Influence of In-situ Soil and Groundwater Level on Hydrological Effect of Bioretention

Junkui Pan1*, Ruiqiang Ni2, Longfei Zheng3

1School of Civil and Transportation Engineering, Henan University of Urban Construction, Longxiang Avenue, Xinhua District, Pingdingshan 467000, China
2China Railway 10th Bureau Group Investment Development Co., Ltd, China Railway Caizhi Industrial South Road, Lixia District, Jinan 250001, China
3Pingdingshan Highway Development Center, Jiaotong building, Chang’ an Avenue, Xinhua District, Pingdingshan 467000, China

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Abstract

Bioretention is an important technology for ecological control of runoff. The purpose of this study was to investigate the coupling effect of in-situ soil and groundwater level on the hydrological performance of bioretention. VADOSE/W was used to simulate the water transport processes during bioretention under a single rainfall event. The effects of four in-situ soil types and two groundwater levels on the surface ponding, underdrain outflow, exfiltration, and runoff regulation effects of bioretention were studied. Under eight geological situations and the rainfall of 0.17 mm/h (6.0 h), the ponding duration and overflow volume of bioretention were 556-649 min and 24.71-39.61 mm/m², respectively; the underdrain outflow peak value and duration were 0.549-0.804 mm/min and 380-730 min, respectively; the exfiltration volume per unit area from the bottom and lateral of bioretention were 106.79-396.10 mm/m² and 50.60-147.45 mm/m², respectively; and the runoff reduction rate, runoff peak reduction rate, and runoff delay time of bioretention were 53.46%-96.19%, 18.43%-68.08%, and 288-318 min, respectively. These results suggest that bioretention without an underdrain and with a relatively smaller Ks (saturated permeability coefficient) of in-situ soil might result in longer ponding times and larger overflow volumes. With an increase in Ks of in-soil, the underdrain outflow weakens, the exfiltration volume increases, and the runoff control effects improve. Although the groundwater level has little effect on surface ponding, it can cause a stronger underdrain outflow. The shallower groundwater level leads to a larger exfiltration volume when the Ks of in-soil is much smaller than that of the planting layer and leads to a reduced runoff regulation effect for bioretention without an underdrain. Therefore, when locating and designing bioretention systems, the in-situ soil type and groundwater level should be comprehensively considered to ensure that the runoff control target is achieved.

Keywords: bioretention, hydrological effect, in-situ soil, groundwater level, VADOSE/W
Introduction

With the acceleration of global urbanisation, the impervious area of urban areas has increased sharply, resulting in a significant reduction in rainwater infiltration. This shortens the concentration time of rainfall and increases the peak of runoff, causing frequent urban waterlogging [1-3]. Moreover, the groundwater in urban areas cannot be effectively recharged, causing the groundwater level to decline year by year [4-6]. In addition, urban surface runoff usually contains pollutants, such as nutrients, heavy metals, suspended solids, petroleum, hydrocarbons, pathogens and salts, which flow into the downstream water system through the urban rainwater pipe network and pose serious adverse impacts on the regional water environment, and also threaten human health [7-12].

As the global water environment continues to deteriorate, some technical measures have emerged to solve urban water problems, such as permeable pavement, green roof, grassed swales, bioretention, constructed wetland and stabilization pond [13-19]. Among them, bioretention integrates landscape, flexible layout, runoff control, and water purification functions and has emerged as a promising and practical rainwater ecological control measure [20-22]. A typical bioretention system is usually composed of a 15-30 cm surface aquifer layer, a 5-8 cm mulch layer, a 30-70 cm planting filler layer, a 15-30 cm sandy gravel layer, an overflow hole, and plants, and the design scale is generally 5-10% of the catchment area (Fig. 1) [23-25]. An underdrain with a diameter of 50-100 mm is usually installed in the sandy gravel layer to strengthen the drainage of bioretention when the in-situ soil permeability coefficient is lower than 1.27 cm/h or the bioretention system is anti-seepage [26]. To control rainwater runoff, when rainwater runoff flows through the bioretention system, the planting filler layer intercepts and stores the water, with part of it slowly penetrating into the surrounding soil to recharge the groundwater and the rest diffusing into the atmosphere through evaporation and plant transpiration after rainfall [27-28].

