units, the GOBIA can avoid the problem of mix pixels, and include spatial information like shape, and context. A GOBIA approach was adopted here to identify both the land cove types and the PGRs distribution.

2.3 Extraction of land cover information

Multi-scale segmentations were carried out to extract land cover information based on the preprocessed images. Then using the nearest neighbor supervised classification, the land cover was classified as six types: impervious surface, woodland, grass, wasteland, farm, and water (Fig. 1). Results with satisfied precision were generated by selecting training samples, configuring the classification features repeatedly, transferring the difference of several characters of grass, farm and woodland to compiled rules and editing manually. The overall accuracy and kappa coefficient were chosen to validate the classification. 342 test samples were generated throughout the study area by the random point method (ArcGIS 10.1 platform). The land cover types of test samples were obtained through higher resolution images in google earth. Then based on those samples, an error matrix was generated. The overall precision was 86% and the Kappa coefficient was 0.81.

2.4 Definition and extraction of PGRs

The PGRs are defined as building roofs suitable for retrofitting into extensive green roof with substrate depth less than 15 cm (Yang et al., 2008), considering the scenario of large-scale roof retrofit in the city. The suitability of a specific roof was determined by two aspects of the roof structure and the building age, from which PGRs were classified into the five categories in the Table 1, according to building types in Beijing and the expert knowledge of green roofs' construction (Beijing Municipal Commission of Urban Planning, 2013; Wilkinson and Reed, 2013; Castleton et al., 2010; Karteris et al., 2016). The researchers ignored the staircase and penthouse setbacks of building roofs and buildings height, and they also ignored roofs with areas of less than 100 m^2 because of the restricted spatial resolution of the images and the very large study area.

The GOBIA approach was also utilized in the extraction of PGRs. First, a vector-based segmentation was conducted based on the vector mask, formed by the road polygon and vegetation areas (Soil Adjusted-Vegetation Index-SAVI more than 0.2) (Huete, 1988). Then, a multi-scale hierarchical representation of the city objects was generated through multi-scale segmentations, which were requested to match segmentation with the edges of roofs as well as other objects. The categories of non-roofs and unsuitable roofs were excluded step by step during the classification process, before the PGRs were eventually derived (Karteris et al., 2016). Different classification methods were adopted for the extraction, considering the characteristics of unsuitable roofs and the interpretation ability of remote sensing image. Three classes of roofs, the cultural relics and historic sites, the venues with trussed structures, and the residential of type 2 (Table 1), were manually selected and classified as unsuitable roofs. In contrast, due to the large number and relatively single spectral characteristics, temporary buildings (shacks) were sorted out through supervised classification in the next step.

Adopting the nearest neighbor supervised classification method, the study area was classified into temporary roofs (unsuitable roofs), PGRs, wasteland, water, shadow and others. Compiled rules and GIS editing tools were conducted to eliminate the leak and error in the extraction. The final distribution of PGRs was shown in Fig. 3.

Similar to the validation method of land cover classification, an error matrix was generated based on the 732 ground truth points which were selected through random point method. And the attribute of those test samples were determined through field surveys and google earth images. Validation analysis was carried out by generating error matrix between the vector data of PGRs, non-PGRs and the test samples. The overall precision was 78% and the Kappa coefficient was 0.75.

2.5 Rainfall-runoff model and parameter determination

The Soil Conservation Service Curve Number (SCS-CN) model is a universal empirical model that has been widely applied to estimate runoff generation at varied scales, from 0.25 ha to 1000 km^2 (Baker and Miller, 2013; Yao et al., 2015). The SCS-CN model also have been widely adopted in the runoff calculation of green roofs (Fioretti et al., 2010; Palla and Gnecco, 2015; Carter and Jackson, 2007; Carter and Rasmussen, 2006). The formulas of SCS-CN model are as follows (NRCS, 1986).

$$Q = \begin{cases} \frac{(P - I_a)^2}{P - I_a + S}, & P \geq I_a \\ 0, & P < I_a \end{cases} \quad (1)$$

$$S = \frac{25400}{CN} - 254 \quad (2)$$

$$I_a = \lambda S \quad (3)$$

Where Q is the runoff depth (mm), P the rainfall depth (mm), I_a the initial abstraction of the rainfall (mm), and S represents the maximum potential retention of the soil/material composing the contributing area. The initial abstraction coefficient λ is a constant that usually ranges between 0.0 and 0.2, and 0.2 value was used in this study according to NRCS (1986). CN is a dimensionless parameter and represents the runoff generation capability of the surface, ranging from 0 to 100.

