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RESEARCH ARTICLE

Field simulation of urban surfaces runoff and estimation of runoff with experimental curve numbers

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ABSTRACT
In this study, runoff responses of typical urban surfaces were investigated by scale models under artificial rainfall simulation, and the Soil Conservation Service (SCS) model was used to assess the impacts of land use changes and green infrastructures implementation on surface runoff of Beijing urban areas. The results showed that: Runoff coefficient of the impervious surface was about 2.1 times than that of the grassland. Time to runoff of the grassland was about 22.0 times that of the impervious surface. The concaved grassland, compared with the impervious surface, can significantly delay by 6.2 minutes the time to runoff, while the porous pavement significantly reduces 28.1% of the runoff coefficient. The runoff coefficient of Beijing urban areas increased from 0.68 in 2002 to 0.72 in 2012, due to the substantially increased impervious surfaces. The runoff coefficient decreased by 2.7%, 15.3% and 22.2% respectively under three green infrastructure scenarios.

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Curve number; green infrastructure; land use changes; runoff responses; scale model; urban surfaces

1. Introduction

Urbanization brings with it a range of environmental challenges for both the local and regional environment as a direct result of the biochemical and physical changes to hydrological systems (Alberti 2008; Fletcher, Andrieu, and Hamel 2013; Grimm et al. 2008; Jacobson 2011; Kuang et al. 2013; Pickett et al. 2011; Shuster et al. 2005). Urban development involves the replacement of vegetated soils with impermeable surfaces, and the introduction of artificial drainage replaces the natural pathway (Miller et al. 2014). This shift is also believed to reduce a landscape's capacity to control floodwaters because paved surfaces (such as roads and parking lots) create large expanses of impervious ground (Gilroy and McCuen 2012; Solín, Feranec, and Nováček 2011). An increased proportion of impervious surfaces is generally believed to foster considerable effects on the runoff generation by altering the hydrological response of an area (Fletcher, Andrieu, and Hamel 2013; Huang et al. 2008; Stone 2004). Recently, the increase in summer flood risk in an urban environment is a major concern in many metropolis of the world (Pitt 2008; Wheater and Evans 2009). Also in China, rapid urbanization has particularly increased urban flood risks and caused serious urban flooding losses (Chen et al. 2015). For example, several highly urbanized areas in China, such as Beijing (Gu et al. 2013; Li 2012) and Shanghai (Quan et al. 2010), have become increasingly prone to flooding in recent years as a result of short-term heavy rains.

While altered urban hydrology is a known result of urbanization, impacts of land use changes on urban hydrological processes are not well understood (Shuster et al. 2005). Many studies have reported that urbanization increases stormwater runoff volume, flow rates and peak flows and decreases flow time and low flows (Cheng and Wang 2002; Dietz and Clausen 2008; Guan, Sillanpää, and Koivusalo 2016; Jang et al. 2007; Sillanpää and Koivusalo 2015). The rainfall-runoff mechanisms of urban surfaces is importance for predicting the flood potential, designing urban drainage systems, and for developing flood control and management systems. However, the complexity of urban land use and cover makes it difficult to monitor the urban surface runoff (Jacobson 2011). In practice, water resources planning guidelines necessitate the use of simple methods for estimating runoff volumes and peak flows from different urban surfaces.

A limited number of studies have specifically investigated the hydrological processes of common urban surfaces based on field observations (Redfern et al. 2016). For investigating the process dynamics of surface hydrology, small-scale portable rainfall simulators are an essential research tool (Iserloh et al. 2013). Due to the field convenience and data reliability of this method, it has been used extensively in surface hydrology research by many scholars. Impervious surfaces (*e.g.*, roofs and roads) convert a large proportion of rainfall into runoff, and the performance is highly variable between different surface materials and condition (Farreny et al. 2011; Ragab et al. 2003; Pandit and Heck 2009). Typically urban green spaces are perceived as pervious surfaces or modelled with similar characteristics to more natural vegetated areas (Gregory et al. 2006). However, increased complexity of vegetation type, the properties of the litter layer, surface condition, age and management regimes are all found to influence physical soil properties and infiltration capacity in urban park areas or residential lawns (Ossola, Hahs, and Livesley 2015; Woltemade 2010).

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Much of the available evidence on the long-term hydrological effects of urbanization has been obtained through the application of hydrological models (Fletcher, Andrieu, and Hamel 2013). Thus, distributed hydrological models such as the Stormwater Management Model (SWMM), Soil and Water Assessment Tool (SWAT), Soil Conservation Service Curve Number (SCS-CN), Hydrologic Engineering Center, Hydrologic Modeling System (HEC-HMS), Long-Term Hydrologic Impact Assessment (L-THIA) and CITY-green have been extensively used to assess the effects of land use changes on hydrologic processes (Choi and Deal 2008; Chu et al. 2010; Franczyk and Chang 2009; Li and Wang 2009; Rose and Peters 2001; Zoppou 2001). The above-mentioned models mainly includes physically based models and empirical models. The physically based models include the principles of physical processes, such as the SWAT model, are required a large number of parameters describing the physical characteristics of the catchment for their calibrations. The empirical models, such as the SWMM model, are observation oriented models which take only the information from the existing data without considering the features and processes of the hydrological system (Devia, Ganasri, and Dwarakish 2015). For instance, existing regulations often demand hydrologic calculations to be performed using the SCS-CN method (NRCS 2009) or by utilizing the runoff coefficient of the rational method. Therefore, several researchers have studied the empirical relationships for estimating runoff volumes and peak flows based on curve number and runoff coefficient (El-Hames 2012; Kadam et al. 2012; Singh et al. 2013; Yao et al. 2015; Zhang, Li, and Wang 2015). Some studies also have estimated the CN values based on field experiments in test beds with artificial rainfall (Edwards 2017; Elhakeem and Papanicolaou 2009; Soulis et al. 2017).