In recent years, the hydrological performance of bioretention systems has been extensively studied through laboratory and field experiments. Davis [29], Pan [30], and Debusk [31] have demonstrated that bioretention can regulate rainfall runoff and improve the regional hydrological cycle. Some studies have shown that the hydrological effects of bioretention are mainly affected by factors such as rainfall characteristics and bioretention design parameters. For example, both Gülbaz [32] and Gao [33] showed that increasing the rainfall intensity or duration increased the surface ponding depth and outflow peak flow rate of bioretention. Li [34] reported that amount of water infiltration increased with the depth of the planting filler layer, and the goal of LID (low-impact development) was achieved more easily. Both Li [35] and Brown [36] demonstrated that by setting up internal water storage areas, bioretention could better reduce runoff volume and runoff peak, extend runoff retention time, and improve hydrological performance.

The numerical model can provide support for the planning, design, and research of water ecological treatment systems [37]. At present, only a few hydrologic models, such as RECARGA, HYDRUS-1D, SWMM, and SUSTAIN, are available to simulate storm-water runoff management of bioretention. The RECARGA model uses the Green-Ampt equation to represent infiltration, which is specifically designed for bioretention. However, it is mainly suitable for long-term water balance analysis and not for simulating the water transport process of bioretention under short-term rainfall. Moreover, it is unable to arbitrarily specify the hydraulic parameters of the medium, which limits
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Material and Methods

Governing Equation of Soil Water Movement

As the bioretention medium and in-situ soil belong tovariably saturated soil, including vertical and horizontal water diffusion, their water movement processes can be described by the two-dimensional Richards’ equation, as shown in Eq. (1).

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[k(\theta)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[k(\theta)\frac{\partial h}{\partial z}\right] + \frac{\partial k(\theta)}{\partial z} - S(x, z, t)
\]

(1)

where \( h \) is the soil negative pressure head (mm); \( k(\theta) \) is the soil permeability coefficient (mm/min); \( \theta \) is the soil volumetric moisture content (mm\(^3\)/mm\(^3\)); \( x \) and \( z \) are the horizontal and vertical positions, respectively (mm); \( S(x, z, t) \) is the source and sink terms, such as evapotranspiration (mm/min), which can be taken as 0 when the duration is short; and \( t \) is the time (min).

When \( h \geq 0 \), the soil is saturated, and \( \theta \) and \( k(\theta) \) in Equation 1 are both fixed values, which are the saturated soil water content \( \theta_s \) and the saturated soil permeability coefficient \( K_s \), respectively. When \( h < 0 \), the soil is in unsaturated, and \( \theta \) and \( k(\theta) \) are variable values, which can be described by the soil water characteristic curve formula (Eq. 2) and the hydraulic conductivity curve formula (Eq. 3), respectively, as proposed by van Genuchten [46].

\[
\theta(h) = \begin{cases} 
\theta_s + \frac{\theta_s - \theta_r}{1 + (\alpha h)^m} & (h < 0) \\
\theta_r & (h \geq 0)
\end{cases}
\]

(2)

\[
K(\theta) = \begin{cases} 
K_s \left[1-(1-S_r)^n\right]^m & (h < 0) \\
K_r & (h \geq 0)
\end{cases}
\]

(3)

where \( \theta_r \) is the residual soil water content (mm\(^3\)/mm\(^3\)); \( \theta_s \) is the saturated soil water content (mm\(^3\)/mm\(^3\)); \( a \), \( n \), and \( m \) are the van Genuchten parameters, and \( m = 1 - 1/n; K_r \) is the saturated soil permeability coefficient (mm/min); \( S_r \) is the effective saturation of soil water, and \( S_r = (\theta - \theta_r)/(\theta_s - \theta_r) \).

Design Rainfall

The determination of the design rainfall is necessary to study the hydrological effects of bioretention. The design rainfall adopted in this study is the once-a-year 6 h design rainfall calculated according to the rainfall intensity formula in the study area (Eq. 4) in which the rainfall intensity is 0.17 mm/min, and the total rainfall is 62.59 mm, which is a uniform rainfall type, to ensure that the water penetrates the bioretention filler layer and in-situ soil with sufficient time and water volume.

\[
q = \frac{15.054(1+0.845\log P)}{(t+14.095)^{0.33}}
\]

(4)

where \( q \) is the rainfall intensity (mm/min); \( t \) is the rainfall time (min); and \( P \) is the rainfall return period (a).
The runoff entering bioretention system is mainly composed of the runoff in the catchment area and the rainfall directly acting on bioretention, which can be calculated using Eq. (5).

\[
q_o = \left( \frac{\Psi F_0 + F_i}{F_i} \right) q
\]

where \(q_o\) is the runoff intensity acting on bioretention (mm/min); \(q\) is the actual rainfall intensity (mm/min); \(\Psi\) is the runoff coefficient, which is taken as 0.9 in this study; \(F_0\) is catchment area (m²); and \(F_i\) is the bioretention area (m²).

