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Influences of setting sizes and combination of green infrastructures on community's stormwater runoff reduction

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ABSTRACT

Implementation of green infrastructures is an effective option for mitigating the impacts of increasing urbanization on stormwater runo ff. In this study, we evaluated the runoff reduction effectiveness under various setting sizes of green infrastructures using a process-based stormwater runoff model. The model was validated with field data from a typical community in Beijing and proved to be accurate in estimating stormwater runoff under larger rain events. The pervious area percentage and soil hydraulic properties were key parameters influencing stormwater runoff. The four types of green infrastructures, including green area expanding, concave green space, storage pond and porous brick pavement were effective in reducing stormwater runoff, but single facility except the storage pond could not fully control runoff of 5-year recurrence storm. With integrated green infrastructures, runoff of 5-year recurrence storm could be 100% reduced by expanding the pervious area percentage to over 50%, or increase storage pond volume to over 1800 m^3, whereas a maximum runoff reduction of 95% could be achieved when the green land was reformed to concave with a depth of 4 cm, or 50% of the impervious area was replaced with porous brick pavement with a storage capacity of 8 mm. The combination of green infrastructures with proper setting sizes is necessary for optimal control of stormwater runoff management.

1. Introduction

Urbanization is characterized by great land use and land cover alterations with an increase in impervious area, which impairs stormwater infiltration and significantly increases surface runoff during storm events, causing urban flooding, stream channel erosion and non-point pollution problems (Brabec, 2009; Hogan and Walbridge, 2007; Lee and Heaney, 2003; Paul and Meyer, 2001; Wissmar et al., 2004). Conventional methods of stormwater management sought to remove runoff from a site as quickly as possible and then store the stormwater at downstream facilities, including detention ponds, wet ponds and infiltration basins, to control the peak discharge (Gilroy and McCuen, 2009; Wang et al., 2014). While these approaches may control the downstream peak discharge rates, the issue of increased runoff volume remains (Holman-Dodds et al., 2003). Recent years, several innovated strategies such as green infrastructure, sustainable drainage system and water sensitive designs are popular as more sustainable solutions for stormwater management (USEPA, 2000; Lu et al., 2013). These approaches can solve the stormwater management problems by capturing and retaining rainwater, infiltrating runoff, and trapping and absorption of pollution through on-site and decentralized rainwater storage and infiltration facilities (Kloss, 2008).

Green infrastructures, also referred to as low impact development (LID) practices, are common technologies that manage stormwater at the source by restoring some of the natural hydrology functions in urbanized areas and create healthier urban environments. At the scale of a city or county, green infrastructure refers to interconnected network of green space that conserves natural systems and provides assorted benefits to human populations (Benedict and McMahon, 2006). At the scale of a neighborhood or site, green infrastructure is an approach to manage stormwater by infiltrating it in the ground using vegetation or porous surfaces, or by capturing it for later reuse. Many researches have studied the hydrological performance of green infrastructure practices on a laboratory, a pilot scale and in-situ full scale (Abbott and Comino-Mateos, 2003; Alfredo et al., 2010; Chapman and Horner, 2010; Dietz, 2007; Fassman and Blackbourn, 2010; Qin et al., 2013). Although the green infrastructure performance on reducing runoff volumes has been extensively investigated, few studies have attempted to compare the reduction effectiveness between integrated green infrastructure and single facilities (Liu et al., 2014).

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Further, factors that influence the effectiveness of green infrastructure have not been conclusively determined (Gilroy and McCuen, 2009). Brander et al. (2004) and Holman-Dodds et al. (2003) showed that the effectiveness of infiltration techniques in reducing runoff were dependent on soil and storm event type. Some researches indicated that the LID performance on runoff reductions generally were more effective for small storms (Damodaram et al., 2010; Holman-Dodds et al., 2003; Hood et al., 2007; Lee et al., 2012; Qin et al., 2013; Schneider and McCuen, 2006; Williams and Wise, 2006). Guo and Cheng (2008) showed that the distribution of the pervious area and the impervious area influences the effectiveness of LID measures. Gilroy and McCuen (2009) showed that the effectiveness of LID practices in a micro-watershed was influenced by the spatial location and the storage volume of cisterns and bioretention pits. The storage volume is positively correlated with percent reduction in the peak discharge rate and total runoff volume. However, few references have showed the flood mitigation mechanism of other green infrastructure facilities (Gao et al., 2013), and examined how the internal factors (i.e., setting sizes) of green infrastructure affect the reduction effectiveness.

To achieve desired levels of practice performance control with minimal investment, it is necessary to study the impacts of setting sizes and combination effects of green infrastructures on stormwater runoff reduction. As stormwater runoff generation is affected by many factors and hydrological processes, proper model with validated data is necessary for optimal design of community to minimize its impacts on urban water environments.

In this research, we studied the effects of various setting sizes of green infrastructures on stormwater runoff using a process-based stormwater runoff model, which was intentionally developed to simulate the runoff reduction functions of green infrastructures. A typical community in Beijing was used for the case study. Field data were collected for model validation. Sensitivity analysis of model parameters was conducted to quantify the impacts of different factors on stormwater runoff generation in the community. Runoff reduction effectiveness under various setting sizes of green infrastructures was studied. An optimal combination of green infrastructures was designed and proposed to implement in the community.

