


A comparative study on rainfall runoff control indicators of green roof

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ABSTRACT

The rainfall runoff reduction effect on green roofs was analyzed and tested by comparative rainfall runoff monitoring on impermeable roofs (sloping, plane). The evaluation index of rainfall runoff interception benefit (relative runoff reduction rate, rainfall control rate) on green roofs was studied. The results show that compared with sloping and level roofs, the change range of green roof runoff reduction rate relative to level and sloping roofs is 20.0–98.3% and 3.8–92.3%, and the mean value is 48.4% and 34.3% respectively. It is obvious that the green roof has better rainfall runoff reduction effect. It can be seen from the single rainfall control effect that the variation range of green roof rainfall runoff control rate is 36.0% to 99.0%, and the total rainfall control rate is 57.6%, which reflects that the green roof has the better rainfall control effect. Through comparative study, it can be concluded that the rainfall runoff control rate is more suitable for the design index of green roofs.

Key words | comparative study, evaluation index, green roof, rainfall monitoring, rainwater resources

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INTRODUCTION

As an important type of urban surface unit, building roofs have an important impact on urban environmental effects. In the past, building roofs in urban areas were mainly impermeable, which amounts to 40% to 50% of urban impervious surface (including road, pavement, etc.) (Li *et al.* 2019). This is one of the important factors that cause a series of environmental problems of urbanization, such as the ‘heat island effect’, ‘rain island effect’, rain flood problems and so on (Vahdati *et al.* 2017). Therefore, how to effectively reduce the building roof rainfall runoff and make efficient use of intercepted rainfall water has become an important issue (Dunnett & Kingsbury 2008).

Green roof, also known as roof greening, is a new type of roof structure which takes the traditional impermeable roofs as the carrier and plants as the top configuration. The structure from top to bottom is vegetation layer, sub-layer, filter layer, drainage layer and waterproof layer. The green roof slope is generally less than 4% (Susca *et al.* 2011).

Nowadays, as an important part of urban green infrastructure, the green roof has attracted much attention because it

can effectively reduce storm runoff, alleviate the heat island effect and reduce building energy consumption (Bannerman *et al.* 1993; Gilbert & Clausen 2006; Berndtsson 2010).

Some research findings have shown that the comprehensive environmental benefits of the green roof are obvious. Firstly, the vegetation layer has high green landscape value, and it can absorb the heat of the surrounding environment through the action of plant evaporation, and effectively reduce the urban temperature and alleviate the heat island effect. Several research findings have shown that green roofs could weaken the heat island effect by up to 20% (Monterusso *et al.* 2005). Secondly, the plants of the vegetation layer can effectively reduce the indoor temperature in the building through reflecting and blocking solar radiation, so that it can reduce the energy consumption of air conditioning both in summer and winter, which receives desirable energy-saving effects (Nagase & Dunnett 2012). Thirdly, the vegetation layer could maintain the rainwater absorption capacity through evapotranspiration (Wolf & Lundholm 2008), while the plant stems and leaves also

have an interception effect on the rainwater (Kang *et al.* 2008), and will gradually increase such ability with the increase of vegetation plant height, coverage and biomass (Gupta & Saul 1996). A UNESCO study showed that if there is more than a 70 percent roof green rate in a city, the city's CO₂ content will drop by 80 percent, and the heat island effect will disappear completely (Wang & Li 2011; Liu *et al.* 2015).

Unfortunately, in the past, a lot of research results have mainly focused on the roof greening structure, the thermal performance of the green roof, the evaluation of energy saving, the ecological benefit and so on, and few people have paid attention to the study of quantitative rainfall interception, the interception effect and the determination of quantitative design indexes of the green roof. At the present, research on the performance of the interception effect of the green roof is mainly focused on performance research based on measurement and the theoretical model based on measurement (Gibson *et al.* 2016). There are few quantitative data on green roof rainfall runoff and few indexes to support green roof design (Berndtsson 2010).

Therefore, in this paper, the rainfall runoff reduction effectiveness of the green roof is analyzed and studied through rainfall runoff comparative measurement with the traditional impermeable roof and the green roof, and a comparative study of the evaluation indexes of the green roof rainwater benefit is carried out and discussed. It is certain that the present findings should provide reference for extending and developing green roof construction technology.