The importance of understanding and managing the hydrological behaviour of urban surfaces will increase as projected changes in extreme precipitation events (Murphy et al. 2009), combined with further urban development and expanding urban surface cover will likely present greater challenges to flood and water management over coming decades (Stocker et al. 2014). A detailed evidence-based description of hydrological processes occurring on urban surfaces will be informing future modelling and flood risk management research and policies (Redfern et al. 2016). Moreover, no universally accepted characterization of urban surfaces for inclusion in hydrological models exists leading to a large number of hydrological models, with a high degree of variability in the representation of hydrological processes in urban areas (Beighley, Kargar, and He 2009; Salvadore, Bronders, and Batelaan 2015; Yao et al. 2016). However, little research has provided detailed assessments of the hydrological properties of urban surfaces, there is currently no thorough understanding of hydrological processes occurring on extant urban surface types (Ferreira et al. 2012; Lane, Croke, and Dignan 2004; Sarkar, Dutta, and Dubey 2015; Schmocker-Fackel, Naef, and Scherrer 2007).

In this study, the field simulation experiment of urban runoff was based on scale models of urban surfaces and artificial rainfall simulation, the evidence extracted from field observations given a more accurate description of existing urban hydrological processes on extant urban surfaces. Then, the experimental rainfall-runoff data was used to calibrate the SCS model and estimate the averaged CN values of different urban surfaces. The estimated CN values derived from field observations data were used to assess the impacts of land use changes and green infrastructure (i.e. porous brick pavement and concaved grassland) implementation on surface runoff of Beijing urban areas. These results are potentially helpful in better understanding of the linkages between urban surfaces and hydrological behavior and the flood mitigation effect of green infrastructures implementation on urban areas, and will improve the representation of diverse urban landscapes within hydrological models.

2. Materials and methods

2.1. *Experimental setup and data acquisition*

The artificial rainfall simulation experiment was designed and conducted at the Proving Ground for Highway and Traffic, Ministry of Communications in the suburbs of Beijing (N39° 44′39″, E116°39′12″). Five scale models of impervious surface, grassland, bare land, porous brick pavement and concaved grassland were designed and constructed as the experimental runoff plots (Figure 1). Each scale model designed a standard

Figure 1. Scale models of urban surfaces.

Note: 'a' to 'f' represents the schematic diagram of scale models, the impervious surface, grassland, bare land, porous pavement, concaved grassland, respectively.)

size with 1.5 m × 1.5 m × 0.4 m and covered by 2.25 m^2 (except the porous pavement surface had a height of 0.5 m), and the entire runoff plot was surrounded by a steel plate. For facilitating the collection of surface runoff, a marked steel V-flume was created at the outlet of each runoff plot. A soil cushion layer of 30 cm thick was padded with sandy loam soil in the inner section of each runoff plot. During the soil padding process, the soil was watered several times until the soil infiltration had saturated and compacted over a period of time. After this, three typical urban surfaces and two green infrastructure surfaces were constructed on the soil cushion layers.

The impervious surface was paved with a 10-cm thick cement surface. The grassland was planted with grass (Tall fescue, *Festuca elata Keng ex E. Alexeev*) on the soil, and the average plant height was about 3–5 cm during the experimental phase. The bare land without any measures, retaining a 30 cm thick soil cushion layer without vegetation. The concaved grassland was constructed as the upper part with the cemented surface (occupying a plot area of 70%), while the lower part (30%) was designed as the grassland with a concaved depth of 5 cm. Porous brick pavement had a 5 cm fine gravel layer between the 5 cm thick porous brick layer and the soil cushion layer. After the construction of the scale models had finished, they were positioned on the outside flat ground. The back of the runoff plot was elevated by bricks to facilitate the collection of surface runoff, and with an averaged slope gradient of about 6%.

Rainfall simulation is a very effective technique for modelling rainfall runoff, making it possible to control the temporal characteristics of precipitation (Chakravarti and Jain 2014). In this study, an artificial rainfall simulator was applied via a Norton ladder-type rainfall simulator set 2.5 m above the scale models. Spraying systems employing Veejet 80100 nozzles with 41 kPa water pressure are spaced 1.1 m apart and computer oscillated across the plot to generate a constant rainfall intensity. Specifically, the median volume of rain-drop size obtained by this simulator was 2.2 mm, and the uniformity coefficient of rainfall reached more than 0.8. Rainfall intensity controller was set to acquire different rainfall intensity events. The rainfall simulation experiments were conducting on windless days in the field. The simulated rainfall experiment was set up for three repetitions of each scale model under three intensities of rainfall. For each repetition, the rainfall intensity was constant, and the rainfall duration was varied according to their time to runoff and saturate time of runoff generation. We used a second counter to record the time simulated rainfall began and the time runoff was yielded in the experiment. During each experiment, the surface runoff was collected at 1-minute intervals and quantified by a graduated cylinder. Surface runoff of each rain event was uniformly monitored within 30 minutes after runoff was first yielded. Rainfall depth and durations were measured and recorded by HOBO RG3 data logging rain gauge with a 0.1 mm per trip.

2.2. *Data analysis and simulation*

On the basis of the monitored rainfall and runoff data, selected hydrological indicators including rainfall intensity, time to runoff, accumulated runoff depth, peak flow and runoff coefficient were calculated and utilized for further analysis. Descriptive statistical analysis was undertaken to detect the general features of the simulated rainfall and related runoff characteristics.

The SCS-CN method, determined by a combination of land use and hydrologic soil group, was developed from observed data by the United States Department of Agriculture, Soil Conservation Service and is widely used for simulating runoff and streamflow (USDA 1985). Theoretically, the SCS-CN method is based on a water balance hypothesis that the ratio of actual retention in a watershed to the potential maximum retention is equal to the ratio of actual direct runoff to the potential maximum runoff (Chin 2017; USDA 1985). Direct surface runoff from the SCS-CN method is expressed by:

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

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

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

where Q is the runoff depth (mm), P the rainfall depth (mm), I_a the initial abstraction of the rainfall (mm), and S represents potential maximum soil water capacity (mm). The initial abstraction coefficient λ is a constant, usually defined as 0.2 (El-Hames 2012; Kadam et al. 2012; Singh et al. 2013), and CN is a dimensionless parameter, ranging from 0 to 100. A higher CN value indicates greater potential for surface runoff as well as reduced infiltration and less surface storage of rainwater. As the above equations illustrate, calculation of surface runoff in this model requires only rainfall data and CN values. The potential maximum soil water capacity S and CN were back-calculated as follows:

$$S = 5\left[P + 2Q - \left(4Q^2 + 5PQ\right)^{1/2}\right] \quad (4)$$

$$CN = \frac{25400}{254 + S} - 245 \quad (5)$$

The model performance was evaluated by the coefficient of determination (R^2). The R^2 value is an indicator of the strength of the relationship between the observed and simulated values. A satisfactory model performance normally meets the criteria that R^2 is greater than 0.6 (Moriasi et al. 2007).

