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ORIGINAL PAPER

Hydrological effect of typical low impact development approaches in a residential district

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Abstract Understanding how low impact development approaches (LIDs) reduce urban stormwater runoff and increase baseflow is significant for urban water resources management. The SCS model and baseflow equation were employed to evaluate the performance of green roofs (GRs), permeable pavement (PP) and rain barrels (RBs) as retrofitting technologies in a high-density residential community in Nanjing, China. In addition, the factors relevant to the performance of LIDs were explored by estimating runoff variations at different rainfall frequencies. The findings are that the application of GR, PP and RB resulted in reduction in surface runoff by 0.6–36.8 % and increased in baseflow by 2.68–60.93 × 10^3 m^3. In addition, there is a negative linear correlation between runoff depth and effective storage, and the effectiveness of RB on runoff reduction is greater than that of PP. The baseflow generated by 100 % LID implementation is 1.94 times greater than that generated by 50 % LID implementation. For PP, generated baseflow increased with the increase in effective storage. The baseflow generated by GR is 1.16 times greater than that generated by RB in the same roof area.

Keywords Green roofs · Permeable pavement · Rain barrels · Low impact development · Runoff · Baseflow

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1 Introduction

Urbanization has caused both short-term and long-term changes in urban watershed hydrology (Rose and Peters 2001; Meybeck and Vorosmarty 2005; Gunn et al. 2012). Urban flood mainly results from modifications of the hydrological cycle by land use transformation. Land use change accompanied by impervious surfaces (IS) can considerably affect flooding in urbanized areas, including timing, intensity and the extent of inundation (Dewan 2013; Su et al. 2014). A series of environmental problems, especially waterlogging hazards in urbanized areas, have been induced by the quick spread of IS areas brought about by rapid urbanization and industrialization.

In recent years, severe waterlogging hazards occurred and caused huge economic losses and negative social impacts in many Chinese cities. Moreover, urban waterlogging disasters are becoming more frequent and serious, causing concerns among both the government and the public. The development of new approaches to dealing with the increase in waterlogging disasters is a great challenge to many cities in China (Jia et al. 2013). Clearly, effective prevention and mitigation of urban waterlogging disaster is an urgent task. And yet, the current management of urban stormwater runoff is dominated by the conventional approach of rapid discharge. In light of a substantial increase in surface runoff area created by the urban sprawl, the existing flood control and drainage systems appear inadequate to handle events of heavy rainfall. Laymen blame the urban waterlogging drainage system, claiming that design standards for drainage pipes are too low, believing that higher network design standards to increase the drainage capacity of surface runoff would suffice to handle the increased runoff volume. However, improving design standards of the conventional drainage network alone falls short of solving the issue at hand. In densely populated built-up urban areas, there are many technological and economic factors that restrict the ability to improve the design and the standards of the existing drainage network (Burns et al. 2012; Gao et al. 2013a, b). The limitations of the conventional concepts and methods of coping with waterlogging problems are evident. In addition, urban rainwater, considered to be a causal factor of waterlogging hazards, is treated as wastewater and drained away as quickly as possible. As a result, it is lost as alternative water resource that could help alleviate the water shortage in many Chinese cities.

Due to insufficiencies in drainage and flood control, resulting from the high percentage of IS in urban areas, many countries have become aware of the limitations of conventional urban stormwater management systems. In order to explore a scientific, effective and sustainable urban flood control and drainage patterns, several countries began parting with the traditional drainage conveyance approach and shifted their focus to rainwater detention, retention and recharge as superior runoff control approaches.

Low impact development approaches (LIDs) are urban stormwater management techniques proposed in the late 1990s to mitigate the negative effects of rapid urbanization and increased impervious area on urban hydrology (Dietz 2007). LIDs use small-scale measures to control runoff and pollution at source by reducing urban impervious areas, extending runoff paths and achieving runoff storage, increasing infiltration and recharging groundwater (Gao et al. 2013a). Compared with traditional urban stormwater management pattern, LIDs have the function of returning the runoff to the natural hydrological cycle, including reduction in runoff volume (Ahiablame et al. 2013b; Jia et al. 2014), infiltration improvement (Ahiablame et al. 2012), reduction in peak flow (Drake et al. 2014), extending lag time (Hood et al. 2007), reduction in pollutant loads (Bedan and Clausen 2009; Liu et al. 2015) and increase in baseflow (Hamel et al. 2013).