RAINFALL MONITORING AND CALCULATION METHODS ON BUILDING ROOFS

Building roof sample selection and configuration

Three types of building roof sample were selected in Zhengzhou, i.e., a level roof (slope: 0%), with an area 219 m², which is covered with a waterproof asphalt layer; a sloping roof (slope: 5%), with an area of 185 m², the roof material of a reinforced steel concrete mixture, and a sloping green roof (slope: 5%), with an area of 165 m², which was covered by a vegetation layer (grass, about 5 cm high). Several kinds

of grasses were selected on the sloping green roof, which have the features of drought tolerance and water saving, heat insulation and cooling, easy management, etc. The matrix layer consists of peat, vermiculite and sandy soil. The ratio (peat:vermiculite:sandy soil) is 4:2:1. The matrix layer has the advantages of light weight, water permeability, water holding, stable performance and convenient maintenance. The thickness of the matrix layer is 6 cm, and the bottom layer is lined with filter cloth (thickness 1–2 cm) to prevent medium loss (Figure 1).

The drainage layer is 5 cm thick, and is made of light-weight plastic, evenly arranged in a bowl-shaped structure to carry runoff and has a drainage outlet. Each roof corresponds to a drop pipe (diameter 110 mm).

Rainfall runoff monitoring methods

The rainfall process was monitored through rain gauges on the roofs, and the rainfall data in different time intervals could be obtained as required.

The roof rainfall runoff process was measured using two methods, i.e., a 'level gauge' and triangular weir, to realize continuous water level and discharge monitoring (Figure 2).

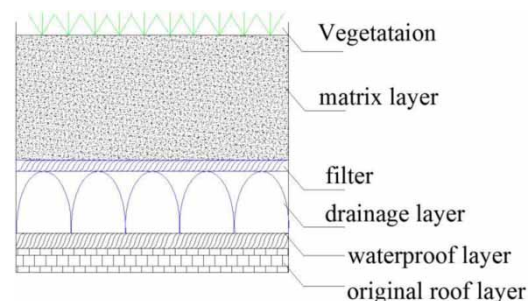


Figure 1 | Green roof structure.

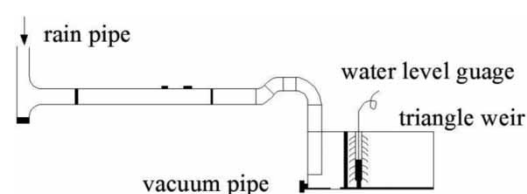


Figure 2 | Schematic diagram of water level and discharge monitoring.

The top angle of the triangular weir is 30° . The bottom area of the triangle weir for the level and sloping roofs is 0.51 m^2 , the bottom area of triangle weir for the green roof is 0.46 m^2 .

Calculation methods

(1) *Rainfall runoff on roofs before overflow*: Before the overflow of the triangular weir, the volume of roof runoff is the product of the water level difference at the beginning and the end of the time interval and the bottom area of the weir:

$$V = (h_{i+1} - h_i) \times A \quad (1)$$

in which V is the roof runoff volume, m^3 ; h_i , h_{i+1} , are the water level at the beginning and the end of the time interval separately, m ; A is the bottom area of the weir, m^2 .

(2) *The discharge over the weir after overflow*: After overflow, the discharge over the weir can be calculated by using the Kindsvater-Shen formula:

$$Q_w(t) = C_D \frac{8}{15} \tan\left(\frac{\theta}{2}\right) \sqrt{2g} H_e^{\frac{5}{2}} \quad (2)$$

in which $Q_w(t)$ is the overflow through the triangular weir, m^3/s ; θ is the top angle of the triangular weir, 30° ; C_D is the discharge coefficient, 0.65, which is related to the shape of the triangular weir; H_e is the effective hydraulic head, m ; g is gravitational acceleration, m/s^2 .