3. Results and discussions

3.1. *Runoff responses of different urban surfaces*

In August and September 2014, 45 rainfall events with three rainfall intensities were simulated to investigate the runoff processes for different urban surfaces. The simulated rainfall characteristics were summarized in Table 1. The rainfall events were recorded with a mean intensity of 0.33 mm/minute, 0.49 mm/minute and 0.65 mm/minute, under three rainfall intensities. Recorded rainfall had a mean amount of 23.1 mm, 31.0 mm and 37.4 mm, respectively, and the

Table 1. The simulated rainfall characteristics.

Rain characteristics	Maximum	Minimum	Mean	S.D.
Rainfall (mm)	73.60	14.90	30.47	11.67
Rain duration (minutes)	76.83	30.83	40.24	15.19
Rain intensity (mm/minute)	0.86	0.28	0.54	0.17
Recurrence period (year)	4.8	0.2	0.5	3.05

duration ranged from 30.8 minutes to 76.8 minutes. The return period of simulated rains ranged from 0.2 to 4.8 year. According to the local rainfall patterns, these simulated rain events are defined as heavy intensity rains, and can lead to a significant surface runoff generation in most cases. Antecedent soil moisture of grassland, bare land and concaved grassland under three rainfall intensities are shown in Table 2. The antecedent soil moisture was found to be an increasing order following: bare land < grassland < concaved grassland, and ranged from 33% to 68.39%.

The runoff responses varied significantly among different surfaces. A cumulative runoff process of grassland under a constant rainfall intensity of 0.58 mm/minute is shown in Figure 2. The time to runoff was found to be in an increasing order following: impervious surface < bare land < porous pavement < concaved grassland < grassland (Figure 3(a)). The impervious surface has the smallest mean time to runoff, indicating a fastest runoff generation. This is due to the cemented surface hindering the runoff infiltration process, thus the rainfall reaching the impervious ground almost completely transferred into surface runoff. The average time to runoff of the grassland far exceeded the other surfaces, and was about 22.0 times that of the impervious surface. The bare land surface has the faster time to runoff, and the time to runoff was shortened with repeated rainfall experiments, it was mainly caused by surface soil sealing resulting from raindrop splash decreasing the rainfall infiltration (Nciizah and Wakindiki 2015). Compared with the impervious surface, the average time to runoff of the porous pavement and the concaved grassland was delayed about 0.5 and 6.2 minutes respectively. The concaved grassland retained rainwater from the impervious surface, indicating that it can effectively delay the time to runoff. However, the reduction effectiveness of the porous pavement on the time to runoff was found to be limited.

For the four surfaces considered in this work, the accumulated runoff depth and peak flow were both in the same decreasing order whereby: impervious surface > bare land > concaved grassland > grassland > porous pavement (Figure 3(b), Figure 3(c)). Runoff coefficient was found to be in a decreasing order such that: impervious surface > concaved grassland > porous pavement > bare land > grassland (Figure 3(d)). The average accumulated runoff depth, peak flow and runoff coefficient of the impervious surface was always higher than the other surfaces, especially the average runoff coefficient was about 2.1 times that of the grassland. This ascertained that the impervious surface

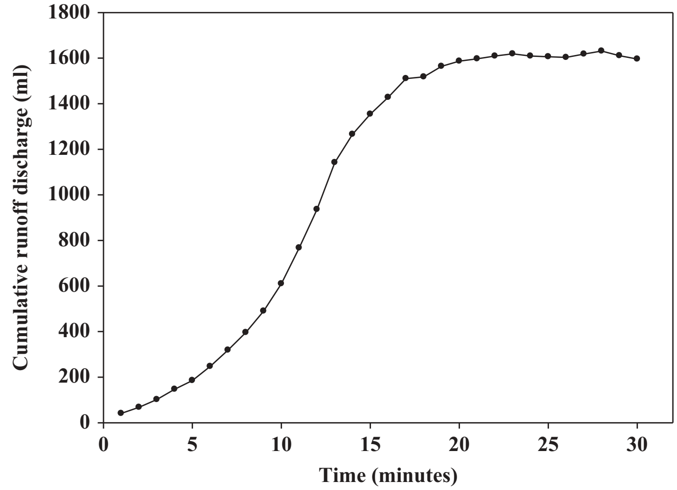

Figure 2. A cumulative runoff process of grassland.

exhibited a faster runoff generation and flow rate. The bare land has higher peak flow and runoff coefficient in this study compared with the grassland. Compared to the impervious surface, the average accumulated runoff depth, peak flow and runoff coefficient of the porous pavement reduced by 30.5%, 22.3% and 28.1%, respectively. The permeable pavement allowed the stormwater stored in the cushion layer to gradually infiltrate into soil strata beneath it. However, the runoff reduction effectiveness of the concaved grassland was lower than the porous pavement surface. In general, the observations evidenced the fact that the concaved grassland can effectively detain the runoff generation and the porous pavement significantly reduces the runoff discharge depth and peak flow rate, thus these green infrastructures can effectively mitigate urban flooding.

