Vol. 15, No. 2
2024

Ecological Safety
and Balanced Use of Resources

Journal homepage: https://esbur.com.ua/en

Received: 04.07.2024. Revised: 30.09.2024. Accepted: 02.12.2024

UDC 628.4

DOI: 10.69628/esbur/2.2024.22

Modelling infiltration processes in rain gardens: Influence of design parameters on hydrological efficiency

Maryna Kravchenko*
PhD in Technical Sciences, Associate Professor
Kyiv National University of Construction and Architecture
03037, 31 Povitriani Syly Ave., Kyiv, Ukraine
https://orcid.org/0000-0003-0428-6440

Tetiana Tkachenko
Doctor of Technical Sciences, Professor
Kyiv National University of Construction and Architecture
03037, 31 Povitriani Syly Ave., Kyiv, Ukraine
https://orcid.org/0000-0003-2105-5951

Viktor Mileikovskyi
Doctor of Technical Sciences, Professor
Kyiv National University of Construction and Architecture
03037, 31 Povitriani Syly Ave., Kyiv, Ukraine
https://orcid.org/0000-0001-8543-1800

Abstract. A rain garden is a stormwater management system designed for on-site water control. Suboptimal rain garden designs may compromise hydrological performance during operation, necessitating developing and validating a mathematical model for engineering calculations and design assessment. This study aimed to model infiltration processes in a rain garden using a mathematical framework that accounts for the height of the water column (HWC) on the surface and the filtration coefficient of soil materials, simulating system behaviour during an extreme rainfall event (36 mm/h). The developed model generated performance curves illustrating the rain garden's efficiency as a function of design parameters: construction depth, catchment-to-garden area ratio, filtration coefficient, and water retention capacity (WRC). Key soil material parameters were determined experimentally under laboratory conditions. The infiltration performance of the system was evaluated by analysing the variation in infiltration time, saturation of all layers, and the water filling level of the rain garden resulting from adjustments to its parameters and changes in HWC on the surface. The modelling results indicated that the primary parameters influencing the predicted time for complete system saturation and HWC formation are the catchment-to-garden area ratio and the filtration coefficient. The WRC of soil materials and the depth of the system layers significantly impact the time required for full saturation and water filling but have minimal effect on the surface HWC. It was demonstrated that a rain garden with a depth of 1.2 m, a catchment-to-garden area ratio of 15, and a filtration coefficient of 100-200 cm/h functions effectively under critical rainfall intensities. The developed model and the resulting data, providing precise calculations and design recommendations, can be utilised by engineers and planners to optimise rain garden designs, thereby enhancing stormwater management efficiency

Keywords: stormwater management; filtration coefficient; water retention capacity; catchment to garden area ratio; height of the water column

---

Suggested Citation: Kravchenko, M., Tkachenko, T., & Mileikovskyi, V. (2024). Modelling infiltration processes in rain gardens: Influence of design parameters on hydrological efficiency. *Ecological Safety and Balanced Use of Resources*, 15(2), 22-35. doi: 10.69628/esbur/2.2024.22.

*Corresponding author

Introduction

Rapid urbanisation and increasing development significantly reduce the permeability of natural land surfaces. This leads to intensified stormwater runoff, a heightened risk of urban flooding, reduced infiltration rates, and higher concentrations of heavy metals and other pollutants in stormwater. Additionally, climate change disrupts precipitation patterns across various regions, resulting in unpredictable rainfall volume and intensity increases. In many countries, including Ukraine, the situation is further exacerbated by insufficient drainage systems for stormwater collection and the limited efficiency of existing sewerage infrastructure, contributing to prolonged waterlogging. These urban challenges cause substantial economic losses, such as damage to agricultural production, urban and rural property, and hydraulic infrastructure, while also exerting significant negative impacts on the environment.

According to C. Jiang *et al.* (2019), stormwater management technologies can be classified into two primary categories: systems based on water infiltration and systems designed for stormwater retention. Infiltration-based systems facilitate the restoration of stormwater flows by replenishing groundwater and subsurface water reserves. Examples include catchment basins, infiltration trenches, bioretention systems (rain gardens), sand filters, and porous pavement. Retention systems, such as wetlands, ponds, green roofs, and rainwater harvesting systems (storage tanks and basins), are intended to slow the flow of water. The operational efficiency of rain garden structures largely depends on three key factors influencing their capacity to manage stormwater. The primary factor affecting infiltration capacity and the volume of retained stormwater is the hydraulic conductivity or filtration coefficient of soil materials, making soil type a critical determinant in retaining stormwater runoff and removing pollutants, as noted by G. Li *et al.* (2021). Furthermore, C. Jiang *et al.* (2019) highlighted that the water retention capacity (WRC) of soil materials is another important characteristic influencing the hydraulic processes within rain gardens. Concerning the structural features of rain gardens, the retention and treatment of stormwater can be enhanced by optimising key design dimensions, such as the depth of the surface depression zone and the thickness of soil layers, as indicated by E. Burszta-Adamiak *et al.* (2023).Variations in environmental conditions across different geographic regions result in differing hydrological process outcomes for identical rain garden designs. Consequently, various models have been developed to provide more precise tools for evaluating the efficiency of rain garden structures, aiding urban planners in stormwater management strategy development.

One widely used model is the Storm Water Management Model (SWMM), which features a flexible infiltration module suitable for landscape-scale applications. This module incorporates surface infiltration using the Green-Ampt method, porous media flow governed by Darcy's law, and groundwater infiltration, as discussed by W.A. Lisenbee *et al.* (2022). The DRAINMOD model, highlighted by J. Kim *et al.* (2023), is commonly employed for rain garden simulations, with infiltration described by the Green-Ampt equation. It requires users to input the soil-water characteristic curve and the parameter for saturated hydraulic conductivity. According to W. Lisenbee *et al.* (2020), DRAINMOD has recently been adapted for urban stormwater management applications. In Australia, the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) serves as the industry standard for modelling rain gardens and other stormwater control measures, as noted by A. Hoban & C. Gambirazio (2021). In MUSIC, infiltration in rain gardens is described using Darcy's equation for flow through porous media, accounting for soil texture and moisture content. Richards' equation is employed to model flow within rain gardens, enabling predictions of peak runoff rates and reductions in stormwater volume. One such numerical model, as referenced by G. Li *et al.* (2021), is known as RECHARGE. This model facilitates the analysis of rain garden infiltration behaviour to support their design and performance evaluation. Since its development, the RECHARGE model has only been validated under isolated phenomena in controlled experimental conditions. However, it has not yet been tested in real-world scenarios or over extended periods encompassing multiple rainfall events. The study by W. Nichols *et al.* (2021) discussed the HYDRUS software packages, which are finiteelement variably saturated models that numerically solve Richards' equation to describe unsaturated water flow. While this approach provides a physically robust and high-resolution simulation of infiltration processes, the model is not specifically tailored for rain gardens. In the study of M. Kravchenko *et al.* (2024a), a universal mathematical model was developed using Darcy's equation. This model offers a detailed description of infiltration processes at specific moments in time, incorporating the height of the water column (HWC) on the surface of the structure.