It is necessary to find solutions to mitigate waterlogging disasters in built-up urban areas in many Chinese cities (Jia et al. 2012; Sang et al. 2013). Rainwater harvesting is an effective way to reduce urban runoff in many cities and has received much attention from many researchers (Matthew and William 2010; Zhang et al. 2012; Kim and Furumai 2012; Zhang and Hu 2014; Zhang et al. 2014). In addition, as some researchers have pointed out, there are limitations to enlarging urban green spaces and wetlands, while the potential for penetration pavement reconstruction in built-up urban areas is immense. Implementing penetration approaches in urban sidewalks, roads, parking lots, playgrounds and public squares, giving these areas a role in storing and retaining rainwater, is practicable (Scholz and Grabowiecki 2007; Fassman and Blackbourn 2010; Li et al. 2013; Gao et al. 2014).

The two main objectives of the present study are as follows: (1) to estimate the hydrological effects of three typical LID practices on runoff and baseflow by simulating runoff generating process at different rainfall frequencies in the selected built-up residential district and (2) to explore the relevant factors affecting the performance of LID practices and the relationship between runoff and baseflow.

2 Study area

The study area, a densely populated residential block covering an area of 0.58 km^2, is located in the Hexi area of Nanjing, China (Fig. 1). The latitude and longitude are 32°03′N and 118°44′E. The study area is adjacent to the Qinhuai River, and its average elevation is below the average water level of the Qinhuai River in the rainy season, making it one of the most seriously waterlogged areas in Nanjing City.

Table 1 and Fig. 2 show the areas of different kinds of surfaces in the study area. Impervious surface areas, including roofs, cement and asphalt surfaces, and stone pavement and brick pavement, account for 73.79 % of the total area. Roof areas, paved roads and squares areas, and greenbelt and water areas account for 26.43, 18.60 and 26.21 %, respectively.

This study is based on 1:500 topographic map data of the study area and the long-term rainfall data (1958–2008) in Nanjing.

3 Methods

The SCS model proposed by the US Soil Conservation Service is one of the most extensively applied hydrological models, as it reflects the influence of underlying surface variation and human activities on the process of runoff. The SCS model, which is characterized by its simplicity and loose requirements of parameters and observation datasets, is used to evaluate the impacts of LID practices on runoff by using the following equations:

$$S = \frac{25400}{\mathrm{CN}} - 254 \tag{1}$$

$$I_{\mathrm{a}} = 0.2S \tag{2}$$

$$R = \frac{(P - I_{\mathrm{a}})^2}{P - I_{\mathrm{a}} + S}, \quad P > I_{\mathrm{a}} \tag{3}$$