(3) *The equation of flow continuity after triangular weir overflow*: (Ouyang *et al.* 2012) According to the principle of mass conservation, the equation of flow continuity after overflow of the triangular weir is as follows:

$$\frac{S_{i+1} - S_i}{\Delta t} = \frac{Q_{r,i+1} + Q_{r,i}}{2} - \frac{Q_{w,i+1} + Q_{w,i}}{2} \quad (3)$$

in which S_{i+1} , S_i are the storage capacity of the triangular weir at times $i+1$ and i respectively, m^3 ; $Q_{r,i+1}$, $Q_{r,i}$ are the inflow from the roofs at times $i+1$ and i respectively, m^3/s ; $Q_{w,i+1}$, $Q_{w,i}$ are the outflow from the roofs at times $i+1$ and i respectively, m^3/s ; Δt is the calculation time interval, s ; i is the number of the time interval.

Combining Equations (2) and (3), when the triangular weir begins to overflow, the roof flow process is obtained by step-step reverse calculus on the basis of the water

level and flow calculation passing over the weir. Such a flow process also reflects the rainfall intercepted and discharged (interception and discharge) (Prasetya *et al.* 2016).

RAINFALL WATER BENEFIT ASSESSMENT INDICATORS

Rainfall runoff coefficient

The rainfall runoff coefficient is one of the important parameters reflecting the rainfall-runoff relationship, which is defined as the ratio of runoff depth to rainfall in a catchment area:

$$\alpha = \frac{R}{P} \quad (4)$$

in which α is rainfall runoff coefficient; P is rainfall, mm ; R is runoff depth, mm .

Relative rainfall runoff reduction rate

To compare the relative rainfall runoff reduction effect among different types of roofs, the relative rainfall runoff reduction index is introduced, as the following formula:

$$D_r = \frac{P_{\alpha_1} - P_{\alpha_2}}{P_{\alpha_1}} \times 100\% = \frac{\alpha_1 - \alpha_2}{\alpha_1} \times 100\% \quad (5)$$

in which D_r is rainfall runoff relative reduction rate of roof type 2 relevant to roof type 1; α_1 and α_2 are the rainfall runoff coefficients of roof type 1 and type 2 under the same rainfall condition respectively; P_{α_1} , P_{α_2} is rainfall relative to rainfall coefficient α_1 and α_2 respectively.

Under the same rainfall condition, when $D_r > 0$, it indicates the rainfall runoff of roof type 2 is less than roof type 1. When $D_r < 0$, it indicates that the rainfall runoff of roof type 2 is greater than type 1; when $D_r = 100\%$, it indicates that rainfall runoff is completely reduced for roof type 2 relative to type 1.

Rainfall runoff control rate

The rainfall runoff control rate refers to the ratio of controlled rainfall (retained on the roof) to the total rainfall. The formula is:

$$E = \frac{P - R}{P} \times 100\% = (1 - \alpha) \times 100\% \quad (6)$$

in which E is the rainfall runoff control rate; P is the total rainfall, mm; R is the runoff, mm.

The total rainfall runoff control rate can be obtained by the weighted average of all rainfalls.

RESULTS AND ANALYSIS

Relative runoff reduction effect

From June to August 2019, the rainfall runoff processes of the level, sloping and green roofs were continuously monitored, and 20 effective rainfall runoff data were monitored, ten as shown in Table 1.

It can be seen from Table 1 that rainfall ranges from 3.6 to 55.6 mm. The variation ranges of rainfall runoff coefficient for level, sloping and green roofs are 0.14–0.72, 0.19–0.96 and 0.01–0.35 respectively. The weighted average values of runoff coefficient combined with rainfall are 0.63, 0.81 and 0.31, respectively. The order from large to small is: sloping roof > level roof > green roof. On the whole, the runoff coefficient of different roofs increases with the

Table 1 | Statistics of rainfall runoff for three types of roofs in Zhengzhou

No.	Time period	Rainfall (mm)	Roof runoff coefficient		
			level	sloping	green
1	02:53 – 05:40, 6 Jun. 2019	38.2	0.68	0.96	0.26
2	21:32 – 22:38, 6 Jun. 2019	10.5	0.63	0.93	0.12
3	14:20 – 16:40, 30 Jun. 2019	15.6	0.21	0.78	0.15
4	07:10 – 11:00, 31 Jun. 2019	26.7	0.35	0.65	0.25
5	20:40 – 21:10, 23 Jul. 2019	5.6	0.14	0.51	0.05
6	20:10 – 23:50, 28 Jul. 2019	55.6	0.72	0.93	0.35
7	08:15 – 09:40, 29 Jul. 2019	6.5	0.24	0.55	0.16
8	21:55 – 22:55, 1 Aug. 2019	9.5	0.16	0.60	0.07
9	02:15 – 08:15, 2 Aug. 2019	3.6	0.15	0.19	0.01
10	20:00 – 21:00, 3 Aug. 2019	15.8	0.65	0.85	0.16