Despite the extensive body of research on rain gardens, the principles for designing effective systems and accurately predicting their stormwater retention performance during operation remain pressing issues requiring further investigation and refinement. This study aimed to examine the influence of engineering parameters – such as the depth of the structure, the catchment-to-garden area ratio, the filtration coefficient, and the WRC – on the efficiency of hydrological processes, using a universal hydrological model. Based on the results obtained, an optimal system configuration was proposed to enhance rain garden performance.

Materials and Methods

To achieve the research objective, a previously developed hydrological mathematical model (Kravchenko *et al.*, 2024a) was utilised, and implemented in Scilab software. The parameters incorporated into the hydrological infiltration model, accounting for HWC and the filtration coefficient, are described in Table 1.

Table 1. Parameters included in the mathematical infiltration model considering HWC and the filtration coefficient

Parameter	Description	Unit of measurement
A_{bassin}	Catchment basin area	m^2
A_{sponge}	Area of the rain garden structure	m^2
H_{sponge}	The total depth of the rain garden structure	m
A_{h_0}	Rain garden area as a function of height h_0 from the upper level	m^2
v_r	Inflow rate of stormwater into the system	m/c
h_0	HWC	m
w	Initial moisture content of soil mixtures	m^3/m^3
w_{sat}	WRC of soil mixtures in a saturated state	m^3/m^3
k_f	Filtration coefficient of soil mixtures	cm/h
δ_j	The thickness of the j-th layer of the rain garden	m
τ	Saturation and filling time of the rain garden	c
y_i	Depth of penetration and saturation of the rain garden structure with stormwater at the current time step τ	m
i, j, n, m	Soil layers of the rain garden, starting with the first layer ($j = 1$) and ending with layer ($m - 1$) where saturation occurs at a specific moment in time	No.

Source: developed by the authors

Assuming that rainfall occurs at a relatively constant intensity over a given period, the total volume of water that a rain garden can retain can be considered as the sum of the water volumes that can be stored on the surface within the depression zone and infiltrated during the rainfall event. This relationship can be used to determine the required surface area of the rain garden according to the equation proposed by the authors:

$$A_{sponge} = \frac{A_{bassin} \times c \times P}{h_0 \times k_{fsponge} \times \tau_r}, \tag{1}$$

where c is the average runoff coefficient of the catchment area; P is the maximum rainfall depth calculated for the rain garden, m; $k_{fsponge}$ is the filtration coefficient (saturated hydraulic conductivity) of the rain garden, cm/h; and τ_r denotes the duration of stormwater inflow into the structure, hours. For small catchment areas, the time difference between rainfall and runoff is usually minimal, allowing τ_r to be approximated as the rainfall duration. The parameter h_0 is particularly significant for predicting the rain garden's capacity to manage runoff from highintensity rainfall events and in scenarios where infiltration capacity diminishes due to factors such as system clogging or a decrease in ambient air temperature. The value of HWC was calculated using the following equation:

$$h_0 = max\left(\left(v_r \times \frac{A_{bassin}}{A_{sponge}} - \frac{d(h_0 \times A_{h_0})}{A_{sponge} d\tau}\right) \times \left(\sum_{j=1}^{n-1} \frac{\delta_j}{k_{f,j}} + \frac{y_i - \sum_{j=1}^{n} \delta_j}{k_{f,n}}\right) - y_i, 0\right), \tag{2}$$

where d is the differential or variable of $h_0 \times A_{h_0}$; $d\tau$ is the differential or variable of the time parameter τ. The process of water percolation and saturation through the layers of the structure, from the depression zone in the uppermost layer of the rain garden to the depth y_i, is described by the following equation:

$$\begin{gathered} \frac{A_{bassin}}{A_{sponge}} \times \left(\int_0^{\tau} v_r \times d\tau\right) - \int_0^{h_0 \times \frac{A_{h_0}}{A_{sponge}}} d\left(h_0 \times \frac{A_{h_0}}{A_{sponge}}\right) = \\ = \int_0^{y_i} w_{sat} \times dy_i = \sum_{j=1}^{m-1} (w_{sat,j} \times \delta_j) + w_{sat,m} \times \left(y_i - \sum_{j=1}^{m-1} \delta_j\right). \end{gathered} \tag{3}$$

The position y_i at time τ, accounting for the height h_0 on the surface of the structure, was determined using the equation:

$$\begin{gathered} y_i(\tau) = \frac{A_{bassin}}{A_{sponge}} \times \left(\int_0^{\tau} v_r \times d\tau\right) - \\ - h_0(\tau) \times \frac{A_{h_0}(\tau)}{A_{sponge}} - \frac{\sum_{j=1}^{m-1} (w_{sat,j} \times \delta_j)}{w_{sat,m}} + \sum_{i=1}^{m-1} \delta_j. \end{gathered} \tag{4}$$

By integrating Darcy's equation from the boundary y_a in layer n_a to the boundary y_b in layer n_b, with consideration of HWC and the filtration coefficient, the rate of stormwater infiltration into the system was determined using the following equation:

$$v_r \times \frac{A_{bassin}}{A_{sponge}} - \frac{d(h_0 \times A_{h_0})}{A_{sponge} d\tau} = k_f(y) \times \frac{dh}{dy}. \tag{5}$$

Under the condition of full water saturation of the structural layers, the rate of water inflow into the rain garden or drainage system was determined according to the equation:

$$v_{out} = v_r \times \frac{A_{bassin}}{A_{sponge}} - \frac{d(h_o \times A_{h_0})}{A_{sponge} d\tau}. \quad (6)$$

