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Hydrologic performance of bioretention in an expressway service area

Jianping Gao, Junkui Pan, Ning Hu and Chengzuo Xie

ABSTRACT

Bioretention can be an effective measure for stormwater treatment. However, there is a lack of systematic analysis of the impact of bioretention design parameters on hydrologic performance. Herein, SWMM and RECARGA models were applied to generate the typical annual rainfall runoff and simulate the water balance of the bioretention system in an expressway service area. The purpose of the investigation was to identify key design parameters for the bioretention system and delineate the priorities in developing the design. Results showed that the average groundwater recharge ratios for bioretention basins with and without an underdrain were 58.29% and 92.27%, respectively, the average overflow ratios were 4.13% and 4.19%, the average evapotranspiration ratios were 4.48% and 4.47%, and the average outflow ratio for bioretention with an underdrain was 33.94%. The ratio of the bioretention area to drainage area, and the saturated infiltration rates of planting soil and native soil were the main factors influencing water balance, while the underdrain diameter and gravel layer depth exerted little effect. Based on the impact analysis, multivariate nonlinear regression models of runoff reduction rate for two types of bioretention basin were established, which both exhibited high determination coefficients and acceptable Nash–Sutcliffe coefficients.

Key words | bioretention, bioretention design, expressway service area, hydrologic performance, rainwater runoff

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INTRODUCTION

With the rapid development of China's expressway network, the demand for expressway service areas is also increasing (Chen 2013). However, impervious areas such as roofing and hardened pavement constitute over 70% of the expressway service area, which leads to reduced rainfall infiltration and destruction of the natural hydrological balance, as well as many problems regarding rainwater discharge (Li 2011). In addition, expressway service areas involve a large amount of motor vehicles, and rainwater runoff thus typically contains many pollutants, including suspended solids (SS), chemical oxygen demand (COD), heavy metals, nutrients (P, N), petroleum by-products, etc. (Lin 2013; Ye *et al.* 2013), which have serious adverse impacts on the local and the regional water environments.

Bioretention basins, also known as rain gardens, are an efficient LID (low impact development) measure designed to reduce rainwater runoff and control pollutant migration from the source (Fletcher *et al.* 2014; Li *et al.* 2014). Bioretention can simulate the hydrologic conditions prior to regional development by slowly exfiltrating water to the surrounding soil and by evapotranspiration (Mangangka *et al.* 2015; Gülbaz & Kazezyılmaz-Alhan 2016; Winston *et al.* 2016). Moreover, bioretention can utilize the chemical, biological, and physical properties of plants, microbes, and soils to remove contaminants from rainwater runoff, thereby improving the quality of runoff water (Palmer *et al.* 2013; Wang *et al.* 2016). In recent years, bioretention has been widely used to control rainwater and runoff pollution in many developed countries (Peng *et al.* 2011).

Relevant studies have shown that bioretention design parameters significantly affect the hydrologic performance of the facility (Sun *et al.* 2011; Tang *et al.* 2015; Li *et al.* 2016). Li *et al.* (2009) found that bioretention showed good performance at

doi: 10.2166/wst.2018.048

reducing peak flow and total runoff volume. Furthermore, the larger the media layer depth, the greater the amount of water infiltration and evapotranspiration, and the closer it approached the LID goal. Sun & Wei (2011) showed that a larger bioretention area led to a greater runoff reduction rate and groundwater recharge ratio, and shorter ponding duration. Yin *et al.* (2015) showed that bioretention basins with large particle filter media had a better infiltration capacity than those with traditional filter media, and significantly reduced the overflow volume and the ponding time. Brown *et al.* (2010) found that a larger saturated hydraulic conductivity of the native soil led to greater runoff reduction and groundwater recharge. However, current research is predominantly focused on determining the influence of single design parameters on the hydrologic performance of bioretention. A systematic study and comparative analysis of different design parameters on the water balance and runoff reduction rate is lacking. Moreover, most current studies are based on single rainfall events, ignoring the hydrologic performance of bioretention under long-term continuous rainfall.

The objectives of the present study are to investigate the influence of major bioretention design parameters on water balance and runoff reduction rate under typical annual rainfall in an expressway service area, and establish the relationship between runoff reduction rate and these parameters in order to provide a theoretical reference for future bioretention design.

BIORETENTION STRUCTURAL DESIGN

Bioretention basins generally consist of a surface ponding area, a mulch layer, a planting soil layer, a gravel layer, and an underdrain (MOHURD 2014). The bioretention system should have a dispersed distribution and not be too large, typically 5–10% of the overall drainage area.