Simulated Scenarios

To study the hydrological performance of bioretention under the coupling effect of in-situ soil and groundwater level, the VADOSE/W model was used to simulate the water transport process of bioretention under eight geological situations, as shown in Table 1. Four types of in-situ soil, including silty loam (SL), loam (L), sandy clay loam (SCL), and sandy loam (SaL), and two types of groundwater levels, 1 m and 3 m below the bottom of the bioretention, were adopted. Different parameters considered for bioretention under various geological conditions include: 10% of the catchment area, the surfer aquifer depth of 20 cm, the mulch layer thickness of 5 cm, the planting filler layer thickness of 70 cm, and the sandy gravel layer thickness of 30 cm. When the in-situ soil was silty loam or loam, an underdrain with a diameter of 5 cm was placed in the middle of the sandy gravel layer to form an internal water storage with a height of 15 cm because its permeability coefficient was lower than 1.27 cm/h. The simulation time of this study was short, and the amount of evaporation and plant transpiration could be ignored. Therefore, the influence of plants was not considered. In addition, the mulch layer of bioretention usually adopts crushed bark or gravel, which has a large permeability coefficient and can be regarded as an aquifer on the planting soil layer. Therefore, the mulch layer is not considered in the simulation, but only its effective pores can be superimposed on the original aquifer. In this study, the depth of the aquifer was 20 cm, which was the depth at which the superposition of the pores of the mulch was considered.

Soil Hydraulic Characteristic Parameters

The soil hydraulic characteristic parameters of the bioretention medium and in-situ soils for the VADOSE/W model are shown in Table 2. In this study, the soil hydraulic characteristic parameters of planting filler and sandy gravel in bioretention are based on the data verified in our previous study when studying the influence of bioretention parameters on the road runoff regulation effect [33], whereas in-situ soils use the data used by Li when studying water unsaturated seepage in rainwater seepage ditch [47]. In addition, the initial water contents of the bioretention medium and in-situ soils are the water content distributions after the free drainage of the medium reaches stability under the saturated state.

Data Analysis

The regulation effect of bioretention on a single rainfall event can be described by three indicators: runoff volume reduction rate, runoff peak reduction rate, and runoff delay time, as shown in Eqs (6)-(7), and (8), respectively.

\[
R_v = \frac{V_{in} - V_{out}}{V_{in}} \times 100\
\]

Table 1. Bioretention design parameters and geological situations.

<table>
<thead>
<tr>
<th>Simulated scenarios</th>
<th>Bioretention design parameters</th>
<th>Geological situations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(A_{bioretention} / A_{catchment}) (%)</td>
<td>Aquifer depth (cm)</td>
</tr>
<tr>
<td>SL-1</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>SL-3</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>L-1</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>L-1</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>SCL-1</td>
<td>No</td>
<td>20</td>
</tr>
<tr>
<td>SCL-3</td>
<td>No</td>
<td>20</td>
</tr>
<tr>
<td>SaL-1</td>
<td>No</td>
<td>20</td>
</tr>
<tr>
<td>SaL-3</td>
<td>No</td>
<td>20</td>
</tr>
</tbody>
</table>
Influence of In-situ Soil and Groundwater Level on Surface Ponding

The range of surface ponding duration and overflow volume are two important indicators of surface ponding bioretention. As shown in Table 3, for bioretention under eight geological situations, the range of these indicators are 556-649 min and 24.71-39.61 mm/m², respectively. The in-situ soil type and the underdrain have a significant impact on the surface ponding, but the impact of the groundwater level is not significant.

Compared with SL and L, the surface ponding duration and overflow volume of bioretention increases to 86 minutes and 6.66 mm/m², respectively, under SCL. This is because the $K_s$ (1.310 cm/h) of SCL is much smaller than that of the planting filler layer (5.040 cm/h), and it is not equipped with an underdrain. Therefore, the water infiltrating into bioretention easily accumulates at the bottom of the bioretention and enters the planting filler layer, which affects the infiltration of rainwater, significantly prolongs the ponding time, and increases the overflow volume. Although the underdrain is not installed, the $K_s$ (4.428 cm/h) of SaL is close to that of the planting filler, so the water is more easily diffused to the in-situ soil, resulting in a relatively shorter surface ponding duration (reduced by up to 93 min) and a significantly smaller overflow volume (reduced by up to 14.90 mm/m²) than SCL.