2. Materials and methods

2.1. Field experiments

Field experiments were conducted in the Wangchunyuan residential community, which is located at the north of Chaoyang district, Beijing (40°02′36″N, 116°24′54″E). The region is classified as a typical monsoon-influenced humid continental climate. The multi-annual average rainfall is about 585 mm and the annual mean temperature is 13.1 °C. The catchment area of the northern outlet of the community is 29,500 m^2 and the pervious 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 instrument measures rainfall, average velocity and depth of flow every 5 min. Stormwater runoff levels were determined by differential pressure, the average velocities were measured using ultrasonic sound waves and the Doppler effects. Data were logged at 5-min intervals and flow rates were calculated using the Flowlink software version 5.1 (Teledyne ISCO, NB, USA).

2.2. Model description

A process-based stormwater runoff model was developed to evaluate the stormwater runoff reduction effects of green infrastructures, which was based on the water mass balance and the processes of urban hydrological cycle. In the model, the urban underlying surfaces are divided into three types of surfaces, namely impervious surfaces, pervious surfaces and water bodies. In a rain event, the rainfall would be routed through interception, evaporation, infiltration and depression processes of the hydrological cycle dependent on the nature of surfaces and dynamic factors to produce the surface runoff. The interception process of vegetation canopy is calculated by the Rutter model (Rutter et al., 1975; Wang et al., 2008). The estimation of potential evaporation is using the Hargreaves–Samani formula. The soil infiltration is calculated by the Green–Ampt equation. The water routing through each surface is calculated independently and then summed up to obtain the total stormwater runoff. Impacts of

Table 1
The parameters used for the default simulation of runoff generation.

Parameters	Values	Units	Sources
Community's characters			
Percentage of impervious areas	69.8	%	Based on local investigation
Percentage of pervious areas	30.2	%	Based on local investigation
Meteorological conditions			
Maximum daily temperature	31	°C	Beijing meteorological data
Minimum daily temperature	22	°C	Beijing meteorological data
Average daily temperature	26.5	°C	Beijing meteorological data
Soil properties			
Saturated hydraulic conductivity	0.144	mm/min	Xie et al., 1998
Wetting front suction	69.696	mm	Fu et al., 2002
Saturated water content	40.627	%	Xie et al., 1998
Initial water content	26.279	%	Xie et al., 1998
Vegetation characters			
Leaf area index	3.85	–	Su and Xie 2003
Extinction coefficient	0.3	–	Wang et al., 2008
Special leaf storage	0.2	mm	Wang et al., 2008
Runoff yield parameters			
Depression of impervious area	3	mm	Xu, 1998
Depression of pervious area	4	mm	Lei et al., 2010

green infrastructures on stormwater infiltration, retention and storage capacity are accounted for in calculating runoff. Detail information on the model can be found in Liu et al. (2014).

2.3. Model parameters and validation

Information extracted from the published literature and data from the Beijing meteorological stations were employed to define the parameter values needed for model simulations (Table 1). Rainfall and synchronously monitored stormwater runoff discharge from the community outlet with 5-min intervals were used for model validation.

The model performance was evaluated by the coefficient of determination (R^2) and Nash–Suttcliffe efficiency (NSE). The R^2 value is an indicator of the strength of the relationship between the observed and simulated values. The NSE is a commonly used goodness of fit measure between the simulated and observed runoff series (Nash and Sutcliffe, 1970), which is expressed as:

$$\mathrm{NSE} = 1 - \frac{\sum_i (Q_{o_i} - Q_{s_i})^2}{\sum_i (Q_{o_i} - \overline{Q_{o_i}})^2}$$

where Q_{s_i} and Q_{o_i} are the simulated and observed values at time i respectively, $\overline{Q_{o_i}}$ is the average of the observed values. A satisfactory model performance normally meets the criteria that R^2 is greater than 0.6 and the NSE value is greater than 0.5 (Moriasi et al., 2007; Santhi et al., 2001).

2.4. Simulation scenarios

The validated model was used to evaluate the effects of various setting sizes of green infrastructures on runoff reduction effectiveness. A large rain event of 115.16 mm was selected for model simulations that stormwater runoff volume could be accurately estimated with pronounced runoff reduction effectiveness. The rainfall input represented a 5 year recurrence interval storm in Beijing (5-year storm). The rainfall event was set based on storm intensity formula of Beijing and Pearson type III rainfall distribution (Wang et al., 2011). Duration of the storm was set to be 24-h with 5-min intervals. A set of model simulations was conducted:

(1) Default simulation: in the default scenario, there is no green infrastructure implemented in the community, following the conditions shown in Table 1.
(2) Simulations for parameter sensitivity analysis: two series of model simulations were conducted that the default parameter values given in Table 1 increased or decreased by 50%. Sensitivity of model parameters was evaluated by comparing the percent change of simulated stormwater runoff volume from the default simulation scenario.
(3) Single green infrastructure simulations: four representative scenarios were designed to evaluate the impacts of single green infrastructure implementations on stormwater runoff reduction under 5-year storm, including: (a) expanding the percent of pervious area from 30% to 40%; (b) changing the green space from flat to concave with a depth of 5 cm; (c) constructing runoff retention structure of a storage pond with 1500 m^3, and assumed the rainwater collection ratio was 100%; (d) converting 50% of the impervious area into the porous brick pavement, the infiltration rate of subsoil was 0.3 mm/min and water storage capacity of porous pavement was 32.86 mm (Wang, 2007).
(4) Integrated green infrastructure simulations: an integrated scenario was designed that the four single green infrastructures were implemented simultaneously in the community, namely, with pervious area percentage of 40%, concave green space with a depth of 5 cm, a 1500 m^3 storage pond, and porous brick pavement in 50% of the impervious area. Four series of model simulations were conducted to examine the runoff reduction effectiveness of each green infrastructure under the integrated scenario in which only the setting size of the targeted green infrastructure changed, the other facility sizes were kept constant as the integrated scenario.

3. Results and discussion

3.1. Runoff hydrograph under different stormwater events: predicted vs. observed

In total, 7 valid rain events were collected during the field experiment period. Four rain events with larger rainfall were measured remarkable runoff flows and were used to validate the model, the other 3 rain events with 3.8, 4.3 and 5.5 mm, respectively, were not available due to less runoff.

Fig. 1 shows the predicted and observed runoff hydrograph under 2 large storm events. The predicted and observed runoff followed similar dynamics of rain events, suggesting the model was capable of simulating the hydrological processes. Under the rain event on July 15, the predicted and observed runoff volume were 1607.16 and 1633.06 m^3, respectively. Under the rain event on August 11 pm, the predicted and observed runoff volume were 608.76 and 612.71 m^3, respectively. The deviations between predicted and observed total runoff volume under the 2 rain

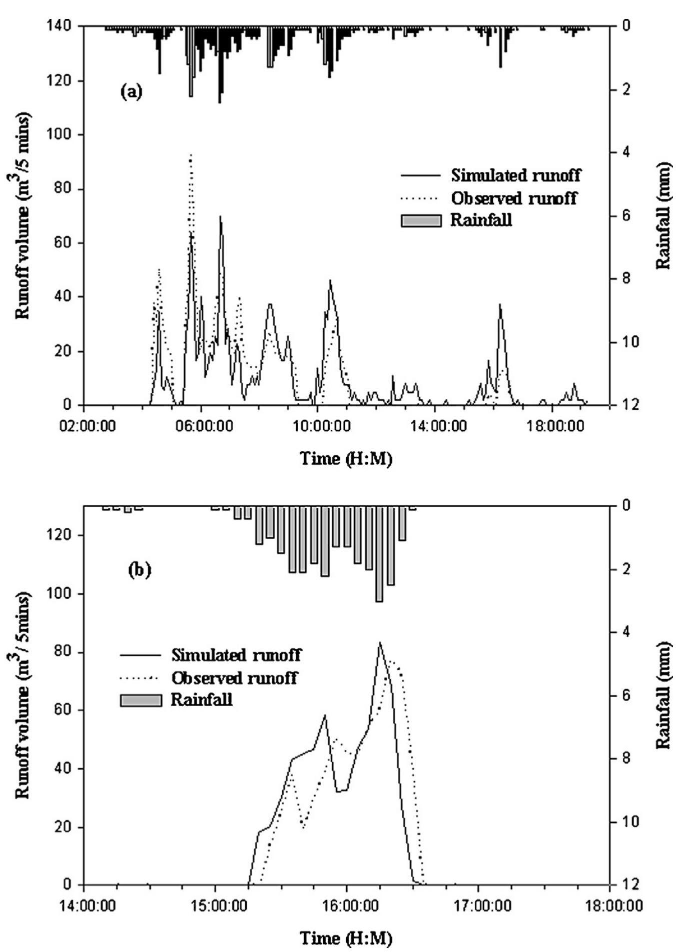

Fig. 1. Observed and predicted runoff hydrograph under: (a) rain event on July 15, 2013 (b) rain event on August 11pm, 2013.

events were −1.61% and −0.65%, respectively. The results indicated that the model performed well in simulating stormwater runoff with larger rainfall amount, but might underestimate the stormwater runoff at a certain extent.

Table 2 summarizes the model performance evaluation statistics under the 4 available rain events during the experiment period. Except the rain event on August 11 am, the R^2 values were more than 0.67 and the NSE values were more than 0.93, indicating that the model adequately tracked the runoff flow trends during these rain events. Under the rain event on August 11 am with smaller rainfall amount of 6.4 mm, the model performance was not well due to field measurements error and stormwater drainage system involved in catchment response. Based on the model performance under the 4 rain events, it can be expected that the model can well track the stormwater runoff generation under the designed storm of 5 year recurrence interval with a rainfall amount of 115.16 mm, which is the basis for the following studies.