The ponding area is located on the surface of the basin and acts as a temporary storage of rainwater runoff. The depth is determined according to plant flood tolerance and soil permeability, usually ranging from 200 cm to 300 cm. When ponding exceeds the maximum depth of the ponding area, runoff will flow out through the overflow outlet located on the surface.

The mulch layer is located at the top of the bioretention basin, and typically consists of fresh broken bark. The depth is typically 50–100 mm. This layer can effectively adsorb and trap most of the heavy metals and some organic pollutants present in rainwater runoff, and can act as a carrier for the growth of microorganisms and also prevent soil erosion.

The planting soil layer can provide water and nutrients for plant growth, and often consists of highly permeable sandy soils. The thickness of the layer is determined according to plant type and water quality requirement (generally 250–1,200 mm). The soil layer contains many types of microorganisms, which can promote the decomposition of organic compounds. Clay particles in the soil can effectively adsorb heavy metals, nutrients, hydrocarbons, and other pollutants present in rainwater runoff.

The gravel layer is located at the bottom of the bioretention basin, at a depth of typically 250–300 mm; it is highly porous, and with a particle size of 5–20 mm. Its main function is to temporarily collect and store some of the rainwater infiltrating into the facility.

The underdrain is wrapped in the gravel layer, and its diameter is typically 100–150 mm. Its role is to strengthen the drainage capacity of the facility to ensure timely removal of water. When the native soil under the basin meets certain permeability requirements (greater than 1.32 cm/h), the underdrain does not need to be installed (PGC 2007).

The typical structure of a bioretention cell is shown in Figure 1.

STUDY AREA

An expressway service area was used as the study area. The area of the service area is 18,503.1 m^2, and the impervious area is composed of a roof, parking lot, traffic road, and fueling area, which together account for 88.3% of the total area. The service area is topographically higher to the northeast, and lower to the southwest, with a slope of 2%. Rainwater runoff discharges into the stormwater inlet along the vertical and horizontal slope and subsequently into the roadside ditch. The hardened area of the site is large, and the comprehensive runoff coefficient is approximately 0.8, resulting in a large runoff effluent load and the risk of waterlogging. In addition, a large volume of rainwater runoff is discharged without effective use, resulting in a loss of rainwater resources. The layout of the expressway service area is shown in Figure 2.

Figure 3(a) shows the annual rainfall distribution in the study area from 1951 to 2013. The most arid year in the study area was 1958, with a total rainfall of 738 mm, while the most abundant rainfall year was 2011, with total rainfall of 1,513 mm. The average rainfall for the study period is 1,090 mm. In 2010, rainfall was 1,045 mm, which is close to the average annual rainfall; therefore, the 2010 rainfall

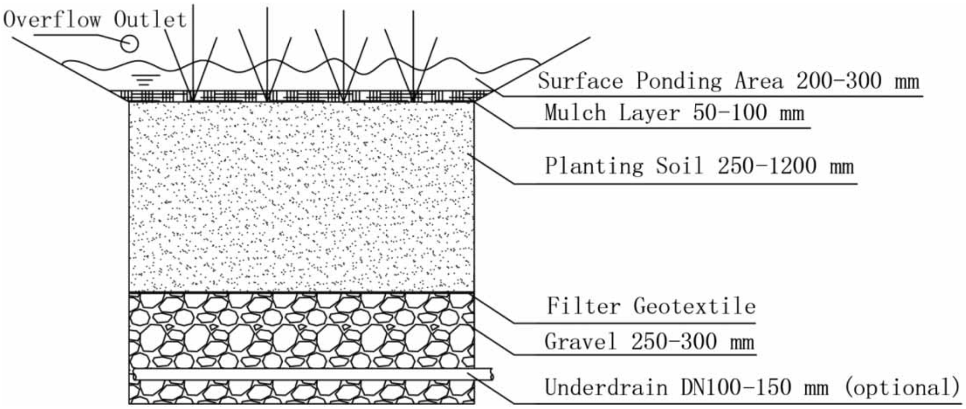

Figure 1 | Cross section of a typical bioretention cell.