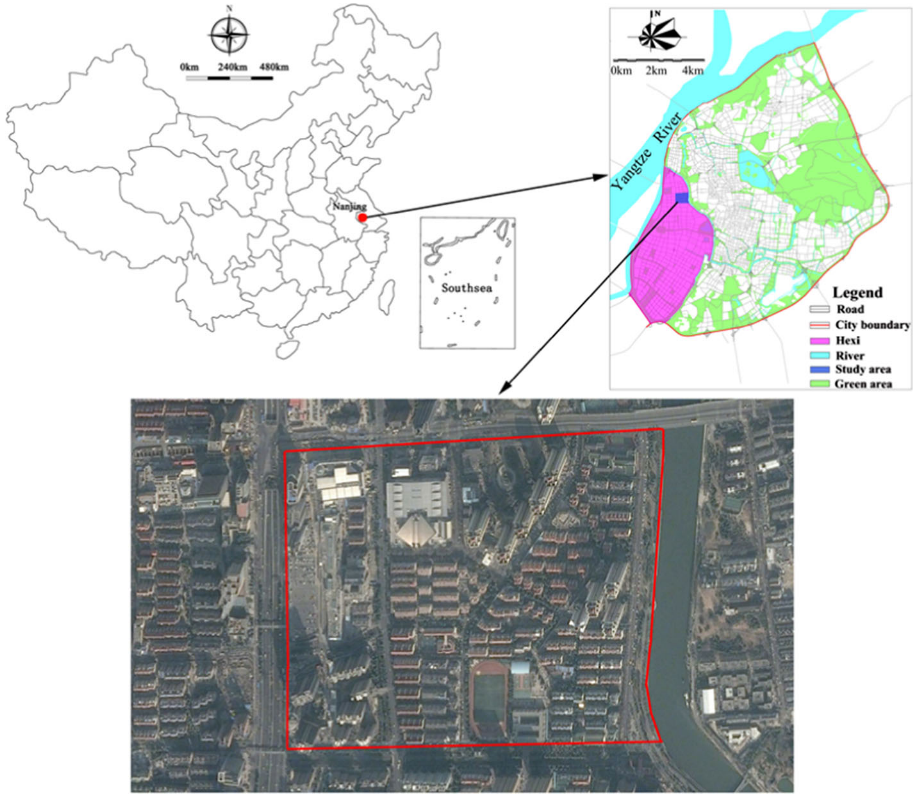

Fig. 1 Location of the study area in Nanjing, China

Table 1 Land use categories and proportions

Type	Roof	Cement and asphalt surfaces	Stone pavement and brick pavement	Greenbelt	Water	Total
Area (m^2)	152,863	217,771	56,191	150,352	1259	578,436
Percent (%)	26.43	37.65	9.71	25.99	0.22	100

$$R = 0, \quad P \leq I_a \tag{4}$$

where S is the maximum potential retention (mm), I_a is the initial abstraction (mm), P is precipitation (mm), R is runoff depth (mm) and CN is the curve number, which reflects the soil and land use characteristics.

LID practices not only affect the runoff generation, but also have impacts on baseflow. The baseflow equation (Ahiablame et al. 2013a, b) is used to evaluate the impacts of LID practices on baseflow:

$$Q_b = 29.896\,\mathrm{BDA}^{0.953} P^{1.424} \mathrm{BFI}^{1.260} \tag{5}$$

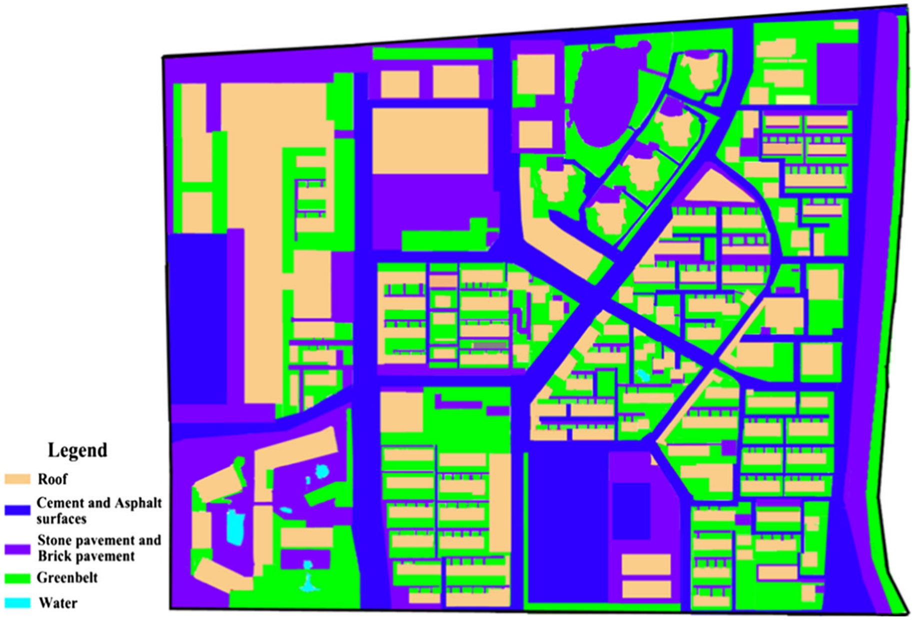

Fig. 2 Land use types of the study area

$$\mathrm{BFI} = -0.00726\mathrm{CN} + 1.142 \tag{6}$$

where Q_b is the annual baseflow (m^3), BDA is the watershed drainage area (km^2), P is precipitation (mm), and BFI is the baseflow index, which is calculated with the CN values ranged of 70–90.