3.2. Parameter sensitivity analysis

As illustrated by Fig. 2, changes of the pervious area percentage (β) were found to have the greatest influence on simulated stormwater runoff volume. The runoff volume changed by 13.39% and −8.94%, respectively, when the β decreased or increased by 50%. It indicates that the stormwater runoff generation is sensitive to the underlying surface conditions, but the response is not linear. The runoff volume was changed by 5.09% and 5.60%, respectively, when the values of saturated hydraulic conductivity (K_s) and saturated water content (θ_s) decreased by 50%. Contrarily, runoff volume changed by −2.98% and 4.16%, respectively, when K_s and initial water content (θ_i) increased by 50%. It suggests that the model is also sensitive to infiltration process represented by K_s,θ_s and θ_i, but at a lesser scale than underlying surface conditions. The other seven parameters including vegetation interception parameters, runoff yield parameters, wetting front suction and average daily temperature had the quite limited impacts on the model simulation results. When they increased or decreased by 50%, simulated stormwater runoff volume hardly changed (less than 4%). It suggests that the model simulation uncertainties due to parameters on plant characteristics, runoff yield and daily temperature are small.

Overall, the model is not sensitive to other parameters except for β which represents community characteristic, and K_s, θ_s and θ_i which reflect soil hydraulic properties. These results can be used for guiding stormwater runoff management and practices in communities.

3.3. Impacts of soil hydraulic parameters on stormwater runoff

The hydrologic soil group of Beijing could be identified as the same class within the entire city (Fu et al., 2013). However, the compaction associated with urban development has a significant influence on soil hydraulic properties such as soil water retention and saturated hydraulic conductivity (Horton et al., 1994), thus negatively affects soil infiltration rates (Pit et al., 1999) and leads to stormwater runoff increased. Given its variability in urban areas

Table 2
Model performance evaluation statistics.[a]

Date	Rainfall (mm)	R^2	NSE
July 15, 2013	62.2	0.68	0.99
August 11 pm, 2013	26.5	0.71	0.96
July 30, 2013	9.3	0.67	0.93
August 11 am, 2013	6.4	0.43	0.67

[a] NSE: Nash–Suttcliffe efficiency.

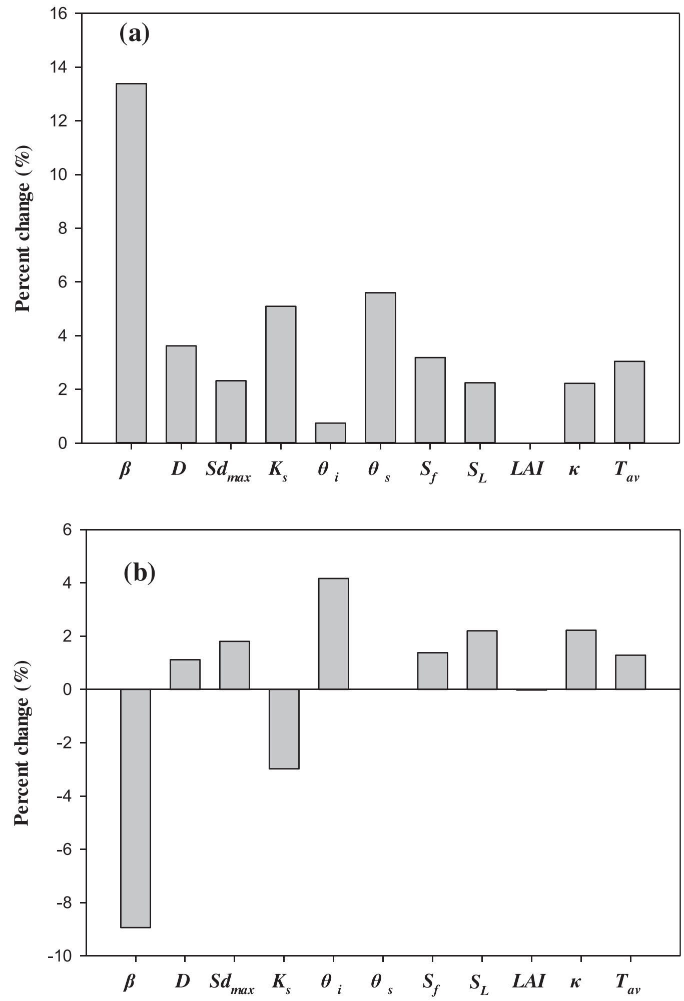

Fig. 2. Relative change of simulated runoff volume. under: (a) parameter decreased by 50%; (b) parameter increased by 50%. (β, percentage of pervious areas; D, depression of impervious area; Sd_{max}, depression of pervious area; K_s, saturated hydraulic conductivity; θ_i, initial water content; θ_s, saturated water content; S_f, wetting front suction; S_L, special leaf storage; *LAI*, leaf area index; κ, extinction coefficient; T_{av}, average daily temperature.)

and sensitivity to the model, changes of soil hydraulic properties on stormwater runoff generation were examined in details.