The methodology is detailed further in M. Kravchenko *et al.* (2024b). Infiltration represents a portion of the total stormwater inflow into the rain garden structure, moving vertically into the soil rather than being diverted to an overflow pipe. The infiltration rate decreases exponentially with increasing rainfall intensity (*P*), with the most significant reductions observed during low and moderate-intensity events ($P < 10$ mm). Therefore, the developed model was applied to optimise the parameters of the rain garden for maximum water retention within the structure and enhanced infiltration. The hydrological model simulates a single event with a rainfall intensity of 36 mm/h to evaluate the rain garden's performance under extreme conditions. This event was selected based on meteorological observations from the Borys Sreznevsky Central Geophysical Observatory, which recorded a historic rainfall event over the past 16 years (2007-2023) in Kyiv, Ukraine, on 22 July 2023. The rainfall amounted to 36 mm/h, equivalent to 36 dm^3/m^2 in one hour.

Modelling the infiltration processes occurring within a rain garden requires the input of actual values for the WRC and filtration coefficient of the soil layers in the system. Experimental cylindrical columns replicating the basic structure of a rain garden were established in the Environmental Parameter Control Laboratory at Kyiv National University of Construction and Architecture (Ukraine). The model structure consisted of three main layers: an upper layer of natural soil, an intermediate sand layer, and a lower gravel-based drainage layer (Fig. 1a). The upper natural soil layer, characterised as loamy sand, is designed for planting vegetation and collecting rainfall through a surface depression zone. This soil material, used for experimental investigations, was sampled from an area in Kyiv at a depth of up to 200 mm. The intermediate layer, responsible for infiltration, comprised river sand. The lower layer functions as drainage to divert water from the system, with gravel of particle sizes ranging from 3 to 7 mm selected as the soil material.

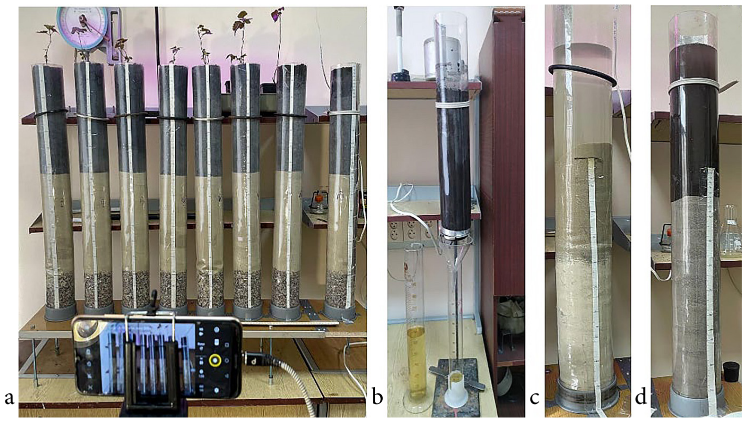

Figure 1. Experimental rain garden constructions

Note: a – general view; b – determination of WRC of the soil layer; c – determination of the filtration coefficient of the sand infiltration layer; d – determination of the filtration coefficient of the natural soil layer

Source: developed by the authors

The primary aim of the experimental setup was to investigate the filtration capabilities of rain gardens, specifically their ability to remove petroleum pollutants from simulated rainwater. Diesel fuel and used motor oil, the most common pollutants in this category, were selected for modelling petroleum hydrocarbons, as described in M. Kravchenko *et al.* (2024b). Concurrently with the experimental investigation, the WRC (Fig. 1b) and filtration coefficient (Fig. 1c; Fig. 1d) of the soil materials were determined under laboratory conditions. The filtration coefficient was assessed under vertical water flow from top to bottom, following saturation of the studied soil sample, following DSTU B V.2.1-23:2009 (2009). The experiments were conducted with constant pressure on the soil and variable water head. The WRC of the soil materials was determined using a method validated by J.T. Nelson *et al.* (2024), employing a funnel and filter paper. This parameter was determined after complete saturation of the sample and free drainage, which lasted for two hours.

Results and Discussion

Rain gardens: General characteristics

A bioretention system or rain garden structure is a landscaped depression designed to manage stormwater runoff effectively in urban areas. As outlined in M. Kravchenko *et al.* (2024c), the primary components of a rain garden system (Fig. 2) include a depression zone for collecting rainwater, vegetation on the surface, a substrate (growing medium), an infiltration layer, a drainage layer, and an underlying drainage system (if required). Stormwater runoff is captured and temporarily stored within the rain garden structure and on its surface in the depression zone. Subsequently, the water infiltrates vertically into the soil medium or discharges into the existing stormwater drainage system.

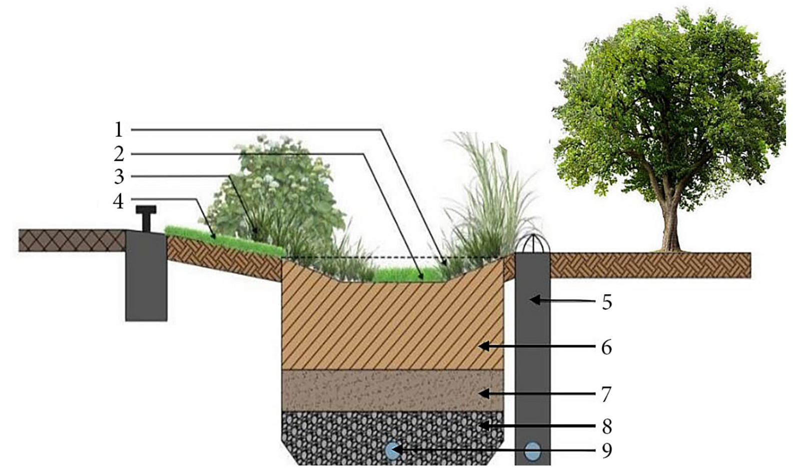

Figure 2. Key elements of a rain garden construction, cross-section

Note: 1 – depression zone for collecting and forming a column of rainwater; 2 – a layer of soil cover materials (mulch); 3 – plant layer; 4 – grass cover; 5 – overflow system; 6 – upper soil layer (for planting plants); 7 – intermediate infiltration layer; 8 – gravel layer; 9 – drainage system

Source: developed by the authors

Special attention should be given to the depression zone in the upper layer of the rain garden, which is designed to collect stormwater runoff from the catchment area and rainwater during precipitation. In this zone, a water column forms, the height of which depends on rainfall intensity and the hydraulic permeability of the system (Fig. 3).