increase of rainfall intensity and volume, and it is also influenced by factors such as rainfall intensity in the early stage and the interval between two rainfalls, which is obviously reflected in the change of green roof runoff coefficient. For example, for rainfall no. 7, due to the heavy rainfall of no. 6, the accumulated rainfall reached 55.6 mm, and the interval between the two rainfalls was short (less than 9 h), resulting in the green roof runoff coefficient of 0.16, which is obviously affected by the former rainfall intensity and volume (Teemusk & Mander 2007).

Taking the sloping and level roof as reference roofs respectively, sorted by runoff from small to large, the relative reduction rates of green roof runoff were calculated according to Equation (5), and the results are shown in Figure 3.

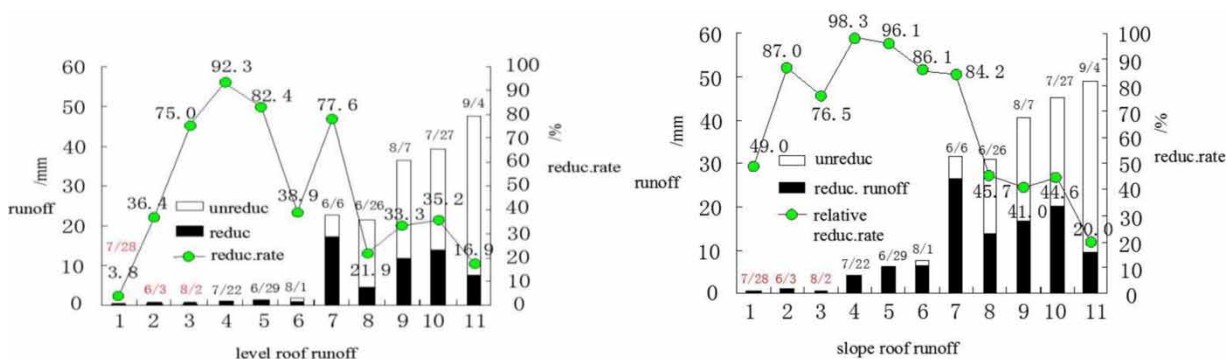


Figure 3 | Runoff reduction rates of green roof relative to sloping and level roofs.

It can be seen from Figure 3 that the variation range of runoff relative reduction rate for the green roof relative to the sloping and the level roof is 20.0% to 98.3%, and 3.8% to 92.3%, respectively, and the weighted average runoff relative reduction rate combined with runoff volume is 48.4% and 34.3%, respectively, and the runoff relative reduction effect is obvious.

Effect of rainfall control

Based on Table 1, the order of rainfall is from small to large, and the rainfall control rate of the green roof is calculated according to Equation (6). The results are shown in Figure 4.

It can be seen from Figure 4 that the change variation of green roof rainfall control rate is from 36.0% to 99.0%, and the average rainfall control rate is 57.6%.

If the rainfall sequence with shorter interval is not considered, the green roof can achieve completely controlled rainfall in the ideal state, which reflects that the green roof has the better rainfall control effect.

COMPARISON AND DISCUSSION OF INDICATORS

Two indicators were used to evaluate, analyze and compare green roof runoff reduction effect, i.e. runoff relative reduction rate and rainfall control rate. The following problems exist for runoff relative reduction rate. (1) The relative reduction rate of green roof runoff varies according

to the materials and types of the roofs (see Figure 1), which increases the difficulty of research. (2) It is difficult to achieve uniform criteria. The relative reduction rate of runoff is a quantitative index to describe the relative reduction effect of runoff. As for the extent of the reduction, it is difficult to reach a unified standard because any green roof has different materials and forms. (3) It is difficult to define exact indicators to support green roof design. Therefore, it is difficult to form a unified green roof design standard because of different roof materials, roof types, different rainfall runoff effect, and different requirements for green roof runoff reduction (Zhang & Guo 2013).