3.2. *Experimental curve numbers of urban surfaces*

We used the event rainfall and runoff depth of each scale model plot from the artificial rainfall experiment to back-calculate S (it represents potential maximum soil water capacity) and the correspondent experimental curve number by Equations (4) and (5) in Section 2.2. Next, we used the same data to calculate the averaged curve numbers. Overall, the averaged curve numbers for urban surfaces ranged from 81.8 to 97.2 (Table 3). The R^2 were all more than 0.85, indicating that the SCS model adequately estimates the surface runoff generation. Overall, all the CN values corresponded with their experimental runoff responses. For example, the highest CN values (97.2) were obtained for the impervious surface. The bare land has the second lowest CN values. In contrast, the lowest CN value, of 81.8, was achieved by the grassland area. Similarly, the CN values of porous pavement and concaved grassland were 90.7 and 88.6 respectively, indicating that the two green infrastructures can still provide measurable runoff mitigation potential

Table 2. Antecedent soil moisture of surfaces under three rainfall intensities.

Surfaces		Grassland			Bare land			Concaved grassland	
Antecedent soil moisture (%)	42.07	38.87	43.63	35.76	33.00	37.33	63.48	55.25	68.39

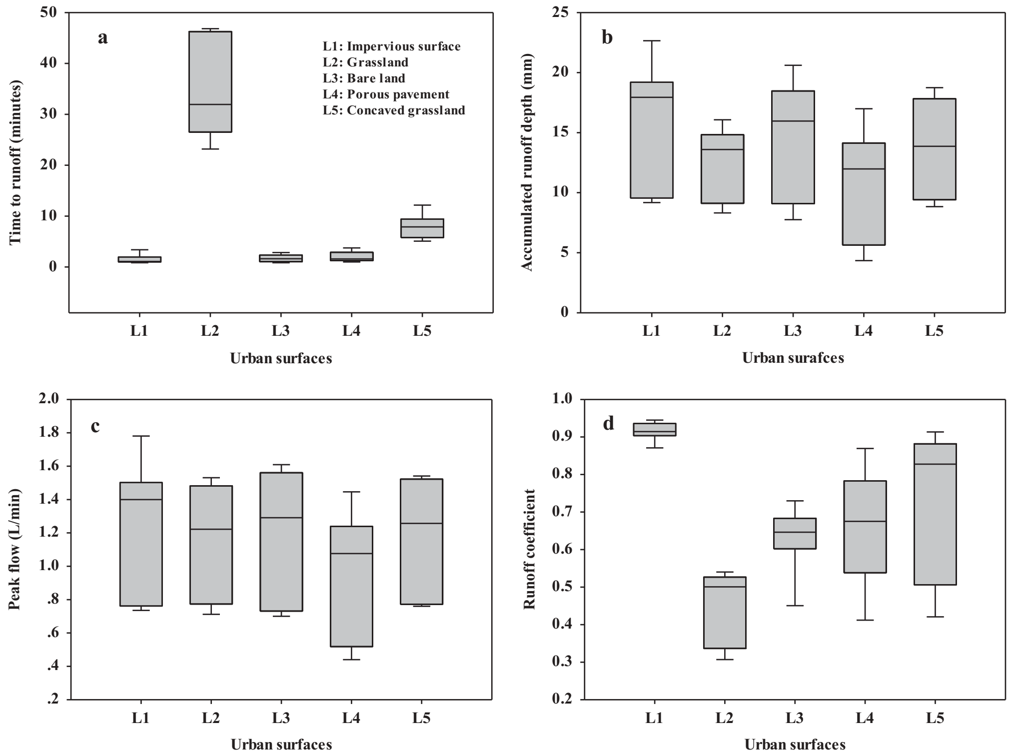

Figure 3. Runoff responses of urban surfaces. (a) time to runoff; (b) accumulated runoff depth; (c) peak flow; (d) runoff coefficient.
(Note: L1 represents the impervious surface, L2 represents grassland, L3 represents bare land, L4 represents porous pavement, L5 represents concaved grassland.)

Table 3. The averaged SCS-CN values for different urban surfaces.

Urban Surfaces	CN	R^2
Impervious surfaces	97.2[a]	0.90
Grassland areas	81.8[b]	0.94
Bare lands	94.1[a]	0.88
Concaved grassland	90.7[b]	0.85
Porous brick pavement	88.6[ab]	0.90

Note: CN values followed by the different letters are significantly different ($P < 0.05$) as determined by t-test followed by Tukey post-hoc test. R^2 denotes the coefficient of determination.

compared to a conventional impervious surface. Except the impervious surface with bare land and porous pavement, and the concaved grassland with porous pavement and grassland, there were statistically significant differences in CN values among the other surfaces (determined by One-way ANOVA followed by Tukey post-hoc test for multiple comparisons, $P < 0.05$, Table 3). However, except the impervious surface, the CN values of other surfaces were relatively high considering the high runoff reductions observed in the experimental rainfall events. This can be attributed to the relatively lower runoff reduction values observed for heavier rainfall depths in this study (Fassman-Beck et al. 2015).

As shown in Figure 4, the predicted total runoff depths exhibited a good linear fit (slope = 0.95, R^2 = 0.90) with the observed total runoff depths. Further, the obtained results substantiated that the model performance was adequate in all the rainfall events. Thus, the simplified relationship provides adequate predictions of the total runoff depth based on the maximum water holding capacity of the urban surfaces.

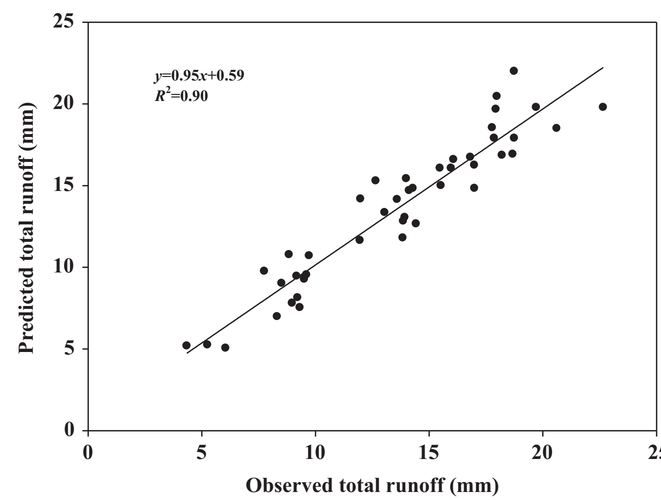

Figure 4. Observed total runoff depth plotted against predicted total runoff depth.