### Results and Discussion

#### Influence of in-situ Soil Type and Groundwater Level on Surface Ponding

The range of surface ponding duration and overflow volume are two important indicators of surface ponding bioretention. As shown in Table 3, for bioretention

### Table 2. Hydraulic characteristic parameters of bioretention medium and in-situ soil

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$K_s$ (cm/h)</th>
<th>$\theta_r$ (cm³/cm³)</th>
<th>$\theta_s$ (cm³/cm³)</th>
<th>$a$ (cm⁻¹)</th>
<th>$n$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioretention medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planting filler</td>
<td>5.041</td>
<td>0.058</td>
<td>0.41</td>
<td>0.057</td>
<td>2.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Sandy gravel</td>
<td>163.00</td>
<td>0.046</td>
<td>0.44</td>
<td>0.153</td>
<td>2.64</td>
<td>0.62</td>
</tr>
<tr>
<td>In-situ soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.452</td>
<td>0.067</td>
<td>0.45</td>
<td>0.020</td>
<td>1.41</td>
<td>0.29</td>
</tr>
<tr>
<td>Loam</td>
<td>1.038</td>
<td>0.078</td>
<td>0.43</td>
<td>0.036</td>
<td>1.56</td>
<td>0.36</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>1.310</td>
<td>0.100</td>
<td>0.39</td>
<td>0.059</td>
<td>1.48</td>
<td>0.32</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>4.428</td>
<td>0.065</td>
<td>0.41</td>
<td>0.075</td>
<td>1.89</td>
<td>0.47</td>
</tr>
</tbody>
</table>

### Table 3. Surface ponding of bioretention under different in-situ soil types and groundwater levels.

<table>
<thead>
<tr>
<th>Simulated scenarios</th>
<th>Time of surface ponding beginning (min)</th>
<th>Time of surface ponding ending (min)</th>
<th>Duration of surface ponding (min)</th>
<th>Maximum surface ponding depth (cm)</th>
<th>Time of overflow occurring (mm)</th>
<th>Time of overflow ending (min)</th>
<th>Overflow volume (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL-1</td>
<td>8</td>
<td>563</td>
<td>555</td>
<td>20</td>
<td>305</td>
<td>300</td>
<td>35.34</td>
</tr>
<tr>
<td>SL-3</td>
<td>3</td>
<td>563</td>
<td>560</td>
<td>20</td>
<td>304</td>
<td>300</td>
<td>35.24</td>
</tr>
<tr>
<td>L-1</td>
<td>8</td>
<td>562</td>
<td>554</td>
<td>20</td>
<td>308</td>
<td>300</td>
<td>32.95</td>
</tr>
<tr>
<td>L-3</td>
<td>8</td>
<td>562</td>
<td>554</td>
<td>20</td>
<td>308</td>
<td>300</td>
<td>32.15</td>
</tr>
<tr>
<td>SCL-1</td>
<td>9</td>
<td>649</td>
<td>640</td>
<td>20</td>
<td>309</td>
<td>300</td>
<td>39.61</td>
</tr>
<tr>
<td>SCL-3</td>
<td>9</td>
<td>614</td>
<td>605</td>
<td>20</td>
<td>308</td>
<td>300</td>
<td>38.49</td>
</tr>
<tr>
<td>SaL-1</td>
<td>8</td>
<td>556</td>
<td>548</td>
<td>20</td>
<td>318</td>
<td>300</td>
<td>24.71</td>
</tr>
<tr>
<td>SaL-3</td>
<td>9</td>
<td>556</td>
<td>547</td>
<td>20</td>
<td>318</td>
<td>300</td>
<td>23.85</td>
</tr>
</tbody>
</table>
Influence of in-situ Soil Type and Groundwater Level on Underdrain Outflow

As shown in Fig. 2, compared with rainfall runoff, under four geological situations, the underdrain outflow start time of bioretention is delayed by 290-300 min, the end time is delayed by 320-660 min, and the outflow peak value is reduced by 53.72-68.42%. Rainwater runoff can be temporarily stored and then slowly released through the infiltration process of the planting filler of bioretention, which has a significant delay and peak elimination effect.

The order of the underdrain outflow start time is L-1 and L-3, and SL-1 and SL-3, and the order of the outflow peak value and end time are both SL-1, SL-3, L-1, L-3. The in-situ soil type have a significant impact on the underdrain outflow; i.e., with the increase in the $K_s$ of in-situ soil, the start time of the underdrain outflow is delayed, the peak value is decreased, and the end time is earlier. In addition, the groundwater level has little effect on the start time of the underdrain outflow, but shallower groundwater levels tend to lead to relatively larger outflow peaks and longer outflow durations. Furthermore, compared with L, the influence of groundwater level on underdrain outflow is more significant as the in-situ soil is SL, which has a relatively smaller $K_s$.