Figure 3. Examples of water column formation on the surface

Note: a – Ivan Mazepa Street, Kyiv, Ukraine; b – San Mateo, California, USA; c – Melhus, Norway

Source: a – created by the authors; b, c – Rain gardens (2023)

The value of HWC is a critical parameter for predicting the infiltration performance of the structure and the potential for overflow. If the rain garden medium becomes fully saturated and the depth of the depression zone reaches its maximum height, overflow occurs. The depth of the depression zone is typically designed within a range of 15 to 30 cm. The presence of a water column in the depression zone is essential for supporting plant and microbial communities during prolonged dry periods and for creating an anaerobic environment that facilitates pollutant removal processes (Goh *et al.*, 2019). However, during frequent rain events, the depression zone may remain continuously filled with water, increasing the risk of mosquito proliferation, overwatering of plants, and soil compaction.

At the onset of a rainfall event, surface runoff is generated, with its volume directly proportional to the intensity of precipitation. Stormwater from the catchment area flows into the depression zone in the upper layer of the rain garden, where it infiltrates vertically through the multi-layered structure. If the inflow rate exceeds the infiltration capacity of the rain garden layers, water accumulates in the depression zone, forming a column with a height of h_0. During high-intensity rainfall, the depression zone may become fully saturated, resulting in overflow. The infiltration process within the rain garden continues as long as water inflow persists or until the depression zone is completely emptied ($h_0 = 0$).

Rain garden models can be categorised into two main types. The first category comprises nonphysically-based models, which are predominantly statistical and tailored to specific experimental sites. These models require only a limited number of parameters for implementation but are often case-specific and challenging to adapt to varying climatic conditions. Additionally, they offer limited predictive capabilities. The second category includes physically-based models, which are numerically more complex. As noted by

N. Alamdari & D.J. Sample (2019), such models typically require significant calibration efforts or access to detailed soil parameters that are difficult to estimate, such as the soil water retention curve. The simulation of infiltration processes in rain gardens is conducted by modelling rainfall events to predict the system's response to changes in precipitation characteristics. Rainfall characteristics are a critical factor to consider during the design phase of rain gardens. Regardless of the arrangement of structural layers within the system, the intensity of prolonged rainfall events may exceed the infiltration rate of the soil layers, leading to surface water accumulation and system overflow.

The experimentally determined water retention capacities (w_{sat}) were as follows: the top layer of natural soil w_{sat1} = 0.33 m^3/m^3; the middle sandy layer w_{sat2} = 0.31 m^3/m^3; and the bottom gravel layer w_{sat3} = 0.1 m^3/m^3. Similar water retention values were also reported by J. Wang *et al.* (2019). Using the RECHARGE model, the authors evaluated rain garden performance as a function of three parameters: retention depth, the ratio of catchment area to rain garden area, and the saturated hydraulic conductivity of the soil medium. The simulated rain garden design was analogous to the experimental setup presented in this study, consisting of the following layers: the root zone (upper soil layer), transition zone (intermediate infiltration layer), and subsoil layer (gravel). The water retention capacities of these layers were determined by the authors as 0.3/0.35/0.2 m^3/m^3.

The activity coefficients of the soil mixtures were determined as follows: upper soil layer k_{f1} = 7.0 cm/h; intermediate/infiltration sandy layer k_{f2} = 45.0 cm/h; bottom gravel layer k_{f3} = 200.0 cm/h. H. Takaijudin *et al.* (2019) experimentally identified the filtration coefficient of loamy sand soil (50% river sand and 50% natural soil) as 107.2 mm/h, equivalent to 10.72 cm/h. Furthermore, the filtration coefficient of a predominantly sandy soil mixture (90% river sand and 10% natural soil) was 569.67 mm/h (56.967 cm/h), which aligns closely with the values obtained in this study. R. Liu & E. Fassman-Beck (2018) measured the unsaturated hydraulic properties of artificial media with varying compositions, determining an unsaturated hydraulic conductivity (k_f) for marine sand at 0.013 cm/s, equivalent to 48.6 cm/h, which also corresponds to the results presented.

Design parameters of rain gardens

According to G. Li *et al.* (2021), the optimal depth of a rain garden system is influenced by soil conditions, the rooting depth of the planted vegetation, and the intended function. B. Zhang et al. (2020) investigated the impact of soil layer thickness on the performance of rain gardens. Their study found that a taller structure (1.2 m) retained stormwater effectively at a rate of 80%, whereas shorter configurations (0.5-0.6 m) achieved only 44% efficiency. The upper soil layer consists of a mixture of organic soil, sand, loamy sand, or loamy, providing suitable conditions for plant growth. The thickness of this layer in a rain garden should depend on the flood tolerance and water permeability of the plants and typically ranges from 10 to 40 cm (Sittisom *et al.*, 2022). This layer should also have sufficient organic matter content to support vegetation growth and a high infiltration capacity. The intermediate layer enhances the permeability of the upper soil and is crucial for the infiltration process. It usually comprises fine gravel or coarse sand. This layer should be well-drained and robust enough to support the weight of the upper layers. The porosity of the intermediate layer should range between 20% and 40%, and its depth should be between 20 and 60 cm (Sittisom *et al.*, 2022). The bottom drainage layer consists of medium to coarse gravel and is designed to retain and temporarily store water before discharging it into the drainage system. The thickness of the gravel layer is calculated based on the density of the infiltration layer but should be no less than 30 cm.