3.3. *Impacts of land use changes and green infrastructure implementation on urban runoff*

Urban landscape conversions inside the 5th Ring Road of Beijing were identified from 2002 to 2012 according to Sun and Chen (2017). Remote sensing images with high spatial resolution were used to identify landscape types in the Beijing urban areas. (1) QuickBird images were acquired on 5 July 2002 with four multi-spectral bands (2.44 m spatial resolution) and one panchromatic band (0.61 m). (2) IKONOS images were collected on 29 July 2012 with four multi-spectral bands (4 m)

Table 4. Changes in urban surface areas of Beijing from 2002 to 2012.

	Area (km^2)		
Urban surfaces	2002	2012	Changed
Impervious land	320.36	401	80.64
Forest land	122.89	147.96	25.07
Grassland	145.92	100.79	−45.13
Bare land	68.8	6.34	−62.64
Water	9.31	11.19	1.88

Source: (Sun and Chen 2017).

and one panchromatic band (1 m) (Sun and Chen 2017). As shown in Table 4, the total urban areas of the 5th Ring Road of Beijing were 667.28 km^2. Impervious lands occupied most of the area, followed by forest lands and grasslands. In 2012, the grasslands occupied 25.1% of impervious surfaces. From 2002 to 2012, the impervious land, forest land and water body areas increased by 80.64, 25.07 and 1.88 km^2, respectively. The largest gain was observed in impervious surfaces with a net increase of 80.64 km^2. The grassland area decreased by 45.12 km^2 and bare land decreased by 62.45 km^2, which was mainly replaced by impervious surfaces from 2002 to 2012.

The field monitored experiments were used to validate the SCS-CN model. The experiments were conducted in the Wangchunyuan residential community, which is located in the north of Chaoyang district, Beijing (40°02′36″N, 116° 24′54″E). The catchment area of the northern outlet of the community is 29,500 m^2 and the grassland area percentage accounts for 30.2%. The rainfall and stormwater runoff flows were measured by adding an ISCO 674 tipping bucket rain gauge (Teledyne ISCO, NB, USA) and an ISCO 750 area velocity module to the ISCO 6712 automatic sampler at the northern outlet from July to September in 2013. The averaged CN values of impervious surface and grassland used to calculate the predicted runoff volume. Finally, the determination coefficient R^2 of model validation reached 0.97 and 0.91 under two rain events with 62.2 mm and 26.5 mm, respectively.

The types and composition of urban surfaces and the rainfall determined the volume of rainwater runoff yields. The rainfall of Beijing urban areas was set to 592 mm according to the annual average rainfall. Using the averaged CN values, the annual runoff volume and runoff coefficient of Beijing urban areas was calculated. As shown in Figure 5, from 2002 to 2012, the annual runoff increased from 269.3 million m^3 to 284.5 million m^3, an increase of 5.6%. With the impervious surface increase under the urbanization effect in the ten years, the percentage of impervious runoff accounting for annual runoff changed from 64.6% to 76.5%. Simultaneously, the contribution percentage of the pervious surface (i.e. forest land, grassland and bare land) runoff to annual runoff decreased from 25.8% to 22.6%. The runoff coefficient of Beijing urban areas in 2002 was 0.68, whereas that increased to 0.72 in 2012 due to the rapid urbanization progress in this period substantially increasing impervious surfaces and decreasing pervious surfaces in urban areas.

The effective urban flooding mitigation of porous pavement and concaved grassland was investigated in this experiment, thus three green infrastructure scenarios

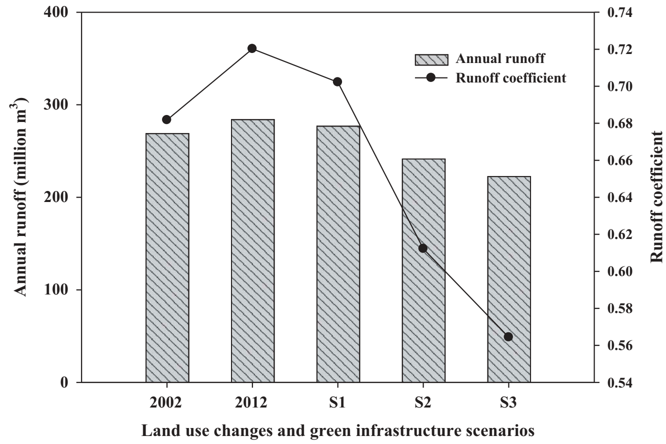

Figure 5. Annual runoff and runoff coefficient of Beijing urban areas under different land use changes and green infrastructure implementation scenarios. (Note: Scenario 1: 50% grasslands were changed to concave, Scenario 2: 25% paving grounds were changed to porous pavement, Scenario 3: integrated S1 and S2.)

were designed to assess the annual runoff volume and runoff coefficient changes in Beijing urban areas under green infrastructure implementation. Under Scenario 1 (50% of grassland was changed to concave), the annual runoff was reduced to 277.4 million m^3, and the runoff coefficient decreased to 0.70 (Figure 5). For Scenario 2 (25% paving grounds was changed to porous brick pavement), the annual runoff was reduced by 15.0%, and the runoff coefficient was 0.61. Under Scenario 3 (integrating Scenario 1 and Scenario 2, i.e. 50% grassland area was changed to concave, and 25% paving grounds was changed to porous pavement), the runoff reduction effectiveness was significantly increased to 21.6%, and the runoff coefficient decreased to 0.56. The runoff coefficient decreased by 2.7%, 15.3% and 22.2% respectively under three green infrastructure scenarios, indicating the greater runoff reduction effectiveness of green infrastructures, especially for integrated measures.