Fig. 3(a) illustrates the changes of the ratio of runoff to rainfall (total runoff amount divided by total rainfall amount) with the saturated hydraulic conductivity (K_s). As the K_s value increased, runoff volume decreased exponentially. When the K_s value was greater than 200 cm/d, runoff volume kept steady, suggesting that the soil infiltration capacity had approached its maximum. According to the K_s values of different soil textures given by (Carsel and Parrish, 1988), the ratio of runoff to rainfall increased from 65.51% to 91.02% as the soil texture varied from sand to clay (the K_s values changed from 712.8 to 0.48 cm/d). The ratio of runoff to rainfall under the loamy soil was 76.04%, less than that under the clay soil (84.87%), but higher than that under the sandy soil (65.51%). The ratio of runoff to rainfall under the loamy soil was similar to that of the default scenario (77.00%) since soil texture in Beijing was close to loam. Fig. 3(b) and (c) shows that the impacts of saturated/initial water content on stormwater runoff were slight. When the saturated water content (θ_s) changed from 36% to 46%, the ratio of runoff to rainfall changed from 77.46% to 76.51%. Similarly, the ratio of runoff to rainfall changed from 75.39% to 77.17% when the initial water content (θ_i) ranged from 7% to 28%.

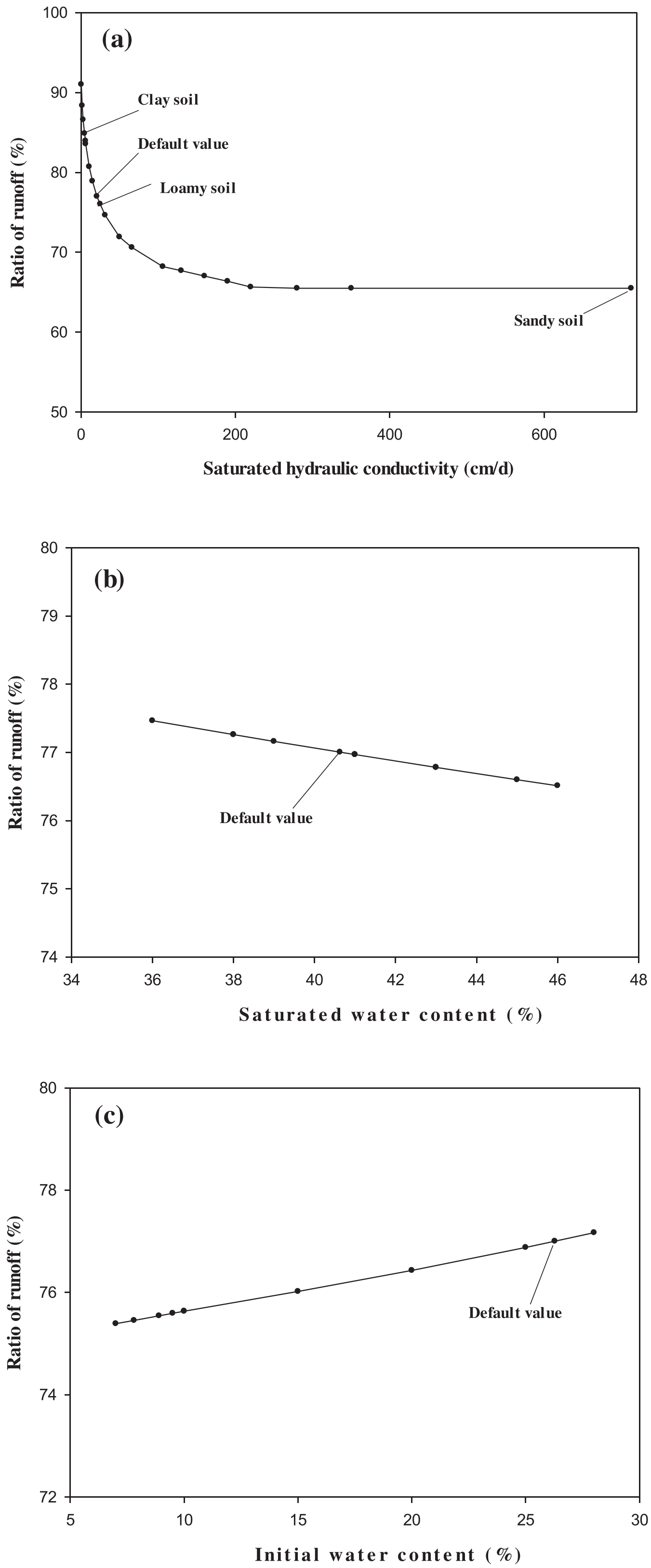

Fig. 3. Impacts of soil hydraulic parameters on the runoff to rainfall ratio.

The stormwater runoff generation of green lands highly depends on soil texture. The sandy and loamy soil which has a lower ratio of runoff (i.e., higher infiltration capacity) are appropriate to use in green lands, while the clay soil will require soil amendment to increase infiltration capacity for optimal stormwater management. When soils are overly compacted, the soil pores are destroyed and the permeability is drastically reduced, causing the infiltrated rate and water storage decreased, and increased stormwater runoff volume. Therefore, minimizing soil compaction should be planned during the design phase for infiltration facility projects.