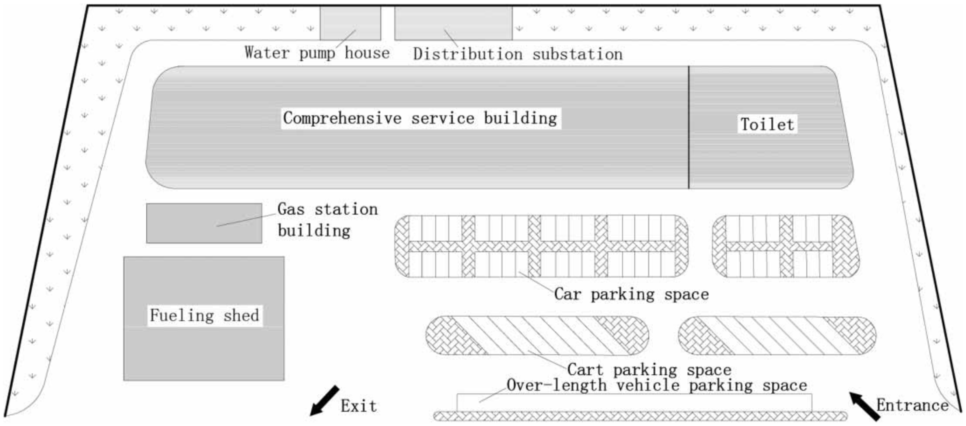

Figure 2 | Layout of the expressway service area used in this study.

data were used as the typical annual rainfall for the study area.

The distributions of hourly rainfall and daily evaporation in the study area in 2010 are shown in Figure 3(b) and 3(c). In 2010, there were 113 rainfall events, with most rainfall being distributed between June and August, and accounting for 56.8% of the total annual rainfall. The daily evaporation trend shows a partial normal distribution, and the largest evaporation months were July and August, in which the average daily evaporation reached 3.18 mm and 4.24 mm, respectively.

METHODOLOGY

To investigate the application of bioretention basins in stemming rainwater runoff, a series of simulation events were run to demonstrate the importance of design parameters in developing the design.

Model approach

The runoff simulation was divided into two parts: surface runoff generation in the study area and the water infiltration and the discharge process in the bioretention basin. Surface runoff generation was simulated using the SWMM model. The surface runoff calculation module of SWMM adopts a nonlinear reservoir method. By simultaneously adopting the continuity equation and the Manning equation, the surface runoff generated by each sub-catchment area was calculated. The water infiltration and the discharge process in the bioretention basin were simulated using the RECARGA model – a mathematical model made specifically for bioretention design. This model uses the Green–Ampt equation to simulate the process of rainwater runoff infiltration into soil. The Van Genuchten equation is used to simulate the soil water discharge process. The model can continuously simulate the transport process of moisture in the basin, and record the