The CN value of different land cover types was determined according to the NRCS look-up table (NRCS, 1986) which was created by the United States Natural Resources Conservation Service (NRCS). The average soil hydraulic conductivity in most areas of Beijing is 18-180 mm/h, placing it in the B class according to analysis of soil infiltration characteristics in Beijing by Fu et al. (2013). And the antecedent moisture condition (AMC) was supposed to be in moderate condition (AMC Ⅱ) in this study.

The CN value of green roofs was obtained according to CN determination method presented by Fassman-Beck et al. (2015). In his study, the optimal value can be attained when the squared difference between the experimental value and the calculated value is minimal, by assigning a certain CN to green roofs. A literature review (Yang, et al., 2015; Sun, et al., 2012; Tang, et al., 2011) was made on green roofs rainfall-runoff experiments locally in Beijing, and there were 17 rainfall-runoff data that can be referred (Table 2). Five rainfalls were abandoned because of their large squared difference. And eventually 89 was accepted as the optimum CN value of extensive green roof.

The result is larger than those obtained by Fassman-Beck et al. (2015) (CN=84).

However, in Fassman-Beck's data source, the climate conditions were mostly warm temperate, while Beijing is characterized by snow climate. The difference in climate could cause different runoff generation of green roofs. There was also some difference from the results of Carter and Rasmussen (2006) (CN=86) due to the different CN calculation methods and the climate conditions. Getter et al. (2007) calculated that in Michigan, the CN values of green roofs for different slopes of 2%, 7%, 15%, and 25% are 84, 87, 89, and 90 respectively. Their CN value is consistent with our research when the inclination is 15%. In our study, greened flat roofs and pitched roofs are supposed to have the same retention capability. So 89 would be an average and reliable CN value for green roofs retrofitting scenarios (Table 3).

Four return periods for two hours rainfall events (T=2, 5, 10, 20 years) were designed according to the relationship of rainfall intensity-duration-frequency in Beijing (Beijing Municipal Engineering Design and Research Institute, 2004). The maximum intensity of those rainfall events are assumed to occur at the middle time of the storms. The cumulative rainfalls are acquired as 57.2 mm, 72.1 mm, 83.3 mm, and 94.5 mm for the four return periods by using the Chicago storm profile (Keifer and Chu, 1957).

2.6 Evaluation of hydrological behaviour of green roofs

The hydrological behaviour of green roofs was assessed by evaluating the runoff reduction in synthetic rainfall events of return periods 2, 5, 10 and 20 years and the flooding mitigation effect during 7.21 Rainstorm, both under three retrofitting scenarios (100%, 50% and 20% with increasing practicability in turn). The 7.21 Rainstorm with a cumulative rainfall of 215 mm is considered to be a rainfall event with 100 years return period. The runoff calculation was conducted with generalized CN in each catchment by employing SCS-CN model. The current configuration of building roofs which corresponds to the ''do nothing'' scenario, is assumed as the reference scenario, while the PGRs be covered by 100%, 50% and 20% proportions of extensive green roofs corresponds the retrofitting scenarios. Two variables, runoff reduction rate (ΔC_i in %) and storage volume (ΔV_i in m^3) were established. ΔC_i was calculated under four synthetic rainfall events, while ΔV_i was computed under 7.21 Rainstorm for indicating the mitigation of happened flooding. Firstly, ΔC_i (formula (4), as defined by Palla and Gnecco, 2015) was calculated as the relative percentage difference between the runoff of the reference and retrofitting scenarios. Secondly, the storage volume ΔV_i in the formula (5) was defined as the difference of runoff volume between the reference and roof greening scenarios. The second index was calculated to infer the potential capability of green roofs to mitigate flooding by comparing the storage volume with the amount of flood water volume in the flooding underpass of the catchment. The flood water volumes of the 20 underpasses in 7.21 Rainstorm were acquired based on the report of Yin and Li (2015).

$$\Delta C_i = \frac{(Q_i - Q_i')}{Q_i} \times 100\% \quad (4)$$

$$\Delta V_i = (Q_i - Q_i') \cdot A_i \quad (5)$$

Where Q_i (in m) refers to the runoff depth computed for the reference situation of *i*th catchment, whereas Q_i' (in m) corresponds to runoff depth for the retrofitting scenarios (100%, 50%, 20% of green roofs), and A_i (in m^2) is the drainage areas of the underpasses within *i*th catchment. All the area of the catchment is considered as the drainage areas of the flooding underpass if there is only one flooding underpass within the catchment, considering that most of those flooding underpasses are located very near to the outlet of their corresponding catchment. When there are more than one flooding underpasses within a catchment, the Voronoi (also known as Thiessen Polygons) was adopted to divide the catchment for determining the drainage areas of each flooding sites. The locations of all underpasses are shown in Fig. 3.