Rain garden designs are generally suitable for small catchment areas. According to design guidelines, the catchment area should not exceed 0.8 hectares (Rain garden and bioretention…, 2017). Larger catchment areas may result in intense and voluminous runoff, increasing the risk of erosion and forming a substantial water column on the surface. To manage large catchment basins, these can be divided into smaller sub-catchments with multiple rain gardens constructed to accommodate runoff effectively. Guidelines recommend that the rain garden's area should constitute 4-10% of the total catchment area (Bioretention…, n.d.). This ratio is considered somewhat conservative; in some cases, specific design requirements, such as rainfall volume and event duration, should also be taken into account. Using laboratory-determined values for WRC (0.33/0.31/0.1 m^3/m^3) and filtration coefficients (7/45/200 cm/h) of the soil layers, the hydrological behaviour of the rain garden was modelled. The model considered HWC as a function of varying area ratios (Table 2). The layer thicknesses were set at fixed values of 0.25/0.4/0.3 m (total depth of 0.95 m) based on the authors' assumptions. As recommended by D. Rinchumphu *et al.* (2023), the effective area of the rain garden is considered to be 4-10% of the catchment area. The simulation examined the hydrological behaviour of the rain garden by varying the A_{bassin}/A_{sponge} ratio from 5 to 25. The analysis accounted for a rainfall intensity of 36 mm/h, the time for complete saturation and filling of the structure, and the resulting HWC on the surface.

Table 2. Impact of the area ratio A_{bassin}/A_{sponge} on the stormwater retention efficiency of the rain garden system considering HWC

Parameters	Rain garden design					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
A_{bassin}, m^2	100	100	100	100	100	100

Table 2, Continued

Parameters	Rain garden design					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
A_{sponge}, m^2	4	5	6.6	10	13	20
A_{bassin}/A_{sponge}	**25**	**20**	**15**	**10**	**7.5**	**5**
h_0, m	0.5995	0.4656	0.3329	0.2016	0.1367	0.0725
τ, s	4,231	4,665.5	5,289	6,385	-	6,264.5

Note: - – the time is not specified because, during the 7,200 seconds of the simulation, full saturation and filling of the structure were not observed

Source: developed by the authors

The modelling results, presented as curves in Figure 4, indicate that the area ratio significantly influences the infiltration process within the rain garden structure. The curves in the upper section of the graph correspond to changes in HWC in the upper layer of the rain garden, while those in the lower section represent the saturation depth within the system. Each curve representing the depth of saturation in the rain garden is divided into four segments: three correspond to full saturation of the respective layer of the structure, and the fourth segment, a horizontal line parallel to the abscissa axis, corresponds to the state of complete filling of the system with stormwater.

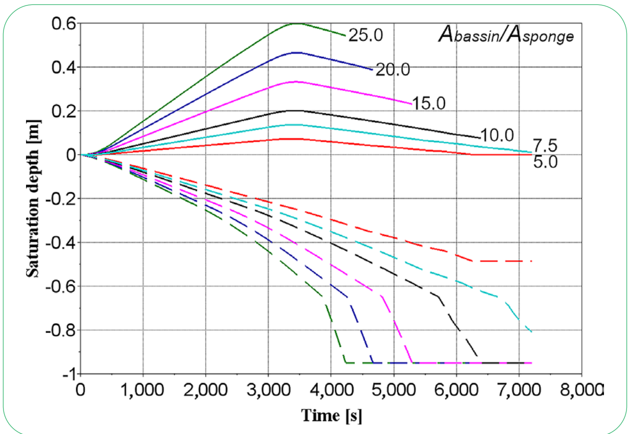

Figure 4. Dependence of the depth of saturation of the rain garden design and changes in HWC over time on the value of the area ratio A_{bassin}/A_{sponge}

Note: green line – rain garden design No. 1; blue – No. 2; pink – No. 3; black – No. 4; light blue – No. 5; red – No. 6

Source: developed by the authors

The results demonstrate that at an area ratio of 25, the rain garden structure reaches full saturation at a depth of 0.95 m within 1 hour and 10 minutes (4,231 seconds). At this point, the HWC value is 0.5995 m, exceeding the recommended range of 0.15-0.3 m (Ellis & Bettin, 2022). For instance, if a rain garden with an area of 4 m^2 is constructed to manage runoff from a 100 m^2 catchment area under a rainfall intensity of 36 mm/h, the system would not operate efficiently. Increasing the rain garden area (and consequently reducing the area ratio) enhances hydrological performance, as evidenced by a longer filling time and a lower water column height. However, based on an analysis of logarithmic relationships, J. Lee *et al.* (2022) observed that pollutant removal efficiency tended to improve with an increase in the area ratio.

The modelling results indicate that the optimal A_{bassin}/A_{sponge} ratio is 15, corresponding to a rain garden area of 6.6 m^2, which falls within the recommended range of 4-10% of the catchment area. At this ratio, the system filling time is 1 hour and 28 minutes (5,289 seconds), with a surface water column height of 0.3329 m. This finding aligns with the study by W. Nichols *et al.* (2021), which utilised the HYDRUS-1D model to assess the efficiency of rain gardens for improved stormwater management. The study found that maximum rain garden efficiency could be achieved at an A_{bassin}/A_{sponge} ratio of 15. Similarly, research by L. Zhang *et al.* (2020) demonstrated effective rain garden performance at an area ratio of 13.78, using a mean rainfall intensity of 28.18 mm/h, comparable to the intensity used in the present study's simulations. The findings of L. Bortolini & G. Zanin (2019) further support these results, showing that in the flat environment of Veneto, rain gardens sized at 10-15% of the roof drainage area can provide sustainable stormwater management alongside high aesthetic functionality.

The effectiveness of rain gardens with areas exceeding the recommended values of 4-10% of the catchment area was evaluated for areas of 13 and 20 m^2 (area ratios of 7.5 and 5, respectively) were evaluated. As shown in Figure 4, at A_{bassin}/A_{sponge} = 7.5, no complete filling of the structure occurs at a depth of 0.8 m within a simulation time of τ = 2 hours (7,200 seconds), and a surface water column forms with a height of 0.1367 m. The smallest HWC value (h_0 = 0.0725 m) is observed at an area ratio of 20; however, at this ratio, the system becomes fully saturated after 1 hour and 44 minutes (6,264.5 seconds), reaching a depth of 0.487 m. A comparative analysis of marginal retention increases across four area ratio values by J. Wang *et al.* (2019) demonstrated that as the catchment area increases, the percentage of stormwater retained by the rain garden decreases. This is attributed to the infiltration volume approaching the total inflow, imposing a limit on further retention. Higher infiltration rates can be achieved not only by increasing the rain garden area but also by modifying the depth of its layers. Moreover, J. Wang *et al.* (2019) identified that the filling volume of the surface depression in a rain garden depends more on the structural characteristics of the garden than on the infiltration flow rate. By increasing the construction depth by 0.3 m, changes in stormwater retention efficiency considering HWC were obtained (Table 3). Figure 5 illustrates the relationship between the saturation depth of rain garden layers and HWC variation over time as a function of total construction depth H_{sponge}, m.