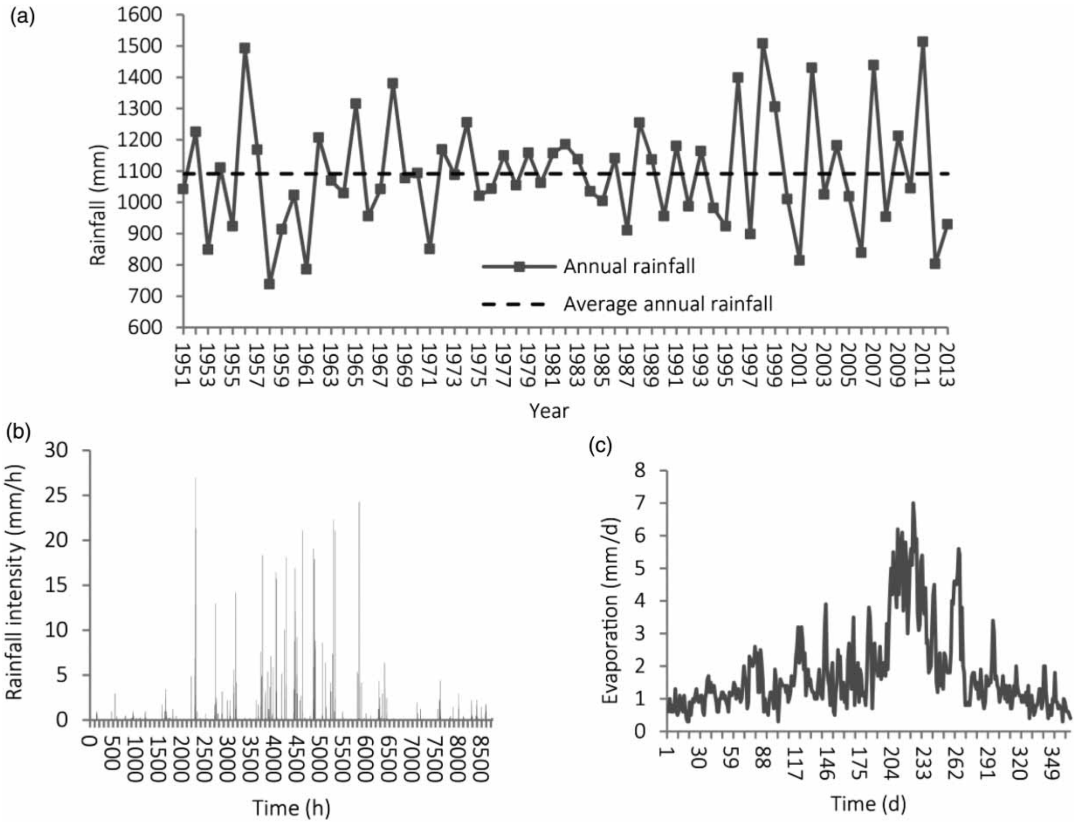

Figure 3 | Distribution of rainfall and evaporation in the study area: (a) Annual rainfall in the study area from 1951 to 2013, (b) hourly rainfall distribution in the study area in 2010 and (c) daily evaporation pattern in the study area in 2010.

water balance, including exfiltration, overflow, underdrain flow, and evapotranspiration.

SWMM and RECARGA were applied together to simulate the hydrologic response of bioretention in the expressway service area. Firstly, the SWMM model made a reasonable generalization of the study area, and hourly rainfall and daily evaporation data from 2010 were used to generate runoff-time data. Subsequently, the generated data were applied to the RECARGA model to obtain the ratio of water balance elements and the runoff reduction rate under different bioretention design schemes. Finally, the influence of design parameters on the hydrologic performance of the bioretention basin was analyzed.

Design parameters

The ratio of bioretention area to drainage area (A_r), depth of the ponding area (D_p), thickness of the planting soil (T_p), saturated infiltration rate of the planting soil (K_p), depth of the gravel layer (D_g), saturated infiltration rate of the native soil (K_n), and diameter of the underdrain (D_u) were taken as the main bioretention design parameters, the values of which are shown in Table 1.

Data analysis

The long-term water balance elements of bioretention systems mainly include groundwater discharge (S), overflow (Y), underdrain flow (D) (not considered for bioretention without an underdrain), and evapotranspiration (Z). The total water amount of the four water balance elements is equal to the amount of rainwater runoff (W) entering the facility. The water balance formula is shown in Equation (1).

$$W = S + Y + D + Z \tag{1}$$

The runoff reduction rate (R) reflects the total ability of bioretention to reduce stormwater runoff, as shown in Equation (2).

$$R = \frac{S + Z}{W} \times 100\% \tag{2}$$

Table 1 | Main design parameters and values for a bioretention basin with and without an underdrain

Design parameter	Basic value	Value 1	Value 2	Value 3	Value 4
A_r (%)	7.5	5	6.25	8.75	10
D_p (cm)	25	20	22.5	27.5	30
T_p (cm)	72.5	25	48.75	96.25	120
K_p (cm/h)	3.695	1.27	2.4825	4.9075	6.12
D_g (cm)	27.5	25	26.25	28.75	30
K_n (cm/h)	0.69 (11.165)	0.06 (1.32)	0.375 (6.2425)	1.005 (16.0875)	1.32 (21.01)
D_u (cm)	12.5	10	11.25	13.75	15

Note: K_n values in parentheses represent those for bioretention without an underdrain.

RESULTS AND DISCUSSION

Statistical analysis of water balance

Using the simulation results of 35 bioretention design schemes with an underdrain, and 30 without an underdrain, the water balance was statistically analyzed. The statistical results are shown in Table 2. The underground discharge ratios of bioretention with and without an underdrain were the largest, and the average values (Table 2) were 58.29% and 92.27% respectively. The much higher underground discharge ratio for bioretention without an underdrain was caused by the larger saturated infiltration rate of native soil for bioretention without an underdrain, and the fact that a perforated drainage pipe was not installed, which effectively promoted the exfiltration of water. The average overflow ratios for bioretention with and without underdrains were 4.13% and 4.19%, respectively, and the average evapotranspiration ratios were 4.48% and 4.47%, respectively, which indicated an insignificant influence of bioretention drainage configuration on both the overflow ratio and the evapotranspiration ratio. In reviewing the standard deviation of different water balance elements, the most significant influence of design parameters was found to be on outflow ratio, followed by the underground discharge ratio and the overflow ratio, while the effect on evapotranspiration ratio was relatively small.