3. Results

3.1 Spatial distribution of PGRs

The result indicated that the area of PGRs is 131.92 km^2 within the fifth ring road of Beijing, which accounts for 19.6% of the total study area (Table 3). This implies that the study area has a relatively strong potential for roof greening.

The area and proportion of PGRs within each district were calculated (Fig. 4). The result showed that the area of PGRs in Chaoyang and Haidian districts are similar (and are the largest), exceeding 35 km^2. Although the area of Haidian district within the study area is smaller than Fengtai district, the area of its PGRs is 1.2 times that of Fengtai district. The area of PGRs within Xicheng, Dongcheng, Daxing and Shijingshan districts decreases in turn. The proportions of PGRs in different districts were also compared. In Xicheng, Haidian and Dongcheng districts, the proportions are higher than the average value (19.6%) of the research area. More specifically, the proportion of PGRs is 27.1% in Xicheng district and where the impervious surface could decrease from 76%, the highest imperious portion among the seven districts, to 49% by retrofitting all the PGRs. The proportion of PGRs in Daxing district exhibits the lowest value, only slightly higher than 10%.

3.2 Runoff reduction by green roofs

In 100% greening scenario, the infiltration condition in the research area could be improved. The average CN value could change from 88 to 86, meaning that the runoff generation condition could be close to wasteland. The average runoff reduction rate of catchments falls from 9.38% to 6.13%, and the area with runoff reduction rate more than 10% decreases from 44% to 17% of the total area moving rainfall from 2 years return period to 20 years (Fig. 5).

Fig. 5 showed the different runoff reduction rate contributed by green roofs spatially. The result demonstrated the runoff reduction rate is generally higher in the inner urban areas than that in the edge areas near to the fifth ring road, and it is higher in the northern areas than that in the southern. Moreover, with the return period increases, the areas where green roofs could play a significant runoff reduction role shrink to the inner of the city. At the rainfall condition with a return period of two years, catchments with runoff reduction rate above 10% distribute throughout the entire research area. However, most of the southern catchments show runoff reduction rate of 5%-10%, lower than the north. When the return period reaches 20 years, the catchments with a runoff reduction rate above 10% only lie in the north of the research area, including the Xicheng district, the inner parts of Haidian district, and the inner parts of northern Chaoyang district.

At the 2-year return period rainfall event, the range of runoff reduction rate is 0%-17.53% under the 100% greening scenario, while 0%-9.06% under 50% greening scenario, and 0%-3.70% under 20% greening scenario. The authors then focused on catchments with noticeable reduction effect (ID 65-77 in Fig. 6, correspond to catchments in pink color of Fig. 5-d) to analysis the dynamic of runoff reduction rate. The runoff reduction rate of these catchments could exceed 15% in the 100% retrofitting scenario, be nearly to 10% when half of the PGRs are retrofitted and be less than 5% in 20% scenario (Fig. 6).

3.3 Flooding mitigation by green roofs

The flooding mitigation by green roofs was shown in Table 4. The storage volume could exceed 362 million m^3 at this rainstorm by implementing all the PGRs. For the catchments where the flooding underpasses are located, the area of PGRs is in the range of 0.51 km^2 to 3.87 km^2, 2.01 km^2 in average, and the average storage volume is 55,325 m^3. The results also indicated that most of the flooding in 7.21 Rainstorm would have disappeared with the three retrofitting scenarios. If all the PGRs had been retrofitted, flooding would have been avoided in all the flooding sites except Shuangying and Xiaocun. Flood water only in five flooding sites with a flooding level higher than 2 m would have been more than the storage volume by green roofs, if half of the PGRs had been greened. The storage volume by green roofs would have been still more than the flood water volume at 13 of the 20 flooding underpasses, if only 20% of PGRs had been accomplished.

4. Discussion

On the whole, retrofitting PGRs with extensive green roofs could make impact on reducing rainstorm runoff in the city scale. According to this study, greening all PGRs within the fifth ring road of Beijing can reduce runoff by 6.13%-9.38% under four return period rainfall events (T=2, 5, 10, 20 years), indicating that the wide spreading of green roofs helps to cope with the excess runoff during rainstorms. But the reduction is weaker at severe rainstorms like a 20-year return period. Compared to the relative research, runoff reduction in the present study was 7.9%, close to Carter and Jackson's result of 7.6% in the case that the proportion of PGRs and the precipitation condition are similar to their study (Carter and Jackson, 2007). The storage volume by one square meter green roofs could be 25.7 L, which is similar to the research in London (80,000 m^3 by 3,200,000 m^2 of green roofs) (Greater London Authority, 2008). The reduction behaviour by green roofs could be rather considerable in our study, considering that annual runoff reduction rate achieved by green space is 17% in Beijing according to Zhang et al. (2015), and that the reduction effect decreases significantly from the small rain events over the year to heavy rainstorms (Stovin et al., 2013).