The key point of the SCS model and baseflow equation is to determine the CN value. The theoretical CN value is between 0 and 100, but the real value is within a range of 40–98.

The CN value for representing the hydrological characteristics of green roofs has been determined to be within the range of 84–90 (Carter and Rasmussen 2006; Getter et al. 2007).

It is difficult to determine the CN values of permeable pavement because there is no direct way to measure. Damodaram and Giacomoni (2010) used S-Storage CN method to determine an appropriate CN value for permeable pavement. In this method, the maximum potential retention (S) is equal to the effective storage (S_e):

$$S = S_e \tag{7}$$

Rain barrels collect rainwater from roofs; however when the capacity of the rain barrels is reached, the roofs become IS areas and begin to produce surface runoff. Consequently, the initial abstraction (I_a) is equal to the rain barrels' effective storage (S_e), which means the CN value of rain barrels is set to the same CN value of the impervious surfaces.

$$I_a = S_e \tag{8}$$

4 Results and discussion

4.1 Analysis of rainfall characteristics

Rainfall characteristics were analyzed using the daily rainfall data (1958–2008). The average, minimum and maximum annual rainfall for this time period approximate 1047, 535 and 1826 mm, respectively. The annual average number of rainy days (rainfall > 2 mm) is 72 days, the average daily rainfall is 14.6 mm, and the maximum daily rainfall is 207.2 mm which occurred on July 5, 2003. Figure 3 shows that the annual rainfall amount has been slightly on the rise for the period investigated. Table 2 shows the cumulative frequency of annual rainfall amount during 1958–2008.

4.2 Performance of LID practices on runoff reduction

4.2.1 Scenarios design

In order to quantitatively evaluate the hydrological effects of green roofs (GRs), permeable pavement (PP) and rain barrels (RBs) on runoff and baseflow generations, eleven scenarios are designed, as shown in Table 3. One scenario is for the performance of GR and five scenarios each for effective storage (S_e) of RB and PP, at the values of 25, 51, 76, 102 and 127 mm (Damodaram and Giacomoni 2010). The two areas of LID implementation are designed to be 18.6 % (the percentage of permeable pavement-implemented roads) and 26.4 % (the percentage of green roofs and rain barrels-implemented roofs).

Leaning on previous studies (Carter and Rasmussen 2006), the CN value for green roofs is set as 86 in the present study. Equations (1), (2) and (3) show that once the CN value is identified, the runoff depth (R) is only relevant to precipitation (P).

Roads and squares were assumed to be plastered with permeable pavement. $R = \frac{(P-0.2S_e)^2}{P+0.8S_e}$ is obtained through Eqs. (2), (3) and (7), indicating that runoff depth of pervious pavement (R) is relevant to precipitation (P) and effective storage (S_e). The CN values are set as 91, 83, 77, 71 and 67 corresponding to effective storages of 25, 51, 76, 102 and 127 mm.

According to the reference CN values provided by the US Soil Conservation Service and some studies (Qin et al. 2005; Quan et al. 2009), the CN value of impervious area for this study is set as 94.

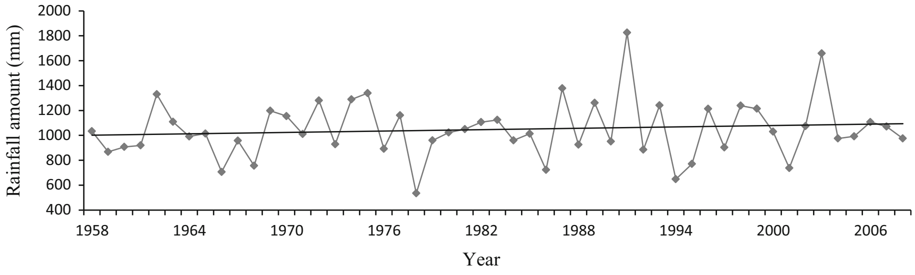

Fig. 3 Trend of annual rainfall amount in Nanjing (1958–2008)