4. Conclusions

Understanding the rainfall-runoff behaviour of urban land surfaces is an important scientific and practical issue, as stormwater management policies increasingly aim to manage flood risk at local scales within urban areas. The main aims of this study were to examine the runoff responses of typical urban surfaces and the impacts of land use changes and green infrastructure implementation on urban runoff. Impervious surface showed the fastest generation of runoff, and exhibited a faster runoff flow rate. Grassland played an effective role in delaying the time to runoff, and recorded the smallest runoff coefficient. Due to the surface soil sealing effect, the bare land surface has a faster time to runoff, higher peak flow and lower runoff coefficient. Compared with the impervious area, concaved grassland can effectively delay the time to runoff while the porous pavement can significantly reduce the runoff discharge and peak flow rates, thus, effectively mitigating urban flooding. The averaged CN values were relatively higher in most surfaces, attributed to the very low runoff reduction values observed for heavier rainfall depths in this study. From 2002 to 2012, the rapid urbanization progress substantially increased the impervious surfaces and decreased pervious surfaces in urban areas, the runoff coefficient of Beijing urban areas increased from 0.68 to 0.72. The runoff coefficient of Beijing urban areas effectively decreased under three green infrastructure implementation scenarios, indicating the greater runoff reduction effectiveness of green infrastructures especially for integrated measures.

The coefficients of determination were all more than 0.85, and the predicted total runoff depths for all the rainfall events exhibited a good linear fit with the observed total runoff depths. Thus it substantiated that the SCS model performance was adequate. Therefore, use of the scale models by rainfall simulation and SCS-CN method for investigating and modelling is considered a valid time- and resource-efficient approach to research runoff responses of urban surfaces. However, there are some uncertainties associated with this approach. Runoff generated from green land areas will be underestimated if assigned with the same CN to the forest land and bare land. When using the averaged CN values derived from small scale experimental results to assess the impacts of land use changes on urban runoff at catchment scale, it may overestimate the runoff coefficient of urban areas. A physical-based distributed water-balance model validated by experimental urban runoff data would be appropriate for exploring the runoff responses of urban surfaces.

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References

Alberti, M., ed. 2008. *Advances in Urban Ecology: Integrating Humans and Ecological Processes in Urban Ecosystems*. New York: Springer.

Beighley, R. E., M. Kargar, and Y. He. 2009. “Effects of Impervious Area Estimation Methods on Simulated Peak Discharges.” *Journal of Hydrologic Engineering* 14 (4): 388–398. doi:10.1061/(ASCE)1084-0699(2009)14:4(388).

Chakravarti, A., and M. K. Jain. 2014. “Experimental Invesitigation and Modeling of Rainfall Runoff Process.” *Indian Journal of Science and Technology* 7 (12): 2096.

Chen, Y., H. Zhou, H. Zhang, G. Du, and J. Zhou. 2015. “Urban Flood Risk Warning under Rapid Urbanization.” *Environmental Research* 139: 3–10. doi:10.1016/j.envres.2015.02.028.

Cheng, S., and R. Wang. 2002. “An Approach for Evaluating the Hydrological Effects of Urbanization and Its Application.” *Hydrological Processes* 16 (7): 1403–1418. doi:10.1002/hyp.350.

Chin, D. A. 2017. “Estimating the Parameters of the Curve Number Model.” *Journal of Hydrologic Engineering* 22 (6): 06017001. doi:10.1061/(ASCE)HE.1943-5584.0001495.

Choi, W., and B. M. Deal. 2008. “Assessing Hydrological Impact of Potential Land Use Change through Hydrological and Land Use Change Modeling for the Kishwaukee River Basin (USA).” *Journal of Environmental Management* 88 (4): 1119–1130. doi:10.1016/j.jenvman.2007.06.001.

Chu, H. J., Y. P. Lin, C. W. Huang, C. Y. Hsu, and H. Y. Chen. 2010. “Modelling the hydrologic effects of dynamic land-use change using a distributed hydrologic model and a spatial land-use allocation model.” *Hydrological Processes* 24 (18): 2538–2554. doi: 10.1002/hyp.7667.

Devia, G. K., B. P. Ganasri, and G. S. Dwarakish. 2015. “A Review on Hydrological Models.” *Aquatic Procedia* 4: 1001–1007. doi:10.1016/j.aqpro.2015.02.126.

Dietz, M. E., and J. C. Clausen. 2008. “Stormwater Runoff and Export Changes with Development in a Traditional and Low Impact Subdivision.” *Journal of Environmental Management* 87 (4): 560–566. doi:10.1016/j.jenvman.2007.03.026.

Edwards, D. R. 2017. “Long-Term Spatio-Temporal Variation in Runoff Curve Number under Consistent Cover Conditions: A Southeastern US Case Study.” *Water Resources Management* 31 (11): 3491–3505. doi:10.1007/s11269-017-1680-z.

Elhakeem, M., and A. N. Papanicolaou. 2009. “Estimation of the Runoff Curve Number via Direct Rainfall Simulator Measurements in the State of Iowa, USA.” *Water Resources Management* 23 (12): 2455–2473. doi:10.1007/s11269-008-9390-1.

El-Hames, A. S. 2012. “An Empirical Method for Peak Discharge Prediction in Ungauged Arid and Semi-Arid Region Catchments Based on Morphological Parameters and SCS Curve Number.” *Journal of Hydrology* 456–457: 94–100. doi:10.1016/j.jhydrol.2012.06.016.

Farreny, R., T. Morales-Pinzon, A. Guisasola, C. Taya, J. Rieradevall, and X. Gabarrell. 2011. “Roof Selection for Rainwater Harvesting: Quantity and Quality Assessments in Spain.” *Water Research* 45 (10): 3245–3254. doi:10.1016/j.watres.2011.03.036.

Fassman-Beck, E., W. Hunt, R. Berghage, D. Carpenter, T. Kurtz, V. Stovin, and B. Wadzuk. 2015. “Curve Number and Runoff Coefficients for Extensive Living Roofs.” *Journal of Hydrologic Engineering* 21 (3): 04015073. doi:10.1061/(ASCE)HE.1943-5584.0001318.

Ferreira, C. S. S., A. J. D. Ferreira, R. L. Pato, M. D. C. Magalhăes, C. D. O. Coelho, and C. Santos. 2012. “Rainfall-Runoff-Erosion Relationships Study for Different Land Uses, in a Sub-Urban Area.” *Zeitschrift Für Geomorphologie, Supplementary Issues* 56 (3): 5–20. doi:10.1127/0372-8854/2012/S-00101.