Both urbanization and climate change induce to the excessive runoff and therefore raise the risk of flooding, while green roofs have high potential to mitigate urban flooding (Brudermann and Sangkakool, 2016). Identification of the spatial variation of runoff reduction effect addresses clear scientific strategies and guidance for urban administration to prevent the surge runoff under different return periods. This study indicated that nearly half of the areas in Beijing can tackle with the excessive runoff like 2-year return period or more frequent rainfall, if all the PGRs are greened. During relatively frequent rainstorms, the overladen runoff can be prevented by retrofitting 50% PGRs in the catchments located in Xicheng district, inner parts of Haidian district and the northern parts of Chaoyang district. However, at heavier rainfall event of 20-year return period, only 100% greening can make a noticeable reduction effect in those catchments. Public buildings (e.g., universities, governmental departments) and commercial buildings are densely distributed in these areas, implying higher flooding risk losses (Yao et al., 2015), which exactly show good potential for roof greening. So they are the right zones for urban policy makers to make flexible exploration to control excessive runoff under rainstorms of both low and high frequency. Those areas should be paid high attention in drawing up roof greening strategies. In addition, catchments within the southern Chaoyang district, the outer areas of Fengtai and Daxing district reduce negligible runoff even with a full retrofitting. And they are of less exploration potential.

In this study, it can be carefully inferred that green roofs can play a very positive role in the flooding mitigation at a heavy rainstorm, based on the assumption that every pieces of the PGRs are related to the flooding in the corresponding catchment. However, it is worth noting that green roofs show marginal runoff reduction effect (less than 10%) in the southern city where flooding are more serious. In 7.21 Rainstorm, severe flooding sites were all in the south city, where lie the seven flooding sites that storage volume by green roofs cannot offset flood water volume with a 20% green roof retrofitting scenario. So the role of green roofs cannot be overemphasized in relieving flooding in Beijing. PGRs resources, which are helpful to mitigate flooding, fail to match spatially to the severe flooding areas, which should be paid high attention by the urban planners in the future.

Additionally, the generalization of green roofs is of great significance for increasing green open spaces within Beijing. By 2015, the existing green roofs in Beijing only account for 1% of the total roofs. According to this research, retrofitting all the PGRs means that 27% of the impervious surface will be transformed into green roofs, after which the urban green rate could reach 43.7% in the study area. And this will alleviate the contradiction between the limited green spaces and the high density people in Beijing.

5. Conclusions

The study of hydrological behaviour of green roofs in city scale may provide an alternative to alleviate the urban flooding. It is also the prerequisite for city administrators to formulate a holistic approach of city's ecological planning. However, few studies have examined the hydrological impacts of green roofs in an entire city range in spite of its significance.

In this study, PGRs were extracted in a metropolis through GIS and remote sensing, from which three greening scenarios were established to investigate the hydrological behaviour of extensive green roofs. A SCS-CN hydrological model was adopted to evaluate the runoff reduction effect of green roofs under four synthetic rainfall conditions, as well as the flooding mitigation effect at a historical rainstorm event. Three conclusions can be addressed as follows.

Firstly, The 131.92 km^2 area of PGRs, accounting for 19.6% of the total area, indicates a strong roof-greening potential within the fifth ring road of Beijing. Spatial explicit analysis reveals an unequal distribution of PGRs across the seven districts within the study area. Secondly, the spreading of green roofs could play a key role in runoff reduction function in Beijing, and the most effective catchments are located in the northern Beijing within Xicheng district, the inner parts of Haidian district and the inner parts of Chaoyang district. Those effective areas can reduce runoff by more than 10% at the rainfall event of 20-year return period when all PGRs are greened. By retrofitting 50% of the PGRs in those catchments, there would be noticeable runoff reduction at the rainfall event of 2-year return period. Thirdly, the roof greening can have a significant effect on mitigating the flooding of underpasses in the case of the 7.21 Rainstorm in Beijing. If only 20% PGRs had been retrofitted, 13 of 20 flooding would have not happened in that event. But the resources of PGRs do not match well to the severe flooding sites spatially, which should be concerned by the municipal planners.

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Fig.1 Location and land cover types of the study area.