Table 2 Analysis of the cumulative frequency of rainfall amount

Rainfall frequency (%)	Rainfall (mm/year)	Rainfall frequency (%)	Rainfall (mm/year)
1	1737.94	25	1188.12
2	1634.01	50	1016.15
5	1488.09	75	872.15
10	1368.28	95	709.92
20	1235.27	99	624.31

Table 3 Designed scenarios

	LID	LID area		
		CN	I_a	S
S1	GR	86	8	41
S2	25-mm PP	91	5	25
S3	51-mm PP	83	10	51
S4	76-mm PP	77	15	76
S5	102-mm PP	71	20	102
S6	127-mm PP	67	25	127
S7	25-mm RB	94	25	125
S8	51-mm RB	94	51	255
S9	76-mm RB	94	76	380
S10	102-mm RB	94	102	510
S11	127-mm RB	94	127	635

GRs, green roofs; PP, permeable pavement; RBs, rain barrels; CN, curve number; I_a, the initial abstraction; S, the maximum potential retention

4.2.2 Performance of LID practices on runoff reduction in different scenarios

Rainfall amount has a direct influence on runoff volume, dictating that different rainfall frequencies need to be considered. Based on the rainfall recurrence interval, three rainfall frequencies, namely 5, 2 and 1 %, are selected, and their corresponding rainfall amounts are 1488.09, 1634.01 and 1737.94 mm, respectively. Runoff volumes generated with the PP and RB practices are related to effective storage and precipitation, whereby precipitation leads to an increase in runoff volume and effective storage to a decrease thereof, as shown in Fig. 4. The linear correlation between runoff depth and effective storage is

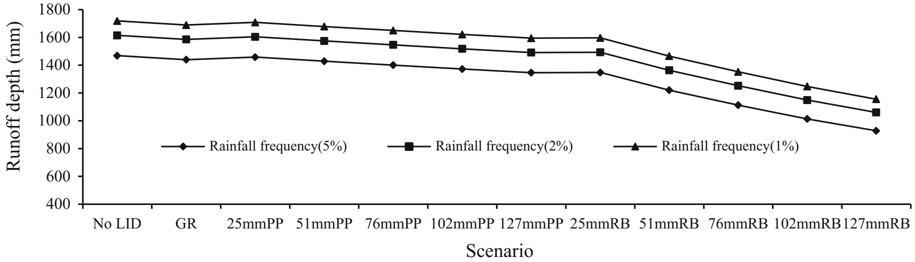

Fig. 4 Runoff at different rainfall frequencies

expressed as: $R = aS_e + b$, where R is runoff depth (mm), S_e is effective storage (mm) and a and b are statistical parameters. As shown in Table 4, there is a negative linear correlation between runoff depth and effective storage with a coefficient of determination (R^2) larger than 0.99. The effectiveness of runoff volume reduction from rain barrels is greater than that from permeable pavement at the same effective storage, meaning that increase in effective storage leads to a greater runoff volume reduction effect. With the increase in rainfall amount, the slope of linear equations becomes steeper, which further illustrates that effective storage is potent in runoff volume reduction during heavy rain and rainstorm events.

The effectiveness of runoff reduction is estimated by comparing runoff depth generated in different scenarios. As shown in Fig. 5, GR, PP and RB lead to reduction in runoff, and the reduction extent is different under different LID practices. The various implementation levels of GR, PP and RB resulted in runoff reduction by 1.7–2.0, 0.6–8.4 and 7.1–36.8 % at different rainfall frequencies, respectively. For PP and RB, runoff reduction percentages under different rainfall conditions vary slightly as the effective storage is limited, and the effect on runoff reduction becomes greater when rainfall amount is smaller.

4.3 Performance of LID practices on increasing baseflow

4.3.1 Scenarios design

According to Eqs. (5) and (6), baseflow is determined by watershed drainage area, precipitation and the CN value. The CN values of GR and RB are set according to different

Table 4 Relationship between rainfall depth (R) and effective storage (S_e) at different rainfall frequencies

Rainfall frequency (%)	Simulation equation	R^2
5	$R_1 = -1.100S_e + 1485.269$	1.000
	$R_2 = -4.107S_e + 1437.414$	0.995
2	$R_1 = -1.109S_e + 1631.420$	1.000
	$R_2 = -4.234S_e + 1586.374$	0.996
1	$R_1 = -1.113S_e + 1735.489$	1.000
	$R_2 = -4.315S_e + 1692.266$	0.996