Table 3. Effect of the total depth of H_{sponge} on the stormwater retention efficiency of the rain garden system considering HWC

Parameters	**Rain garden design**			
	No. 1	**No. 2**	**No. 3**	**No. 4**
H_{sponge}, m	**0.6**	**0.9**	**1.2**	**1.4**
δ_1, m	0.1	0.2	0.3	0.4
δ_2, m	0.2	0.4	0.5	0.6
δ_3, m	0.3	0.3	0.4	0.4
A_{bassin}/A_{sponge}	15	15	15	15
h_0, m	0	0.3213	0.3388	0.3415
τ, s	2,500	4,588	6,747.5	-

Note: - – the time is not specified because, during the 7,200 seconds of the simulation, full saturation and filling of the structure were not observed

Source: developed by the authors

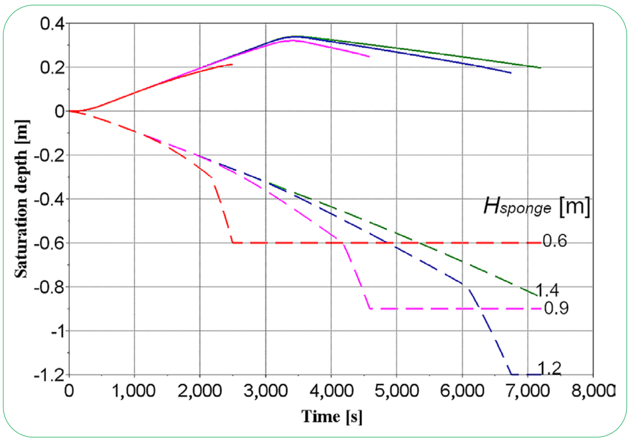

Figure 5. Dependence of the saturation depth and HWC variation over time on the total depth of the rain garden design, H_{sponge}

Note: red line – rain garden structure No. 1; pink – No. 2; blue – No. 3; green – No. 4

Source: developed by the authors

At a minimum depth of H_{sponge} = 0.6 m, the rain garden fills with stormwater within 42 minutes (2,500 seconds), with no surface water column (h_0 = 0). Increasing the depth of the structure by increments of 0.3 m extends the time for complete filling by an average of 38 minutes (2,258 seconds). However, the height of the surface water column changes by an average of just 0.01 m, indicating a minimal effect of H_{sponge} on this parameter. At the maximum depth of H_{sponge} = 1.4 m, the system does not reach full saturation within 2 hours (7,200 seconds), with a surface water column height (h_0) of 0.334 m, aligning with recommended values. A study by E. Burszta-Adamiak *et al.* (2023) assessed the efficiency of a rain garden in urban settings for capturing runoff from a 73.0 m^2 rooftop. The total area of the rain garden was 7.6 m^2. Although the system had a maximum depth of 0.3 m, the results showed that the rain garden exhibited favourable hydrological performance under rainfall depths of up to 5.3 mm and durations of up to 10 hours and 33 minutes. G.M. Bethke *et al.* (2022) utilised the Environmental Protection Agency's SWMM (EPA-SWMM) to evaluate the hydrological performance of rain gardens across varying environmental conditions. Their findings identified the thickness of soil materials and soil porosity as critical factors influencing the filling and overflow processes in rain garden structures.

Water retention capacity of a rain garden

The relationship between water content θ and matric potential ψ in soil under equilibrium conditions is referred to as the water retention characteristic or WRC. It represents the maximum volume of water that soil can retain when saturated. When the soil transitions from a saturated to an unsaturated (drier) state, the matric potential decreases from zero to a negative value. This parameter is significant because: it allows for the assessment of water availability in the soil environment for plants and enables irrigation management; it serves as a key hydraulic property for modelling unsaturated water flow in the soil layers of a rain garden; WRC reflects the effective pore size distribution within the medium. An increase in WRC is associated with higher infiltration rates and reduced runoff, especially during intense rainfall events (Williams *et al.*, 2018). The WRC of soils is primarily influenced by pore quantity, pore size distribution, and the specific surface area of the soil. As bulk density decreases, pore distribution changes, with a higher proportion of small pores emerging, particularly in coarse-textured soils (Abdallah *et al.*, 2021). For example, sandy soils have a significantly smaller surface area than clay soils and therefore retain much less water under higher stresses.

Additionally, the WRC of soil can also be improved by increasing the organic matter content (Libohova *et al.*, 2018). The addition of organic materials enhances the specific surface area of soil, thereby increasing its WRC. J. Hallam & M.E. Hodson (2020) investigated the impact of the anecic earthworm *Lumbricus terrestris* and the endogeic earthworm *Allolobophora chlorotica* on aggregate formation and WRC across different soil types (loam, silty loam, and loamy sand), noting a significant increase in WRC. F.G.A. Verheijen *et al.* (2019) studied the effect of biochar on bulk soil density and WRC under laboratory conditions using two agricultural soils from Portugal: sandy and loamy sand. The findings indicated that the addition of biochar effectively improved the soil's WRC. Similarly, in a study by M. Nuruddin & A.A.B. Moghal (2024), soil amended with biochar exhibited substantial improvements in WRC, ranging from 16% to 274.1%, depending on the biochar content (0-100%). The effects of soil layer WRC on the ability of a rain garden to retain stormwater, including considerations of HWC, are presented in Table 4. The modelling results, illustrated as curves in Figure 6, reveal that variations in WRC of the upper natural soil layer (w_{sat1}), the middle infiltration layer (w_{sat2}), and the lower gravel layer (w_{sat3}) influence the degree of water saturation and the time required for full saturation of the rain garden system. However, the HWC value at the surface remains nearly unchanged.