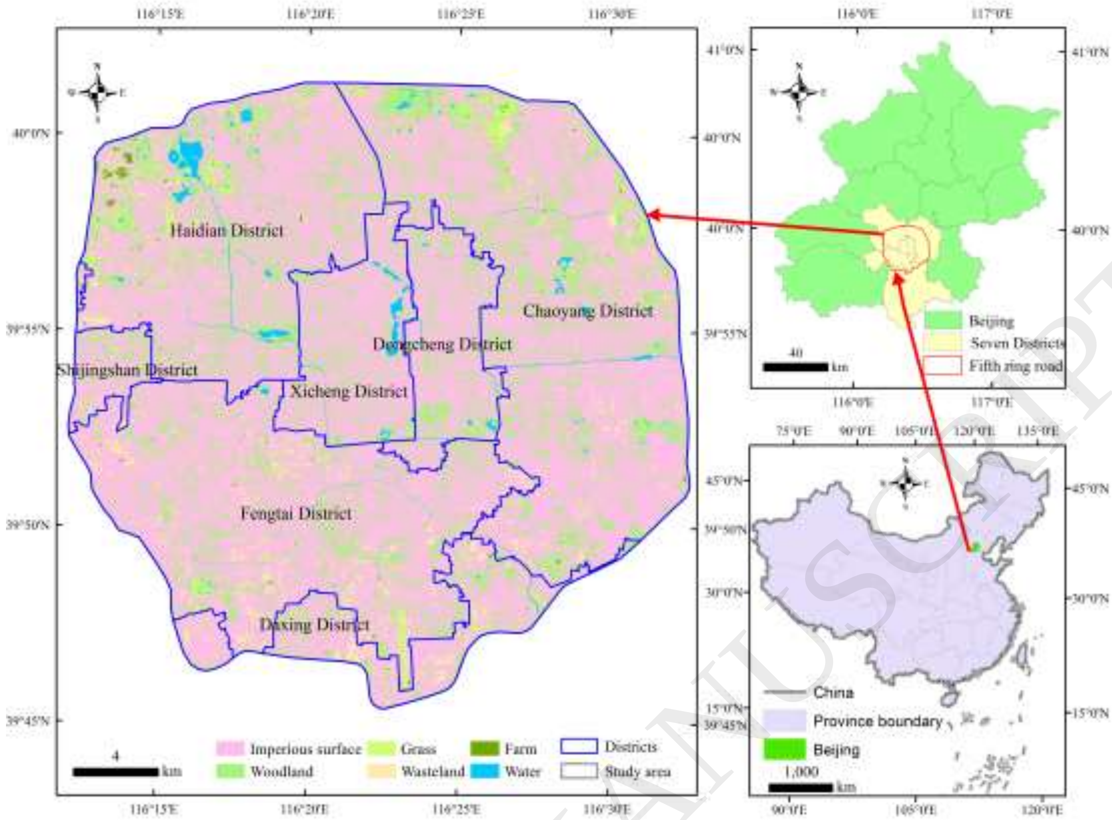


Fig.2 Flowchart of the study.