3.4. Effects of single green infrastructure on stormwater runoff reduction

3.4.1. Effects of pervious percentage on runoff reduction

As vegetative covers decrease with urbanization, the natural hydrologic cycle is disrupted in urban areas (Arnold and Gibbons, 1996). Creation of more green areas is an effective solution to the recent calls for a more ecological and greener urbanization (Van Herzele and Wiedemann, 2003; White, 2002). Fig. 4a illustrates the diminishing trend of stormwater runoff volume with increasing pervious area percentage. When the pervious area percentage increased from 10% to 90%, by expanding green lands in the community, the ratio of runoff to rainfall significantly decreased from 88.05% to 43.85%. The ratio of runoff to rainfall exceeded 40%, even at the pervious area percentage of 90%, suggesting that the runoff generation process is dominated by the impervious area. Some researches also examined the effects of impervious area change on stormwater runoff, the results are similar with the above simulated results. Increased green cover by 10% in the residential land reduces runoff by 4.9%, and increased tree cover by the same amount reduces the runoff by 5.7% (Gill et al., 2007). Doubling impervious cover from 30% to 60%, by replacing bare soil and short vegetation classes with impervious cover, increased total runoff by 33%, and reduced pervious runoff by 53% (Wang et al., 2008). The influence of pervious and impervious area contributions on the hydrologic response can depend on the distribution of the imperviousness (Mejia and Moglen, 2010). These analysis of land cover change on stormwater runoff are beneficial for urban planners.

There are three kinds of typical communities in Beijing, according to their green area percentages. (1) The new communities which have a requirement of the pervious percentage of 30% are consistent with the default condition. (2) The older districts built in the last century have a low pervious percentage of 10%. (3) The villa communities commonly have a high pervious percentage, which can be reached to 50%. As shown in Fig. 4(a), the older communities had a high ratio of runoff to rainfall of 88.05%, which might cause serious stormwater runoff problems. Realizing the stormwater problem with these older communities, the government has taken some actions to reduce the stormwater runoff discharge by building rainwater collection facilities, and/or by increasing the pervious area through green roof and porous pavement. Comparing with the old communities, the ratio of runoff to rainfall decreased to 77.00% for the new communities, and further decreased to 65.95% for the villa communities. Therefore, it is essential to control the pervious area percentage in the future developmental activities of communities in order to reduce the stormwater runoff discharge. However, improving the pervious area alone is not enough for an optimal management of stormwater runoff.

3.4.2. Effects of concave depth on runoff reduction

Given the high population density, increasing the coverage of green lands is commonly limited in urban areas. Whereas, the infiltration capacity of the existing green area is not sufficiently fulfilled as most of them are built in flat in Beijing. Thus, reforming the flat green spaces to concave can be an effective solution to reduce stormwater runoff. As illustrated by Fig. 4(b), the ratio of runoff to rainfall decreases from 77.00% to 65.51%

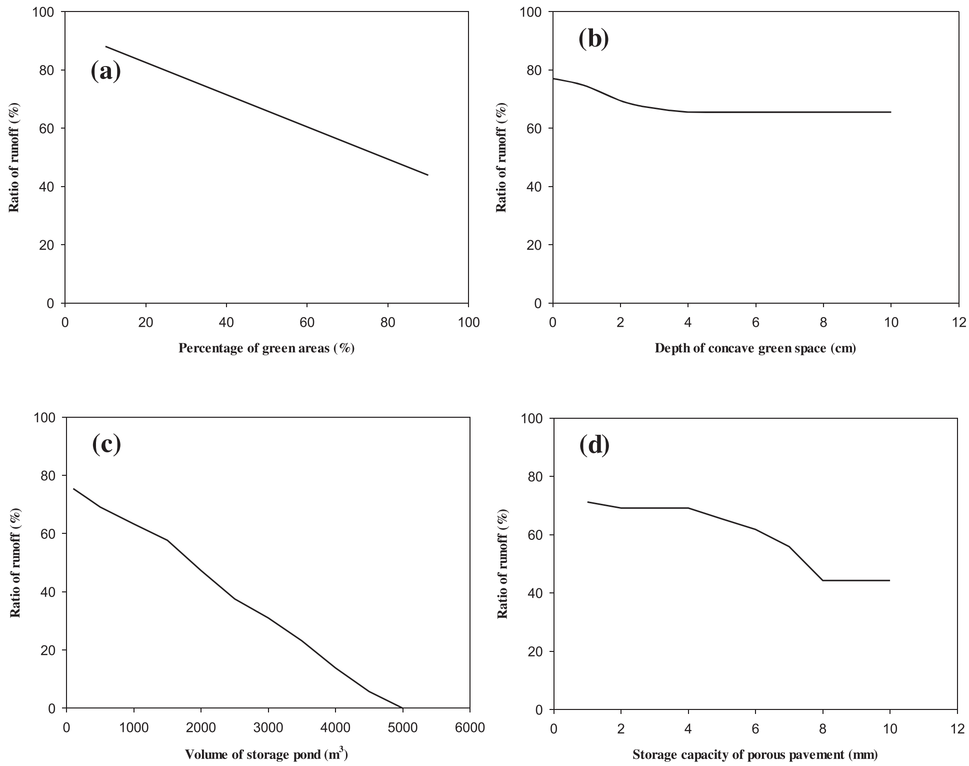

Fig. 4. Effects of setting sizes of single green infrastructure on runoff reduction.