Table 4. Impact of soil layer WRC (w_{sat}) on stormwater retention efficiency in a rain garden system considering HWC

Parameters	Rain garden design			
	No. 1	**No. 2**	**No. 3**	**No. 4**
w_{sat1}, m³/m³	**0.42**	**0.36**	**0.34**	**0.30**
w_{sat2}, m³/m³	**0.36**	**0.34**	**0.32**	**0.28**
w_{sat3}, m³/m³	**0.15**	**0.15**	**0.1**	**0.1**
A_{bassin}/A_{sponge}	15	15	15	15
h_0, m	0.3290	0.3320	0.3326	0.3334
τ, s	6,386	5,924	5,418	4,907

Source: developed by the authors

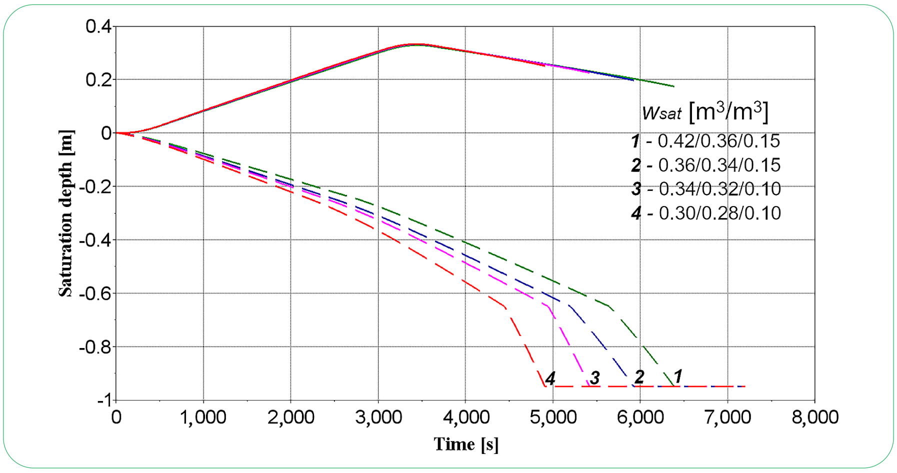

Figure 6. Relationship between rain garden saturation depth and HWC changes over time as a function of WRC (w_{sat})

Note: green line – rain garden design No. 1; blue – No. 2; pink – No. 3; red – No. 4

Source: developed by the authors

At the highest w_{sat} values of soil materials (0.42/0.36/ /0.15 m³/m³), the longest time to achieve full saturation of the rain garden system was recorded at 1 hour 46 minutes (6,386 s), with a surface water column height of 0.3290 m. Reducing WRC values resulted in a decrease in the time required for full saturation and complete filling of the system by an average of 8 minutes (493 s). Meanwhile, the value of h_0 on the surface of the structure remains practically unchanged at 0.33 m. As demonstrated by M. Kravchenko *et al.* (2024b), WRC influences the hydrological behaviour of rain gardens during modelling that does not account for the water column height. When the parameter h_0 is considered, WRC is not a primary characteristic for controlling or modifying the functional efficiency of the system. These findings align with the conclusions of J. Wang *et al.* (2019), where WRC was evaluated through sensitivity testing. It was established that this parameter has a significantly smaller impact on hydrological processes in the rain garden compared to hydraulic conductivity.

Filtration coefficient of rain garden systems

The filtration coefficient of a rain garden is a measure of the hydraulic capacity of the system, which affects its ability to infiltrate surface water before the next rainfall event and manage prolonged low-intensity precipitation. For rain gardens in temperate climates, the recommended range of

k_f values is 100-300 mm/h (Adoption guidelines…, 2015). When selecting the filtration coefficient, previously recorded values from field studies of rain gardens can be used, or the parameter can be determined under laboratory conditions, as in the present study. If the soil is welldrained and possesses a high infiltration capacity (e.g., greater than 10 cm/h), it can be used as a material for rain gardens. In cases where the soil has a low infiltration capacity, replacement with a specially designed soil mix may be required. For example, loamy sand and sand enhance infiltration, whereas a high clay content reduces soil permeability and pore size, diminishing the system's retention capacity (Putri *et al.*, 2023).

Based on scientific findings, it is challenging to recommend a precise proportion of sand, clay, or silt in rain garden soil mixtures to achieve a sufficiently high filtration coefficient. However, H. Takaijudin *et al.* (2019) suggested a widely accepted soil mix composition of 30-60% sand, 20-40% compost, and 20-30% natural soil. Additionally, infiltration tests conducted in rain gardens by D. Técher & E. Berthier (2023) demonstrated that plant roots and the biological processes occurring around them increase soil porosity, thereby enhancing the infiltration rate of stormwater. Thus, it can be argued that the infiltration capacity of rain gardens will be sufficient if: sand predominates in the soil composition; plants with a developed root system are planted in the upper soil layer; and there is no mechanical compaction of the soil medium. A low infiltration rate reduces the vertical movement of water through the soil and increases the HWC on the surface. As noted by J. Wang *et al.* (2019), lower infiltration capacity in rain gardens prolongs the presence of the surface water column, which may take up to 48 hours to recede. This condition can result in waterlogging of the vegetation and facilitate the proliferation of mosquitoes. Therefore, modelling the relationship between the stormwater retention efficiency of a rain garden and the variation in the filtration coefficient of its structure is critical during both the design and operational phases of these systems. In laboratory conditions, the filtration coefficients of soil layers in experimental rain gardens were determined as 7.0/45.0/200 cm/h. By altering the values for each layer, the overall filtration coefficient of the system ($k_{fsponge}$) can be adjusted. For the given water retention capacities (0.33/0.31/0.1 m^3/m^3), layer thicknesses of 0.25/0.4/0.3 m (total rain garden depth of 0.95 m), and an area ratio of A_{bassin}/A_{sponge} = 15, the dependency of stormwater retention efficiency on variations in $k_{fsponge}$ was derived during the modelling process (Table 5). As can be seen from the graphs of changes in the saturation depth of the rain garden layers and HWC over time depending on the filtration coefficient $k_{fsponge}$ (Fig. 7), this parameter has a significant impact on the hydrological behaviour of the system.