Through comparative analysis, the index of rainfall control rate is more reasonably an indicator for green roof design. The advantages are as follows:

1. Simple concept, stable control relationship. It is based on the rainfall runoff relationship of the green roof itself, it does not involve reference to the roof runoff comparison problem, and the rainfall control relationship is stable.
2. The target is clear and the criterion is reasonable. By comparing the green roof rainfall control rate with the requirement of the rainfall controlled, the green roof rainfall control standard can be easily judged.
3. Strong support to green roof design. From the point of view of rainfall control, the design of the green roof can be effectively guided by the index of rainfall control rate according to the indicator of unreleased rainfall.

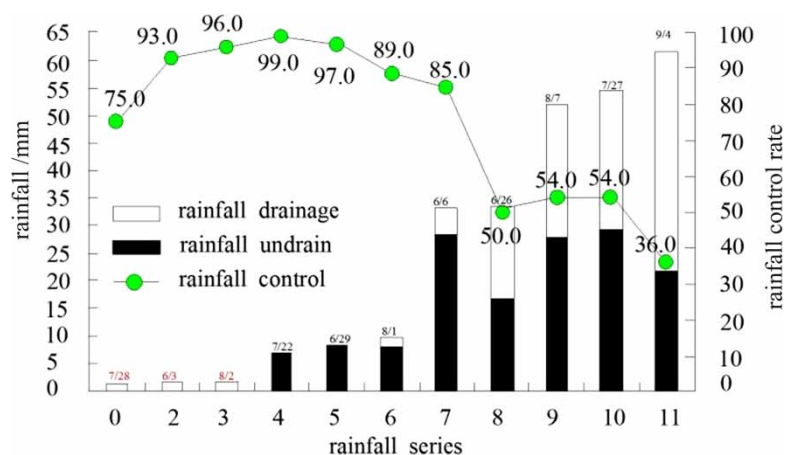


Figure 4 | Rainfall control rate of green roof.

By comparison of rainfall runoff relative reduction rate calculation Equation (5) and rainfall control rate calculation Equation (6), the two indicators are equivalent under certain conditions:

1. When the reference roof runoff coefficient is 1.0, the relative reduction rate of rainfall runoff is equal to 0. However, because the reference roof rainfall runoff coefficient is generally not equal to 1.0, the relationship between the two indicators is mostly affected by the change of the reference roof rainfall runoff coefficient.
2. When the green roof runoff coefficient is equal to 0, the control rate of rainfall and the relative reduction rate of runoff are 100%, which shows that the green roof can completely achieve rainfall runoff reduction.

CONCLUSIONS

- (1) The monitoring results of different roof rainfall runoffs show that the variation ranges of level, sloping and green roof rainfall runoff coefficients are: 0.14–0.72, 0.19–0.96 and 0.01–0.35, and the mean values are 0.63, 0.81 and 0.31 respectively. The order from large to small is: sloping roof > level roof > green roof.
- (2) As for the rainfall runoff reduction effect, the change range of green roof rainfall runoff reduction rate relative to level and sloping roofs is 20.0–98.3% and 3.8–92.3%, and the mean value is 48.4% and 34.3% respectively, and the relative reduction effect of rainfall runoff is obvious. It can be seen from the single rainfall control effect that the variation range of green roof rainfall runoff control rate is 36.0% to 99.0%, and the average rainfall control rate is 57.6%, which reflects that the green roof has the better rainfall control effect.
- (3) Comparing the relative rainfall runoff reduction rate with the index of rainfall control rate of the green roof, it is often difficult to find a consistent change law for the former because of the different roof materials and types, so it is difficult to establish a unified identification standard to support green roof design. The latter is based on the rainfall runoff relationship of the green roof itself, the control relationship is stable, the target is clear, the identification standard is reasonable, and it is more

suitable for evaluation of the green roof rainfall interception effect.

- (4) It is suggested that more kinds of roof materials and design types, as well as grass plantations, should be selected to find the best design indicators for green roof construction.

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