Impact analysis of bioretention design parameters on water balance elements

To compare and analyze the influence of different bioretention design parameters on water balance elements, each design parameter value was normalized, and dimensional data were transformed into dimensionless data. The normalized formula is shown in Equation (3).

$$x_0 = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{3}$$

where x_0 represents the normalized data for a bioretention design parameter value, x is the value of a bioretention design parameter, and $x_{\min}$ and $x_{\max}$ are the minimum and maximum values of a bioretention design parameter, respectively.

The influence of bioretention design parameters on each water balance element is shown in Figure 4.

Impact on overflow ratio

As shown in Figure 4(a), for bioretention with an underdrain, the overflow ratio decreased as A_r, D_p, T_p, and K_p

Table 2 | Statistical values of water balance elements for bioretention with and without an underdrain

Water balance element	*n*	Minimum value	Maximum value	Average value	Standard deviation
Overflow ratio (%)	35 (30)	0.72 (0.45)	15.31 (15.20)	4.13 (4.19)	2.74 (3.20)
Underground discharge ratio (%)	35 (30)	28.88 (81.22)	69.83 (95.41)	58.29 (92.27)	6.61 (3.04)
Evaporation (%)	35 (30)	3.04 (3.04)	5.88 (5.88)	4.48 (4.47)	0.39 (0.42)
Outflow ratio (%)	35	13.96	63.96	33.94	7.12

Note: Values in parentheses represent water balance elements for bioretention without an underdrain.