Fletcher, T. D., H. Andrieu, and P. Hamel. 2013. “Understanding, Management and Modelling of Urban Hydrology and Its Consequences for Receiving Waters: A State of the Art.” *Advances in Water Resources* 51: 261–279. doi:10.1016/j.advwatres.2012.09.001.

Franczyk, J., and H. Chang. 2009. “The Effects of Climate Change and Urbanization on the Runoff of the Rock Creek Basin in the Portland

Metropolitan Area, Oregon, USA." *Hydrological Processes* 23 (6): 805–815. doi:10.1002/hyp.7176.

Gilroy, K. L., and R. H. McCuen. 2012. "A Nonstationary Flood Frequency Analysis Method to Adjust for Future Climate Change and Urbanization." *Journal of Hydrology* 414: 40–48. doi:10.1016/j.jhydrol.2011.10.009.

Gregory, J. H., M. D. Dukes, P. H. Jones, and G. L. Miller. 2006. "Effect of Urban Soil Compaction on Infiltration Rate." *Journal of Soil and Water Conservation* 61 (3): 117–124.

Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs. 2008. "Global Change and the Ecology of Cities." *Science* 319 (5864): 756–760. doi:10.1126/science.1150195.

Gu, X. T., N. Li, Y. Zhou, and J. D. Wu. 2013. "Thinking on Urban Waterlogging Disaster Defense Initiated by 7–21 Extraordinary Rainstorm in Beijing." *Journal of Natural Disasters* 2: 1–6. (in Chinese).

Guan, M., N. Sillanpää, and H. Koivusalo. 2016. "Storm Runoff Response to Rainfall Pattern, Magnitude and Urbanization in a Developing Urban Catchment." *Hydrological Processes* 30 (4): 543–557. doi:10.1002/hyp.10624.

Huang, H., S. Cheng, J. Wen, and J. Lee. 2008. "Effect of Growing Watershed Imperviousness on Hydrograph Parameters and Peak Discharge." *Hydrological Processes* 22 (13): 2075–2085. doi:10.1002/hyp.6807.

Iserloh, T., J. B. Ries, J. Arnáez, C. Boix-Fayos, V. Butzen, A. Cerdà, … J. A. Gómez. 2013. "European Small Portable Rainfall Simulators: A Comparison of Rainfall Characteristics." *Catena* 110: 100–112. doi:10.1016/j.catena.2013.05.013.

Jacobson, C. R. 2011. "Identification and Quantification of the Hydrological Impacts of Imperviousness in Urban Catchments: A Review." *Journal of Environmental Management* 92 (6): 1438–1448. doi:10.1016/j.jenvman.2011.01.018.

Jang, S., M. Cho, J. Yoon, Y. Yoon, S. Kim, G. Kim, L. Kim, and H. Aksoy. 2007. "Using SWMM as a Tool for Hydrologic Impact Assessment." *Desalination* 212 (1–3): 344–356. doi:10.1016/j.desal.2007.05.005.

Kadam, A. K., S. S. Kale, N. N. Pande, N. J. Pawar, and R. N. Sankhua. 2012. "Identifying Potential Rainwater Harvesting Sites of a Semi-Arid, Basaltic Region of Western India, Using SCS-CN Method." *Water Resources Management* 26 (9): 2537–2554. doi:10.1007/s11269-012-0031-3.

Kuang, W. H., J. Y. Liu, Z. X. Zhang, D. S. Lu, and B. Xiang. 2013. "Spatiotemporal Dynamics of Impervious Surface Areas across China during the Early 21st Century." *Chinese Science Bulletin* 58 (14): 1691–1701. doi:10.1007/s11434-012-5568-2.

Lane, P. N. J., J. C. Croke, and P. Dignan. 2004. "Runoff Generation from Logged and Burnt Convergent Hillslopes: Rainfall Simulation and Modelling." *Hydrological Processes* 18 (5): 879–892. doi:10.1002/hyp.1316.

Li, C. 2012. "Ecohydrology and Good Urban Design for Urban Storm Water-Logging in Beijing, China." *Ecohydrology & Hydrobiology* 12 (4): 287–300. doi:10.2478/v10104-012-0029-8.

Li, Y., and C. Wang. 2009. "Impacts of Urbanization on Surface Runoff of the Dardenne Creek Watershed, St. Charles County, Missouri." *Physical Geography* 30 (6): 556–573. doi:10.2747/0272-3646.30.6.556.

Miller, J. D., H. Kim, T. R. Kjeldsen, J. Packman, S. Grebby, and R. Dearden. 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. doi:10.1016/j.jhydrol.2014.04.011.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. "Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations." *Transactions of the ASABE* 50 (3): 885–900. doi:10.13031/2013.23153.

Murphy, J. M., D. M. Sexton, G. J. Jenkins, B. B. Booth, C. C. Brown, R. T., Clark, and S. J. Brown, eds. 2009. *UK Climate Projections Science Report: Climate Change Projections*. Exeter: Met Office Hadley Centre.

Nciizah, A. D., and I. I. C. Wakindiki. 2015. "Soil Sealing and Crusting Effects on Infiltration Rate: A Critical Review of Shortfalls in Prediction Models and Solutions." *Archives of Agronomy and Soil Science* 61 (9): 1211–1230. doi:10.1080/03650340.2014.998203.

NRCS (Natural Resources Conservation Service). 2009. "National Engineering Handbook." September 16. http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=22526.wba

Ossola, A., A. K. Hahs, and S. J. Livesley. 2015. "Habitat Complexity Influences Fine Scale Hydrological Processes and the Incidence of Stormwater Runoff in Managed Urban Ecosystems." *Journal of Environmental Management* 159: 1–10. doi:10.1016/j.jenvman.2015.05.002.

Pandit, A., and H. H. Heck. 2009. "Estimations of Soil Conservation Service Curve Numbers for Concrete and Asphalt." *Journal of Hydrologic Engineering* 14 (4): 335–345. doi:10.1061/(ASCE)1084-0699(2009)14:4(335).

Pickett, S. T. A., M. L. Cadenasso, J. Morgan Grove, C. G. Boone, P. M. Groffman, E. Irwin, S. S. Kaushal, V. Marshall, B. P. McGrath, and C. H. Nilon. 2011. "Urban Ecological Systems: Scientific Foundations and a Decade of Progress." *Journal of Environmental Management* 92 (3): 331–362. doi:10.1016/j.jenvman.2010.08.022.