R_1, runoff depth generated with permeable pavement; R_2, runoff depth generated with rain barrels; S_e, effective storage

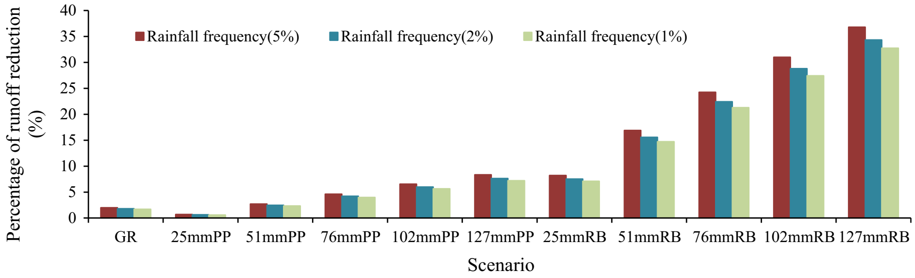

Fig. 5 Percentages of runoff reduction resulted from different LID practices

effective storages. Namely, 50 and 100 % GR implementations were applied on the roofs, 50 and 100 % PP implementations were applied to roads and squares, and 50 and 100 % RB implementations were applied in connection with rain barrels. Therefore, there are 14 scenarios; they are GR (50 %), GR (100 %), 25-mm PP (50 %), 51-mm PP (50 %), 76-mm PP (50 %), 102-mm PP (50 %), 127-mm PP (50 %), 25-mm PP (100 %), 51-mm PP (100 %), 76-mm PP (100 %), 102-mm PP (100 %), 127-mm PP (100 %), RB (50 %) and RB (100 %).

4.3.2 Performance of LID practices on increasing baseflow in different scenarios

The estimated baseflow in different scenarios at three rainfall frequencies is shown in Fig. 6. For the three LID practices, the baseflow generated by 100 % LID implementation is 1.94 times greater than that by 50 % LID implementation. Moreover, baseflow generated by GR is 1.16 times greater than that by RB at the same roof area.

It is noteworthy that the effectiveness of LID practices does not increase in proportion with the increase in implementation areas, for the baseflow generated by 100 % LID implementation is not two times greater than that by 50 % LID implementation. Therefore, it is necessary to make a cost–benefit analysis to select a suitable scale and storage volumes before the LIDs are applied.

For permeable pavement, linear correlation between baseflow and effective storage is expressed as: $Q_b = aS_e + b$, where Q_b is the baseflow (10^3 m^3), S_e is the effective storage (mm) and a and b are statistical parameters. As shown in Table 5, there is a positive linear correlation between baseflow and effective storage with a coefficient of determination (R^2) of 0.99. Baseflow increases with increasing effective storage. With the increase in rainfall amount, the slope of linear equations becomes steeper, which illustrates that the effective storage has great influence on increasing baseflow in heavy rain and rainstorm events.

Figure 7 shows the baseflow increment resulting from LID practices compared to the baseflow in the absence LID practices. The CN values are the same in the two cases of RB implementation and without RB implementation, indicating that baseflow is unchanged in both cases. However, GR and PP implementations resulted in an increase in baseflow volume by 5.16–12.46 and 2.68–60.93 × 10^3 m^3, respectively. Contrary to the hydrological effect on runoff, the hydrological impact on baseflow volume increases alongside the amount of rainfall.

The CN method is widely used for LID practices evaluation (Damodaram and Giacomoni 2010; Ahiablame et al. 2012; 2013b) and forms the basis for a variety of other models, for instance the SCS model, THIA-LID and L-THIA-LID (Ahiablame et al.