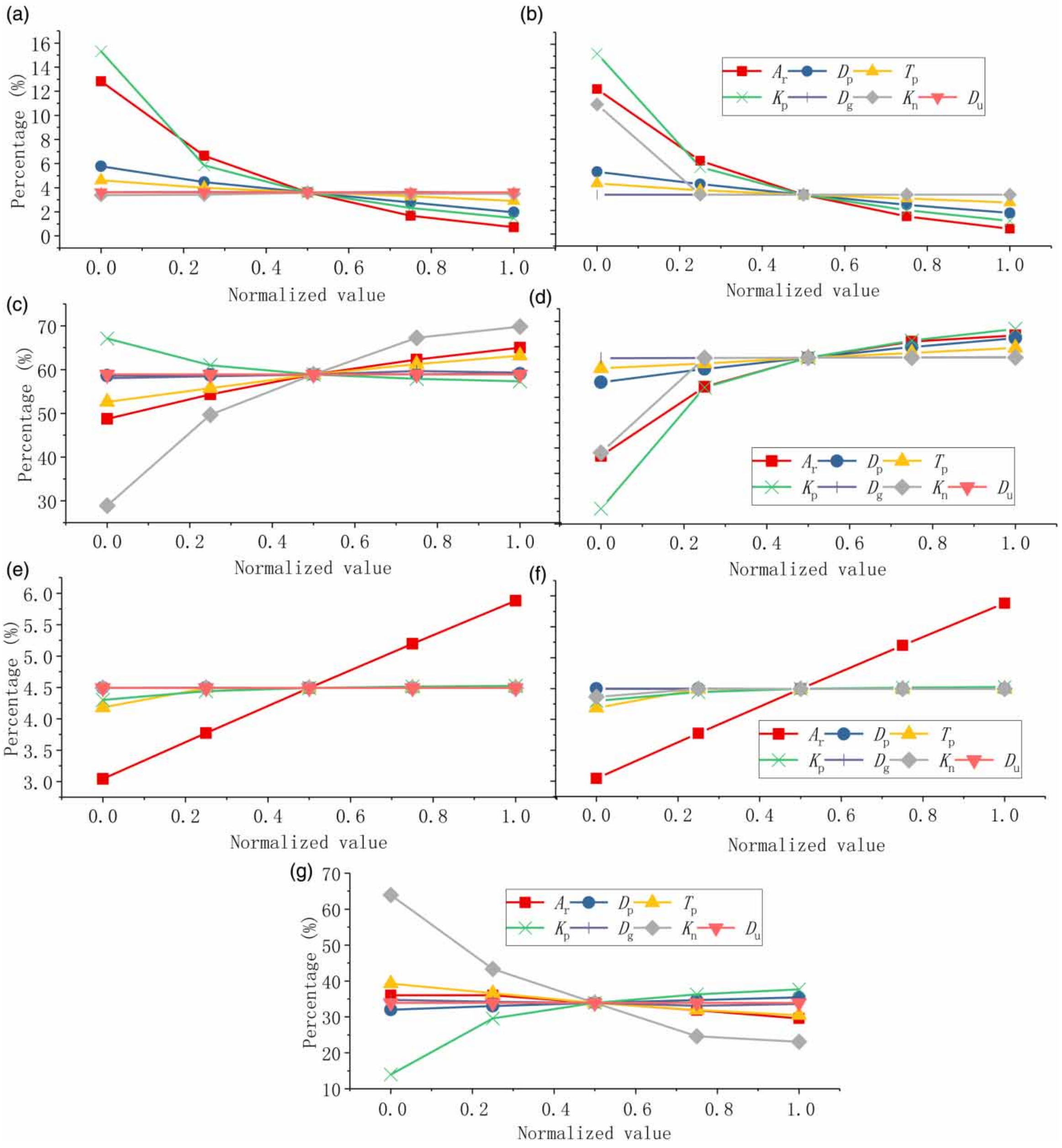

Figure 4 | Influence of bioretention design parameters on water balance elements: (a) and (b) overflow ratio, (c) and (d) underground discharge ratio, (e) and (f) evapotranspiration ratio and (g) outflow ratio, where (a), (c), and (e) are for a bioretention basin with an underdrain and (b), (d), and (f) are for a bioretention system without an underdrain.

increased. Among all the design parameters, A_r and K_p had the greatest influence on the overflow ratio, followed by D_p and T_p, while D_g, K_n, and D_u had little effect. The effect of A_r, D_p, T_p and K_p on the overflow ratio was similar for bioretention without an underdrain (Figure 4(b)), although the overflow ratio was higher, with a K_n value of 1.32 cm/h. This result can be attributed mainly to the fact that, when the saturated infiltration rate of native soil is lower than that of planting soil, the infiltration capacity of the bioretention basin is mainly determined by the saturated infiltration rate of the native soil. By contrast, when it is higher than the saturated infiltration rate of planting soil, the infiltration capacity depends mainly on the saturated infiltration rate of the planting soil.

Impact on underground discharge ratio

The underground discharge ratio of bioretention with an underdrain increased with an increase in A_r, T_p and K_n, and decreased with an increase in K_p (Figure 4(c)). K_n had the greatest influence on the underground discharge ratio, followed by A_r, K_p, and T_p, while D_p, D_g, and D_u had little effect. For bioretention without an underdrain, all design parameters except D_g influenced the underground discharge ratio (Figure 4(d)). Among them, A_r, K_p, and K_n were the most influential, followed by D_p and T_p. In addition, the effect of K_p on the underground discharge ratio differed for the two types of bioretention, and this outcome can be attributed to the installation of a perforated pipe at the bottom of the bioretention basin with an underdrain. The presence of this pipe meant that an increase in the saturated infiltration rate of planting soil promoted outflow from the underdrain, resulting in a relative decrease in water exfiltration.

Impact on evapotranspiration ratio

The impact of design parameters on the evapotranspiration ratio did not differ between the two types of bioretention basin (Figure 4(e) and 4(f)). Among them, water evapotranspiration ratio was predominantly affected by A_r, while other design parameters exerted relatively little effect.

Impact on outflow ratio

As shown in Figure 4(g), the outflow ratio increased with an increase in K_p and D_p, and decreased with an increase in K_n, T_p, and A_r. K_n and K_p had the greatest influence on the outflow ratio, followed by T_p, A_r, and D_p, while D_u and D_g had little effect.

Impact analysis of bioretention design parameters on runoff reduction rate

To analyze the effect of bioretention design parameters on the runoff reduction rate, the correlation between design parameters and runoff reduction rate was determined (Figure 5), and the relationships were evaluated based on the determination coefficient (R^2). The value of R^2 can range from 0 to 1, and the closer the value is to 1, the better is the curve fitting. The runoff reduction rate showed a positive linear relationship with A_r for bioretention both with and without an underdrain, with R^2 values of 0.9839 and 0.8955, respectively, indicating a high correlation. There was a logarithmic correlation between the runoff reduction rate and K_p and K_n. For bioretention with an underdrain, the R^2 values were 0.9516 and 0.9778, respectively, and for bioretention without an underdrain, the R^2 values were 0.927 and 0.8289, respectively, indicating significant correlations. For bioretention without an underdrain, both D_p and T_p had an effect on the