Influence of in-situ Soil Type and Groundwater Level on Exfiltration

As shown in Figs 3a) and 3b), the lateral and bottom accumulated exfiltration volume of bioretention gradually increases and tends to be stable over time. Moreover, the time of stability reaches earlier with the increasing $K_s$ of in-situ soil. The exfiltration volume per unit area from the bottom and lateral of bioretention is 106.79-396.10 mm/m$^2$ and 50.60-147.45 mm/m$^2$, respectively, and the bottom can reach 1.72-7.82 times the lateral, 24 hours after the end of rainfall, under eight geological situations.

The $K_s$ of in-situ soil plays a leading role in bottom exfiltration; i.e., with the increase in the $K_s$ of in-situ soil, the bottom exfiltration volume increases significantly. The order of cumulative exfiltration volume of bioretention is SaL-1 and SaL-3, SaC-3, SaC-1, L-3, L-1, SL-3, SL-1. The influence of the groundwater level on bottom exfiltration differs according to the in-situ soil type. When the in-situ soil is SL, L, or SaC, the shallower groundwater level tends to result in a smaller exfiltration volume, whereas when...
the in-situ soil is SaL, there is almost no effect. This may be due to the larger $K_s$ of sandy loam, and the water infiltrated into the in-situ soil can quickly spread to both sides. Therefore, the groundwater level has no obvious effect on the bottom penetration capacity of bioretention.

For lateral exfiltration, the order of the cumulative exfiltration volume of bioretention is SCL-1>SCL-3>L-1>L-3>SL-3>SaL-1 and SaL-3. The lateral exfiltration volume of the SCL is relatively larger, mainly because the $K_s$ of SCL is much smaller than that of the planting filler, and the underdrain is not set. Therefore, the water easily accumulates at the bottom of the bioretention, thus increasing the lateral exfiltration. In addition, the influence of the groundwater level on lateral exfiltration is relatively weaker than that of bottom exfiltration.

Influence of in-situ Soil Type and Groundwater Level on Runoff Regulation Effect

As shown in Figs 4a) and 4b), the ranges of $R_v$ and $R_{peak}$ of bioretention under the eight geological situations are 53.46-96.19% and 18.43-68.08%, respectively. The order of the $R_v$ and $R_{peak}$ are both SaL-1 and SaL-3>SCL-1 and SCL-3>L-3>L-1>SL-3>SL-1, which are significantly affected by the in-situ soil type; i.e., with the increase in $K_s$ of in-situ soil, the $R_v$ and $R_{peak}$ both increase. In addition, the shallower groundwater level tends to result in a relatively smaller $R_v$ and $R_{peak}$ when the in-situ soil is SL and L (with underdrain), whereas the influence can be ignored when the in-situ soil is SCL and SaL (without underdrain). This is mainly because the groundwater level has a significant influence on the underdrain outflow, and the influence on surface overflow is weak. As shown in Fig. 4c), the range of $R_{delay}$ of bioretention under the eight geological situations is 288-318 min, and the order of the $R_{delay}$ is SaL-1 and SaL-3>SCL-1 and SCL-3>L-1 and L-3>SL-1 and SL-3. The $R_{delay}$ is significantly affected by the in-situ soil type, as it significantly increases with the increase in $K_s$ of in-situ soil. However, the influence of the groundwater level can be ignored.

Conclusion

VADOSE/W was used to study the influence of in-situ soil type and groundwater level on the hydrological performance of bioretention under a single rainfall event. The following conclusions were drawn:

For the in-situ soil with a much smaller $K_s$ (such as SCL), an underdrain should be configured to reduce overflow risk. The smaller $K_s$ of in-situ soil and shallower groundwater level is more likely to lead to the enhancement of underdrain outflow. The exfiltration of bioretention is dominated by bottom seepage, which increases with the increase in $K_s$ of in-situ soil. For in-situ soil with a much smaller $K_s$, the shallower groundwater level is more likely to reduce the exfiltration volume. The runoff control effect of bioretention is significantly improved with the increase in $K_s$ of in-situ soil. For bioretention with an underdrain, the shallower groundwater level is more likely to weaken the runoff control effect of bioretention.

The results suggest that when locating and designing bioretention, native soil types and groundwater levels should be carefully considered to ensure that the runoff...
control target is achieved. In addition, this study only considered a single rainfall event, and the impact of in-situ soil type and groundwater level on the long-term hydrological performance of bioretention should be further studied.

Acknowledgments

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Conflict of Interest

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal’s policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

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