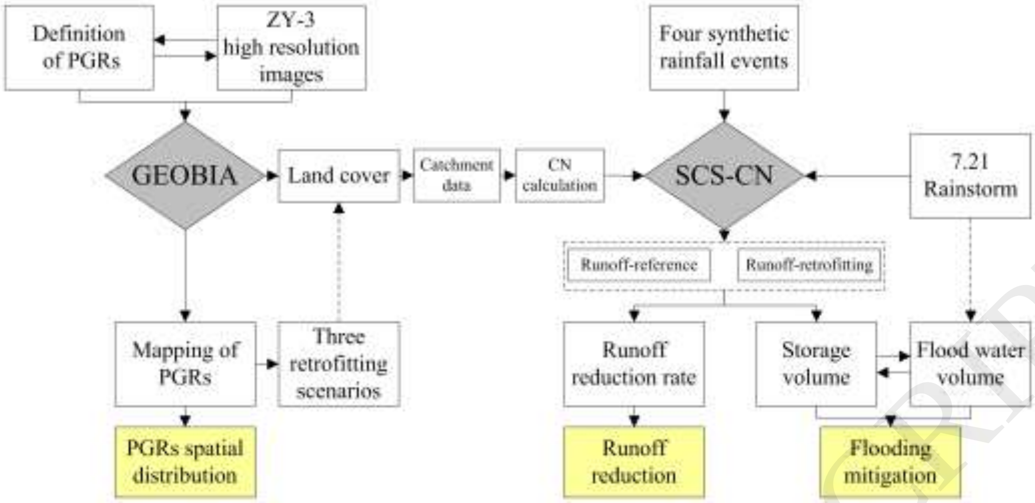
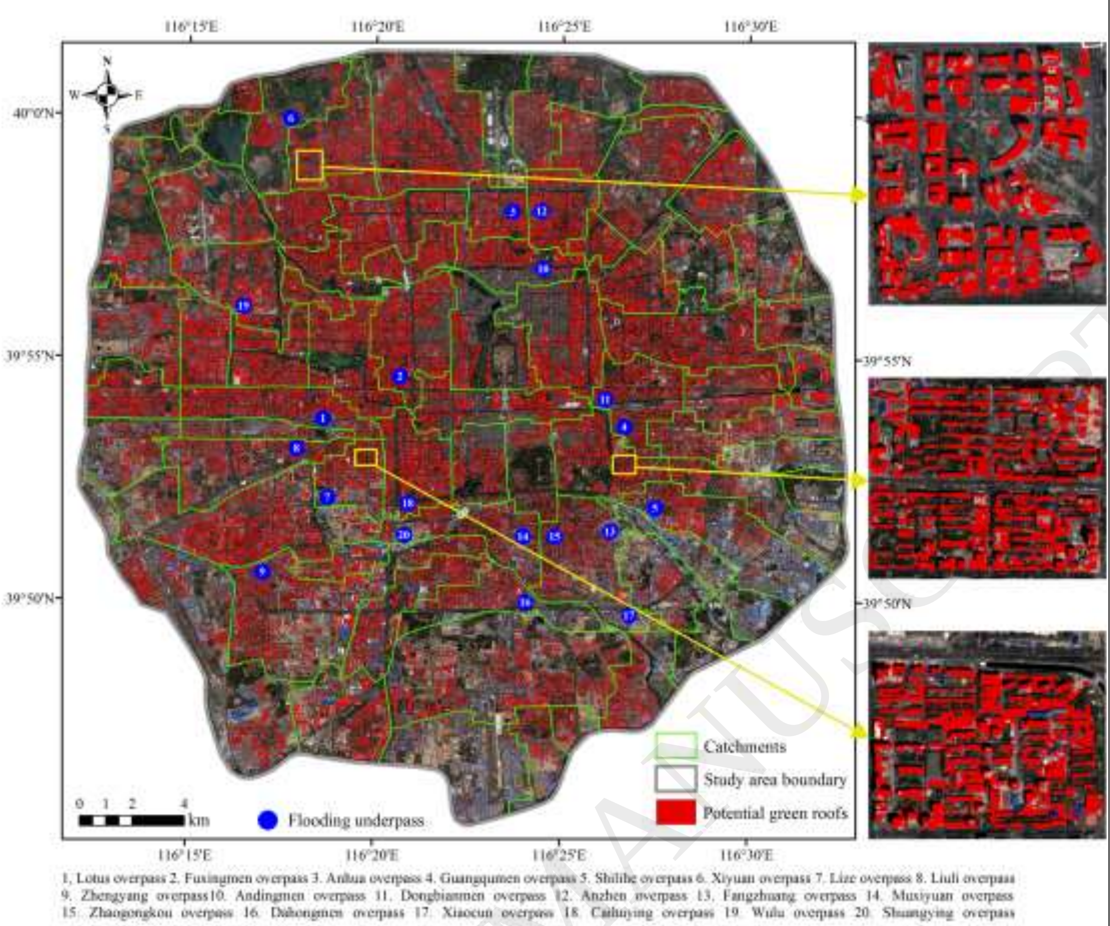


Fig.3 Spatial distribution of PGRs, catchments and flooding underpasses during the 7.21 Rainstorm.



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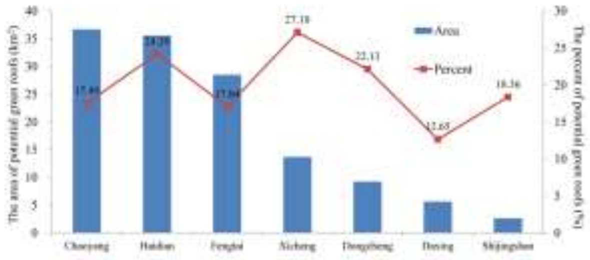

Fig.5 Runoff reduction rate under the 100% green roofs retrofitting scenario and four synthetic rainfall events a), b), c), d) represents T=2, 5, 10, and 20 years respectively.