when the concave depth increased from 0 cm (flat) to 10 cm. A moderate runoff reduction can be achieved after reforming the flat green spaces to concave. The concave green spaces had no additional runoff reduction effect after the depth with more than 4 cm. The runoff retention capacity of concave green land is saturated at that case. These model simulation results indicated that the infiltration capacity of green area could be greatly enlarged with a shallow concave depth of 4 cm. Some researches also confirmed that the runoff reduction effectiveness of concave green space is better than the flat green space, and the reduction effectiveness is increased with the concave depth increased (Cong et al., 2006; Ren et al., 2000). The concave green land can fully utilize the limited green space, increase the runoff reduction potential of green land, and further recharge groundwater in urban areas.

3.4.3. Effects of storage pond volume on runoff reduction

The volume of storage facilities directly determined the magnitude of retained runoff volume and controlled runoff discharge. As illustrated by Fig. 4(c), the ratio of runoff to rainfall decreased linearly from 75.42% to 0% as the storage volume increased from 0 to 5000 m^3. The storage pond size needs to be 4858 m^3 for a full reduction of 5-year storm in the community. The linear diminishing trend demonstrated that the runoff reduction is dependent on the storage capacity of storage pond. Gilroy and McCuen (2009) also indicated that the storage volume of urban bioretention ponds and cisterns is positively correlated with percent reduction in the total runoff volume. Ideally, the storage pond can fully retain all the stormwater runoff only if there is adequate space in the community. The standard LID detention volume under a certain design standard is used to compensate for the runoff increment caused by urban development (Guo, 2010). In actual engineering practice, due to the seasonal characteristic and cost factor, the appropriate volume of storage pond should design based on the local rain characters, community size, buildable space, and serves effectiveness (Cong et al., 2006). In all, the storage ponds had quite an effective reduction effect in controlling stormwater runoff. The harvested rainwater can be beneficially used for multiple puroposes.

3.4.4. Effects of the storage capacity of porous pavement on runoff reduction

The infiltration functions of impervious surface may be restored by replacing it with porous pavement, such as permeable brick with cushion layers of gravel underneath. Different construction materials and methods lead to variable storage capacity, which may vary from 1 to 10 mm according to the literature. In case that 50% of the impervious areas were paved with porous bricks, the ratio of runoff to rainfall reduced from 71.18% to 44.25% when the storage capacity per unit area varied from 1 to 10 mm (Fig. 4(d)). A linear diminishing trend shows that the runoff reduction is dependent on the infiltration and water storage of the subsoil of porous pavement. Infiltration capacity approached the maximum at the storage capacity of 8 mm. It was effective in reducing runoff that a stormwater runoff reduction of 26.93% could be achieved after changing 50% of the impervious area to the porous brick paved area. Experiments confirmed that the permeable pavements could eliminate runoff generation and decrease runoff rate (Bean et al., 2007). The pre-development hydrology can be achieved with permeable pavements through infiltration (Fassman and Blackbourn, 2010). Therefore, porous pavement can effectively mitigate the waterlogging problem of impervious pavements in urban areas.

3.5. Runoff reduction under integrated green infrastructures

The simulation results of four single green infrastructure scenarios indicated that single facility except storage pond could