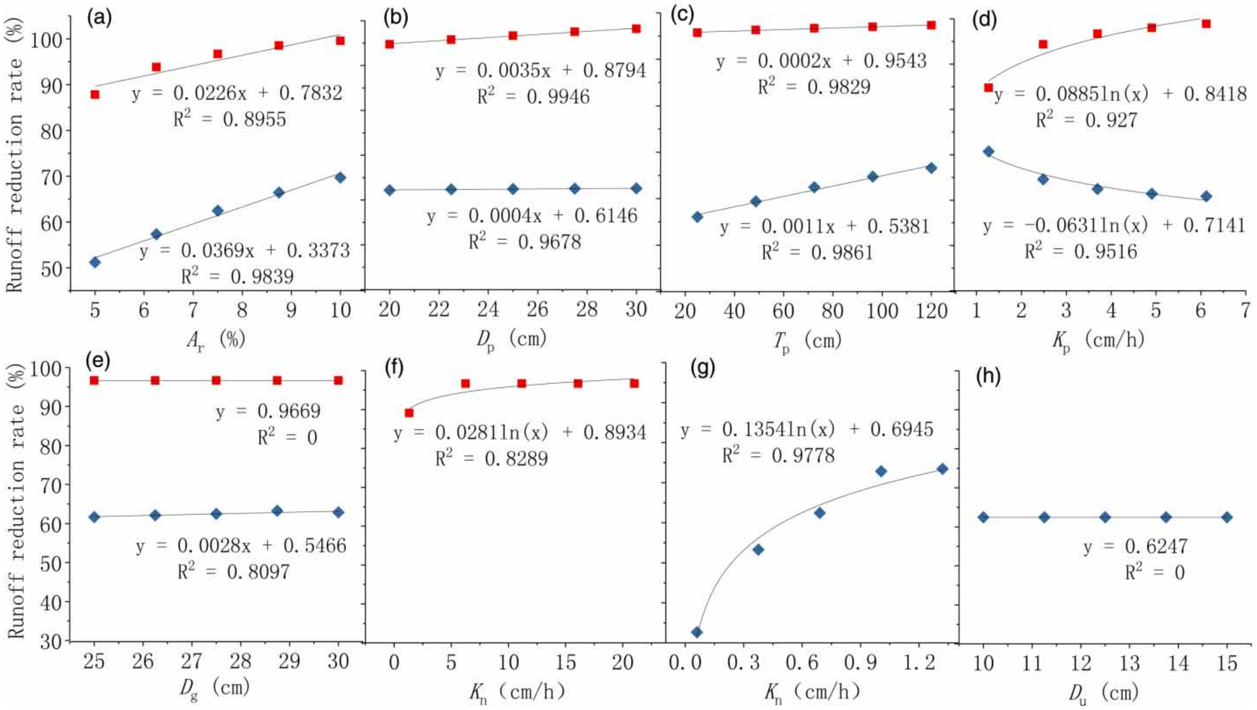

Figure 5 | Effects of bioretention design parameters on the runoff reduction rate: diamond and square symbols indicate bioretention basins with and without an underdrain, respectively.

runoff reduction rate, with R^2 values of 0.9946 and 0.9829, respectively, while D_g had little effect. For bioretention with an underdrain, the influence of T_p on the overflow ratio was more significant, with an R^2 of 0.9861, while other design parameters had little effect.

Predictive model of runoff reduction rate

These results show linear or logarithmic correlations between the runoff reduction rate and bioretention design parameters. Therefore, a multivariate nonlinear regression model of SPSS statistical analysis was applied to predict the runoff reduction rate of bioretention with and without an underdrain. The fit between the predicted and simulated values was evaluated using the R^2 value. The Nash–Sutcliffe efficiency coefficient (Ens) was chosen to verify the predicted results. Ens is a dimensionless statistical parameter between 0 and 1 that describes the accuracy of predicted values. The predicted results are acceptable when Ens is between 0.5 and 0.65, good when between 0.65 and 0.75, and excellent when over 0.75. The multiple regression model formulae for both types of bioretention are shown in Equations (4) and (5), and comparisons between the predicted and simulated results are shown in Figure 6.