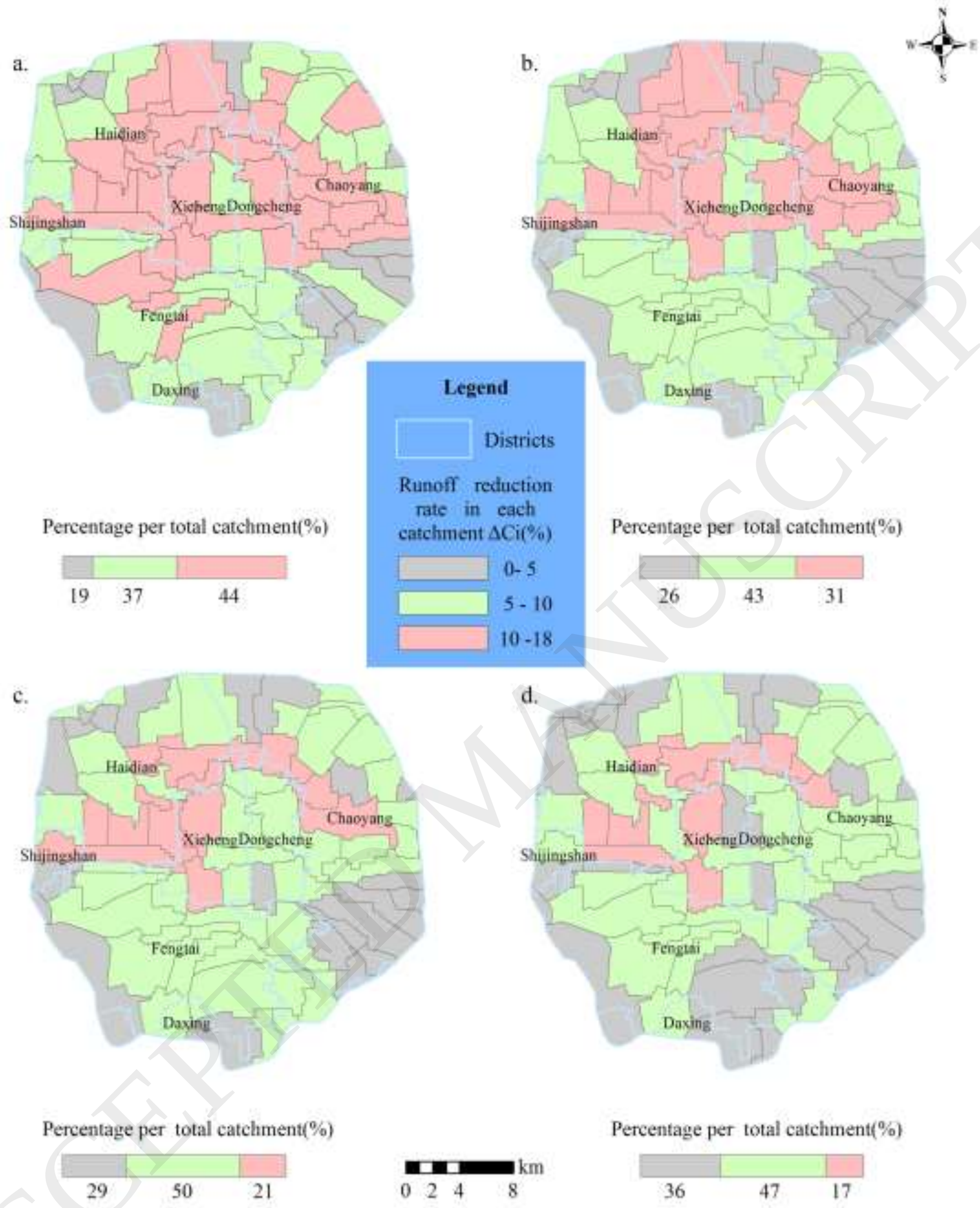

Fig.6 Runoff reduction rate by three retrofitting scenarios of green roofs within each catchment at the synthetic rainfall event with return period T=2 years.

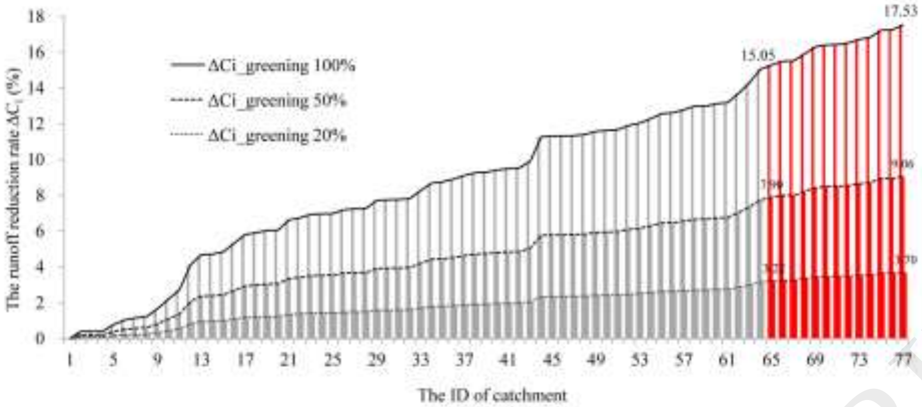

Table 1 Greening suitability of different type's buildings in Beijing.