Pitt, M. 2008. *The Pitt Review: Learning Lessons from the 2007 Floods*. London: Cabinet Office 20.

Quan, R.-S., M. Liu, M. Lu, L.-J. Zhang, J.-J. Wang, and S.-Y. Xu. 2010. "Waterlogging Risk Assessment Based on Land Use/Cover Change: A Case Study in Pudong New Area, Shanghai." *Environmental Earth Sciences* 61 (6): 1113–1121. doi:10.1007/s12665-009-0431-8.

Ragab, R., J. Bromley, P. Rosier, J. D. Cooper, and J. H. C. Gash. 2003. "Experimental Study of Water Fluxes in a Residential Area: 1. Rainfall, Roof Runoff and Evaporation: The Effect of Slope and Aspect." *Hydrological Processes* 17 (12): 2409–2422. doi:10.1002/hyp.1250.

Redfern, T. W., N. Macdonald, T. R. Kjeldsen, J. D. Miller, and N. Reynard. 2016. "Current Understanding of Hydrological Processes on Common Urban Surfaces." *Progress in Physical Geography* 40 (5): 699–713. doi:10.1177/0309133316652819.

Rose, S., and N. E. Peters. 2001. "Effects of Urbanization on Streamflow in the Atlanta Area (Georgia, USA): A Comparative Hydrological Approach." *Hydrological Processes* 15 (8): 1441–1457. doi:10.1002/hyp.218.

Salvadore, E., J. Bronders, and O. Batelaan. 2015. "Hydrological Modelling of Urbanized Catchments: A Review and Future Directions." *Journal of Hydrology* 529: 62–81. doi:10.1016/j.jhydrol.2015.06.028.

Sarkar, R., S. Dutta, and A. K. Dubey. 2015. "An Insight into the Runoff Generation Processes in Wet Sub-Tropics: Field Evidences from a Vegetated Hillslope Plot." *Catena* 128: 31–43. doi:10.1016/j.catena.2015.01.006.

Schmocker-Fackel, P., F. Naef, and S. Scherrer. 2007. "Identifying Runoff Processes on the Plot and Catchment Scale." *Hydrology and Earth System Sciences* 11 (2): 891–906. doi:10.5194/hess-11-891-2007.

Shuster, W. D., J. Bonta, H. Thurston, E. Warnemuende, and D. R. Smith. 2005. "Impacts of Impervious Surface on Watershed Hydrology: A Review." *Urban Water Journal* 2 (4): 263–275. doi:10.1080/15730620500386529.

Sillanpää, N., and H. Koivusalo. 2015. "Impacts of Urban Development on Runoff Event Characteristics and Unit Hydrographs across Warm and Cold Seasons in High Latitudes." *Journal of Hydrology* 521: 328–340. doi:10.1016/j.jhydrol.2014.12.008.

Singh, P. K., B. K. Yaduvanshi, S. Patel, and S. Ray. 2013. "SCS-CN Based Quantification of Potential of Rooftop Catchments and Computation of ASRC for Rainwater Harvesting." *Water Resources Management* 27 (7): 2001–2012. doi:10.1007/s11269-013-0267-6.

Solín, Ľ., J. Feranec, and J. Nováček. 2011. "Land Cover Changes in Small Catchments in Slovakia during 1990–2006 and Their Effects on Frequency of Flood Events." *Natural Hazards* 56 (1): 195–214. doi:10.1007/s11069-010-9562-1.

Soulis, K. X., N. Ntoulas, P. A. Nektarios, and G. Kargas. 2017. "Runoff Reduction from Extensive Green Roofs Having Different Substrate Depth and Plant Cover." *Ecological Engineering* 102: 80–89. doi:10.1016/j.ecoleng.2017.01.031.

Stocker, T. F., D. Qin, G. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, eds. 2014. *Climate Change 2013: The Physical Science Basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5)*. Cambridge: Cambridge University Press.

Stone, B. 2004. "Paving over Paradise: How Land Use Regulations Promote Residential Imperviousness." *Landscape and Urban Planning* 69 (1): 101–113. doi:10.1016/j.landurbplan.2003.10.028.

Sun, R., and L. Chen. 2017. "Effects of Green Space Dynamics on Urban Heat Islands: Mitigation and Diversification." *Ecosystem Services* 23: 38–46. doi:10.1016/j.ecoser.2016.11.011.

USDA. 1985. *National Engineering Handbook: Hydrology, Section 4*. Washington, DC: US Department of Agriculture, Soil Conservation Service.

Wheater, H., and E. Evans. 2009. "Land Use, Water Management and Future Flood Risk." *Land Use Policy* 26: S251–S64. doi:10.1016/j.landusepol.2009.08.019.

Woltemade, C. J. 2010. "Impact of Residential Soil Disturbance on Infiltration Rate and Stormwater Runoff." *JAWRA Journal of the American Water Resources Association* 46 (4): 700–711. doi:10.1111/j.1752-1688.2010.00442.x.

Yao, L., L. Chen, W. Wei, and R. Sun. 2015. "Potential Reduction in Urban Runoff by Green Spaces in Beijing: A Scenario Analysis." *Urban Forestry & Urban Greening* 14 (2): 300–308. doi:10.1016/j.ufug.2015.02.014.

Yao, L., W. Wei, and L. Chen. 2016. "How does imperviousness impact the urban rainfall-runoff process under various storm cases?." *Ecological Indicators* 60: 893–905. doi: 10.1016/j.ecolind.2015.08.041.

Zhang, B., N. Li, and S. Wang. 2015. "Effect of Urban Green Space Changes on the Role of Rainwater Runoff Reduction in Beijing, China." *Landscape and Urban Planning* 140: 8–16. doi:10.1016/j.landurbplan.2015.03.014.

Zoppou, C. 2001. "Review of Urban Storm Water Models." *Environmental Modelling & Software* 16 (3): 195–231. doi:10.1016/S1364-8152(00)00084-0.