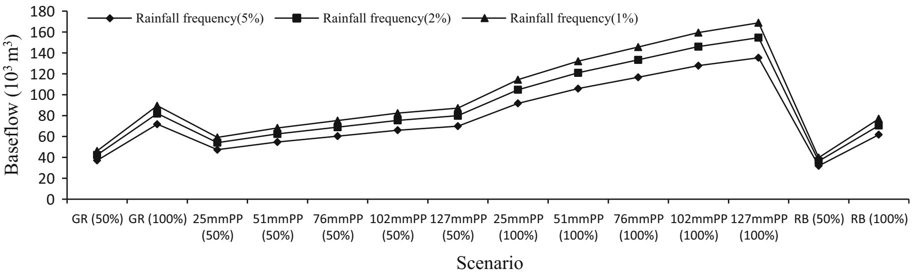

Fig. 6 Baseflow at different rainfall frequencies

Table 5 Relationship between baseflow (Q_b) and effective storage (S_e) at different rainfall frequencies

Rainfall frequency (%)	Simulation equation	R^2
5	$Q_{b1} = 0.220S_e + 42.798$	0.990
	$Q_{b2} = 0.429S_e + 82.846$	0.990
2	$Q_{b1} = 0.253S_e + 48.890$	0.990
	$Q_{b2} = 0.490S_e + 94.645$	0.990
1	$Q_{b1} = 0.276S_e + 53.376$	0.990
	$Q_{b2} = 0.535S_e + 103.335$	0.990

Q_{b1}, baseflow generated by 50 % implementation; Q_{b2}, baseflow generated by 100 % implementation; S_e, effective storage

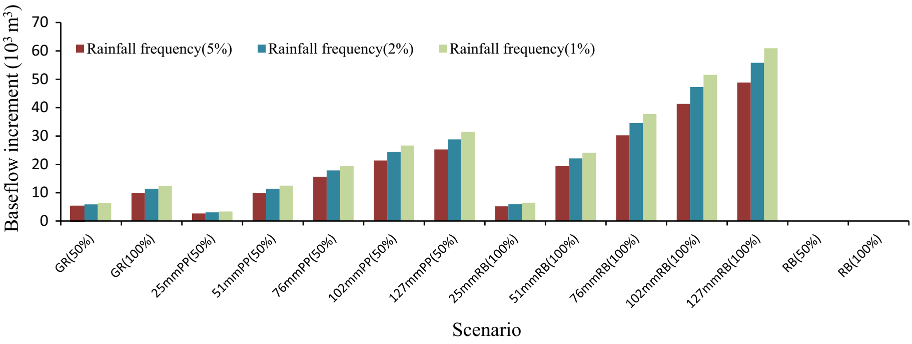

Fig. 7 Baseflow increment resulted from the different LID practices

2013b). However, it is difficult to set the CN values to represent LID practices accurately. In this study, the CN values are based on previous studies, so that biases in the simulated results are likely. Moreover, this study lacks data on runoff volume in the study area, and as a result, the model cannot be calibrated and validated to reduce biases. However, since performance evaluation is based on scenario comparison, it does not directly simulate observed results. For this reason, the impact of the biases on the calculated results due to uncertainties of CN values is negligible and does not diminish the value of the findings presented in this study.

5 Conclusions

This study estimates the effects of three LID practices on runoff and baseflow based on SCS model and baseflow equation in a high-density residential district of Nanjing, China. The results show that green roofs, permeable pavement and rain barrels are effective for urban stormwater runoff management. Green roofs, permeable pavement and rain barrels have the hydrological effects of reducing runoff, and green roofs and permeable pavement have the additional effect of increasing baseflow. In built-up urban areas, all three LID practices are practicable retrofitting technologies for urban stormwater runoff management.

Runoff generated by green roofs is relevant to precipitation, whereas runoff generated by permeable pavements and rain barrels are relevant to precipitation and effective storage. For permeable pavement and rain barrels, there is a negative linear correlation between runoff depth and effective storage. The effectiveness of runoff reduction resulting from rain barrels is better than that resulting from permeable pavement at the same effective storage.

Baseflow generated by 100 % LID implementation is 1.94 times greater than that by 50 % LID implementation. This finding indicates that the effectiveness of LID practices does not increase in proportion to the increase in implementation areas; therefore, it is necessary to make a cost–benefit analysis to select suitable scales and storage volumes before LIDs are applied. In addition, baseflow generated by green roofs is 1.16 times greater than that by rain barrels in the same roof area. For permeable pavement, there is a positive linear correlation between baseflow and effective storage, and the effects of effective storage on baseflow are greater under conditions of high-intensity rainfall.

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