Category	**Types/functions**	**Features**			**Potential for greening**
		Structure of roofs	Ages of buildings	Other characteristics	
Public buildings	Governments, schools and hospitals	Concrete	New	More flat, height less than 30m	Yes
Commercial buildings	Malls, commercial offices and hotels	Concrete	New	Flat and sloped roofs, high height of the buildings, complex shapes	Yes
Residential	Type 1	Concrete	New	More sloped, buildings vary in height	Yes
	Type 2	Brick and tiles	Old	Sloped, very low height of buildings	No
Industrial buildings	Storages	Truss structure	New	Curved roofs, relatively low height	No
		Concrete	New	Flat, low height	Yes
	Temporary buildings	Steel-framed	New	-	No
Cultural and recreational buildings	Museums and stadiums	Truss structure	New	Curved roofs	No
		Concrete	New	Flat or sloped	Yes
	Ancient architecture	Timber-framed	Very old	-	No

Table 2 Retention characteristics of green roofs in Beijing in relation to rainfall conditions of the published experimental data.

Source	Roof area (m^2)	Roof slope (^{0})	Depth of substrate (mm)	Rainfall (mm)	Antecedent dry period (h) /Soil moisture (%)	Retention rate (%)
Yang, et al. (2015)	120	3	150	190.4	21.30**	17.1
	120	3	150	69.4	26.00**	23.5
	120	3	150	53.4	18.60**	90.1
	120	3	150	52.9	27.50**	30.6
	120	3	150	26.9	24.90**	57.2
	120	3	150	10.5	26.10**	99.1
Sun, et al. (2012)	100	5	100	45.4	5.1*	51.8
	100	5	100	84.8	98.7*	74.6
	100	5	100	12.4	27.3*	77.4
	100	5	100	16.8	224.3*	86.9
	100	5	100	18.4	75.5*	83.7
	100	5	100	17.6	288.6*	80.7
	100	5	100	16	71.7*	77.5
	100	5	100	6.8	7.4*	76.5
Tang, et al. (2011)	1	1	100	59.8	-	26.9
	1	1	150	70.1	-	39.9
	1	1	200	65	-	40

* represents antecedent dry period, ** represents soil moisture.

Table3 Area of different land cover types and their corresponding CN values (including PGRs).

Land cover types	Area (km^2)	Percentage (%)	CN
PGRs	131.92	19.6%	89
Other imperious	357.32	53.0%	98
Woodland	135.31	20.0%	58
Grass	27.96	4.1%	61
Farmland	1.25	0.2%	78
Wasteland	13.65	2.0%	86
Water	7.48	1.1%	100

Table 4 Potential mitigation capacities for the 20 flooding underpasses contributed by the PGRs during the 7.21 Rainstorm.

Flooding underpasses	Water depth (m)	Potential green roofs area (km^2)	Drainage areas of underpasses (km^2)	100% Storage volume ΔV_i (10,000 m^3)	100% Storage volume/ Flood water volume	50% Storage volume/ Flood water volume	20% Storage volume/ Flood water volume
Lotus	2.5	3.10	9.34	8.52	1.81	0.90	0.36
Shuangying	2.5	0.84	3.52	2.31	0.49	0.24	0.10
Guangqumen	2	2.35	10.11	6.47	1.92	0.96	0.38
Xiaocun	2	0.51	5.38	1.41	0.42	0.21	0.08
Shilihe	2	1.86	14.86	5.10	1.51	0.76	0.30
Fangzhuang	0.8	0.93	5.06	2.56	3.00	1.50	0.60
Anhua	0.75	1.59	4.83	4.37	5.64	2.82	1.13
Wulu	0.7	2.77	11.28	7.60	10.88	5.44	2.18
Muxiyuan	0.6	1.96	9.89	5.38	9.70	4.85	1.94
Fuxingmen	0.6	3.87	11.90	10.64	19.20	9.60	3.84
Zhaogongkou	0.6	0.82	3.69	2.25	4.07	2.03	0.81
Dahongmen	0.5	1.36	9.15	3.73	8.85	4.43	1.77
Liuli	0.5	2.16	11.27	5.94	14.09	7.04	2.82
Zhengyang	0.5	3.35	13.31	9.20	21.83	10.91	4.37
Caihuying	0.5	2.89	8.81	7.93	18.80	9.40	3.76
Dongbianmen	0.5	2.50	9.36	6.86	16.27	8.14	3.25
Anzhen	0.3	2.47	7.09	6.78	34.59	17.29	6.92
Andingmen	0.3	1.86	7.71	5.11	26.08	13.04	5.22
Lize	0.3	2.16	9.92	5.92	30.22	15.11	6.04
Xiyuan	0.1	0.94	9.45	2.57	68.14	34.07	13.63