$$y_1 = 36.218 + 4.298x_1 + 0.114x_3 - 6.994\ln x_4 + 13.048\ln x_5$$
$$\left(R^2 = 0.968,\ \text{Ens} = 0.652\right) \tag{4}$$

$$y_2 = 41.095 + 3.295x_1 + 0.342x_2 + 0.018x_3 + 10.115\ln x_4 + 3.214\ln x_5\ \left(R^2 = 0.936,\ \text{Ens} = 0.597\right) \tag{5}$$

where y_1 and y_2 is the runoff reduction rate for bioretention with and without an underdrain (%), respectively, x_1 is the ratio of the bioretention area to the drainage area (%), x_2 is the depth of the surface ponding area (cm), x_3 is the thickness of the planting soil (cm), x_4 is the saturated infiltration rate of the planting soil (cm/h), and x_5 is the saturated infiltration rate of the native soil (cm/h).

As shown in Figure 6, the R^2 values of the runoff reduction rate obtained using the regression model for bioretention with and without an underdrain were 0.968 and 0.936 in the prediction period, respectively, which indicated a good similarity between predicted and simulated values. Ens values of the regression models for bioretention with and without an underdrain were 0.652 and 0.597 in the verification period, respectively, indicating that the models are acceptable and can be used to forecast the runoff reduction rate when using the same type of bioretention system.

CONCLUSIONS

The SWMM model was used to simulate the typical annual rainfall runoff in an expressway service area, and the hydrologic performance of a bioretention basin was calculated using the RECARGA model. The influence of bioretention design parameters on water balance and runoff reduction rate was studied, allowing several conclusions to be drawn.

It was determined that the ratio of bioretention area to drainage area, and the saturated infiltration rates of planting soil and native soil were the main factors influencing the water balance, followed by the thickness of the planting soil and the depth of the ponding area, while the diameter of the underdrain and the depth of the gravel layer had little effect.

The runoff reduction rates showed a positive linear relationship with the ratio of bioretention area to drainage area for bioretention basins both with and without an

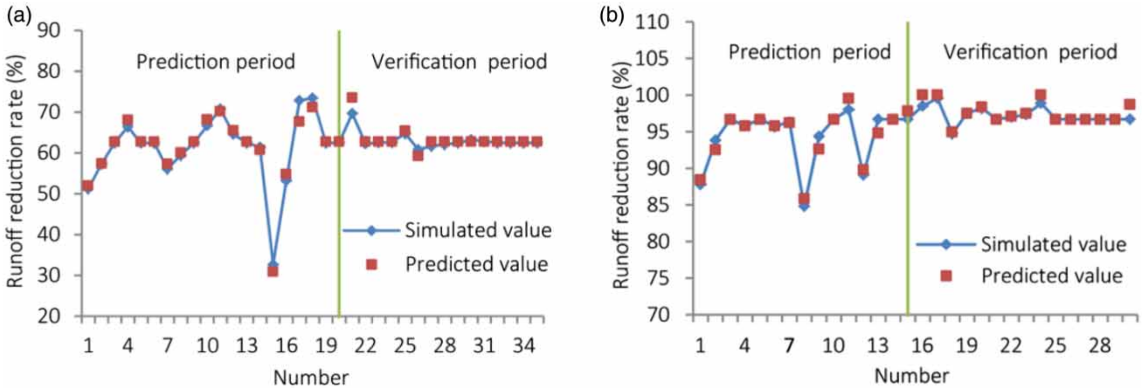

Figure 6 | Multivariate nonlinear regression analyses of runoff reduction rate of bioretention: (a) with and (b) without an underdrain.

underdrain. A logarithmic relationship was observed between the runoff reduction rate and the saturated infiltration rates of planting soil and native soil for bioretention basins both with and without an underdrain. For bioretention without an underdrain, the depth of the ponding area and the thickness of the planting soil affected the runoff reduction rate, while the gravel layer had little effect. For bioretention with an underdrain, the thickness of the planting soil had a significant effect on the runoff reduction rate, while other design parameters exerted little effect.

A multivariate nonlinear regression model was established to predict the runoff reduction rate of a bioretention system with and without an underdrain. The determination coefficients were high in the prediction period and Nash–Sutcliffe efficiency coefficients were found to be acceptable in the verification period, thus indicating that the curves fitted well. Overall, it can therefore be concluded that the present model can be used to predict the runoff reduction rate of a bioretention basin, both with and without an underdrain.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (No. 51378520).

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First received 6 October 2017; accepted in revised form 23 January 2018. Available online 8 February 2018