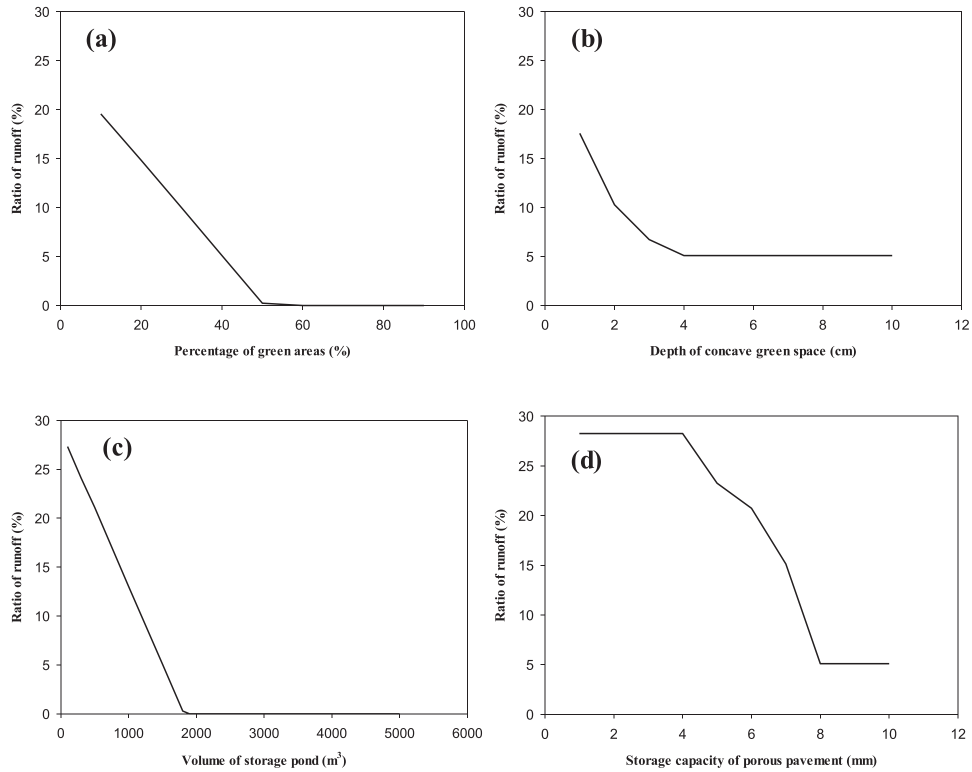

Fig. 5. Effects of setting sizes of green infrastructures on runoff reduction under the integrated scenario.

not fully control stormwater runoff (5 year recurrence interval in this study). The storage pond size needs to substantially increase for a fully stormwater runoff reduction, which is impractical in many cases. Some researches also demonstrated that single green infrastructure was limited in the runoff reduction and might be ineffective in bigger storms, and it would never fully solve the urban runoff problem, thus the combination of different facilities was needed (Elliott and Trowsdale, 2007; Mentens et al., 2006; Schneider and McCuen, 2006; Williams and Wise, 2006).

Fig. 5 illustrates the changes of setting sizes of four green infrastructure facilities on runoff reduction under the integrated scenario. 100% runoff reduction could be achieved by expanding the pervious area percentage to over 50%, or increasing storage pond volume to over 1800 m^3, with implementing other green infrastructures at the time. For the other two cases, the maximum runoff reduction was 95% when the green land was reformed to concave with a depth of 4 cm, or 50% of the impervious area was replaced with porous brick pavement with a storage capacity of 8 mm. Compared with the single green infrastructure scenarios, the higher reduction effectiveness can be easily achieved under integrated green infrastructures with lower setting sizes. It indicated that the integrated facilities not only improved the reduction effectiveness but also saved the construct cost of facilities and achieved multiple benefits. Given the space and cost limitation, it is necessary to optimize the setting sizes and combined structures of these green infrastructures to maximize the stormwater runoff reduction effectiveness. Aiming a zero stormwater runoff discharge with minimum rainwater collection, the community may take the following optimal practices: (1) directing the runoff from rooftops into the adjacent green spaces, which reformed concave with a 6-cm depth; (2) roads, square spaces and pavement (assuming these areas account for 50% of the impervious area in the community) paved by porous bricks with water storage capacity of 8 mm; (3) constructing a storage pond with 223 m^3 to retain the stormwater runoff. After these optimal practices implemented in the community, there will be no stormwater runoff discharge out under 5-year storm. For larger storms, the optimal setting sizes of green infrastructures should be appropriately increased to achieve the same aim.

4. Conclusions

In this study, we evaluated the runoff reduction effectiveness under various setting sizes of green infrastructures in a typical community in Beijing using the model we developed. The collected field data were used to validate the model, and parameter sensitivity analysis was conducted to quantify the impacts of different factors on stormwater runoff generation. Based on the evaluated results, an optimal green infrastructure practice was designed for the community. The major findings are as follows:

(1) The model is capable of simulating the hydrological processes and can well track the stormwater runoff generation under larger rain events.
(2) The stormwater runoff generation is sensitive to the pervious area percentage and soil hydraulic properties. For mitigating the negative impacts of stormwater runoff, measures such as maintenance of moderate pervious area percentage, soil amendment and minimizing soil compaction should be considered in future developmental activities of communities.
(3) Single green infrastructure is effective in stormwater runoff. 100% runoff reduction can be achieved with the substantially larger size of storage pond, which is 4858 m^3 for the study community. For the other three single green infrastructure, the runoff to rainfall ratio can decrease from 77.00% under the default simulation (without green infrastructure) to 43.85%, 65.51% and 44.25%, respectively, at a pervious area percentage

of 90%, concave green space with a depth of 4 cm, and porous brick pavement with a storage capacity of 8 mm.

(4) The integrated facilities can highly improve the stormwater runoff reduction effectiveness with smaller setting sizes. Zero stormwater runoff discharge can be achieved under two integrated scenarios. For the other two integrated scenarios, the runoff to rainfall ratio can be reduced to 5%.

(5) In this study, we selected a 5-year recurrence storm for simulation. For small storms, the reduction effectiveness would be more pronounced. Whereas, the optimal setting sizes of green infrastructures should be appropriately increased to achieve the zero stormwater runoff discharge aim for larger storms.

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