Table 5. Impact of filtration coefficient ($k_{fsponge}$) of soil layers on stormwater retention efficiency in rain gardens with consideration of HWC

Parameters	Rain garden design				
	No. 1	No. 2	No. 3	No. 4	No. 5
$k_{fsponge}$, cm/h	**122.0**	**190.0**	**258.0**	**326.0**	**394.0**
k_{f1}, cm/h	7.0	15.0	23.0	31.0	39.0
k_{f2}, cm/h	15.0	25.0	35.0	45.0	55.0
k_{f3}, cm/h	100.0	150.0	200.0	250.0	300.0
h_0, m	0.3368	0.2476	0	0	0
τ, s	5,968.5	3,653	2,826.5	2,352	2,039

Source: developed by the authors

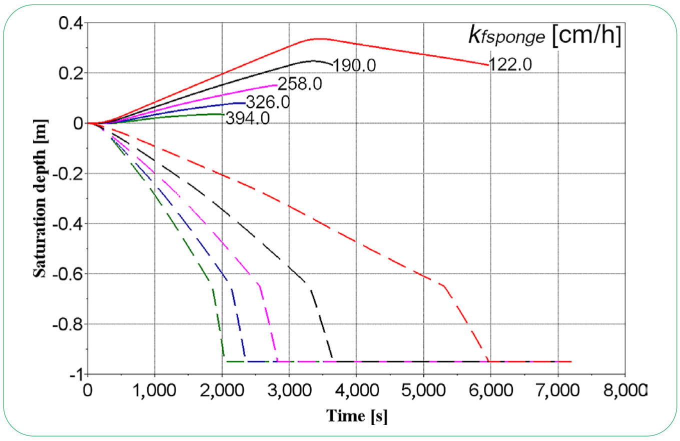

Figure 7. Dependence of the saturation depth of the rain garden structure layers and changes in HWC over time on the filtration coefficient $k_{fsponge}$

Note: red line – rain garden structure No. 1; black – No. 2; pink – No. 3; blue – No. 4; green – No. 5

Source: developed by the authors

At the minimum $k_{fsponge}$ of 122 cm/h, the rain garden structure reaches full saturation and fills with stormwater within 1 hour and 40 minutes (5,968.5 seconds). During this period, a water column 0.3368 m high forms on the surface of the rain garden. As the filtration coefficient increases, the system fills with water more quickly, and the surface HWC value decreases. For example, at $k_{fsponge}$ values of 326 and 394 cm/hour, the value of h_0 is 0 m, but the structure fills up quite quickly, in 39 minutes (2,352 s) and 34 minutes (2,039 s), respectively. In such cases, to ensure effective system operation and prevent overflow, it is necessary to include a drainage system that diverts excess stormwater into underground storage tanks or the sewer network. These findings align with results reported by J. Wang *et al.* (2019), which demonstrated that the highest productivity increase in rain gardens occurs when the filtration coefficient increases from 0.1 to 1 cm/h, with an area ratio of 17.5. Beyond k_f of 10 cm/h, the incremental productivity gain per unit increase in k_f diminishes, indicating a sharp decline in water retention time for k_f values below 10 cm/h. This highlights the particular sensitivity of rain garden performance to low k_f values (e.g., below 10 cm/h). Thus, at critical rainfall intensities (36 mm/h), a rain garden structure with a depth of 1.2 m (layer thicknesses of 0.3/0.5/0.4 m), an area ratio of 10 to 15, and a system filtration coefficient ranging from 100 to 200 cm/h can function effectively for up to 2 hours. This configuration significantly reduces the volume of stormwater and decreases surface runoff velocity. The main reasons for the differences with other studies are the different parameters of the rain garden structure setup, in particular, the properties of the soil materials.

Conclusions

This study demonstrated that a mathematical infiltration model incorporating Darcy's equation effectively simulates rain garden performance based on variations in its key parameters. The analysis of results enables the selection of optimal structural characteristics and appropriate soil materials during the design phase, ensuring effective operation during the system's service life. For instance, the modelling results indicated that to ensure the efficient functioning of a rain garden under critical rainfall intensity (36 mm/h), the system should meet the following parameters: a depth of 1.2 m (with layer thicknesses of 0.3/0.5/0.4 m), an area ratio of 10 to 15, and a filtration coefficient ranging from 100 to 200 cm/h.

The obtained results indicate that the ratio of the catchment area to the rain garden area and the filtration coefficient are the primary parameters determining the predicted time required for the system to fill completely and the formation of a water column on the surface. It was determined that the optimal A_{bassin}/A_{sponge} value is 15, corresponding to a system area of 6.6 m^2 for a catchment area of 100 m^2, which falls within the recommended range. Under these conditions, the system fills in 1 hour and 28 minutes (5,289 seconds) with a surface water column height of 0.3329 m. The model is significantly less sensitive to parameters describing the WRC of soil materials and the layer depths within the structure. It was found that changes to these parameters influence the time required for full saturation and system filling, while the surface HWC remains constant. A reduction in WRC decreases the total saturation and filling time by an average of 8 minutes (493 seconds). Increasing the system depth by 0.3 m extends the filling time by an average of 38 minutes (2,258 seconds).

For further refinement and enhancement of the proposed mathematical model, future research should focus on implementing rain gardens under real-world conditions. This approach would enable the calibration of the model based on empirical data, thereby improving prediction accuracy and the overall effectiveness of the system. Additionally, an important aspect of future investigations is the analysis of the influence of antecedent soil moisture from consecutive rainfall events. This would provide deeper insights into how systems respond to prolonged or intense precipitation and assess their resilience to frequent storms.

Acknowledgements

None.

Conflict of Interest

None.

References

[1] Abdallah, A.M., Jat, H.S., Choudhary, M., Abdelaty, E.F., Sharma, P.C., & Jat, M.L. (2021). Conservation agriculture effects on soil water holding capacity and water-saving varied with management practices and agroecological conditions: A review. *Agronomy*, 11(9), article number 1681. doi: 10.3390/agronomy11091681.

[2] Adoption guidelines for stormwater biofiltration systems: Cities as water supply catchments – sustainable technologies. (2015). Retrieved from https://watersensitivecities.org.au/content/stormwater-biofilter-design/.

[3] Alamdari, N., & Sample, D.J. (2019). A multiobjective simulation-optimization tool for assisting in urban watershed restoration planning. *Journal of Cleaner Production*, 213, 251-261. doi: 10.1016/j.jclepro.2018.12.108.

[4] Bethke, G.M., William, R., & Stillwell, A.S. (2022). Rain garden performance as a function of native soil parameters. *Journal of Sustainable Water in the Built Environment*, 8(1), article number 04021021. doi: 10.1061/JSWBAY.0000967.

[5] Bioretention – rain garden – recommendations. (n.d.). Retrieved from https://greatriversgreenway.org/design-guidelines/environmental/bioretention-raingarden/.

[6] Bortolini, L., & Zanin, G. (2019). Reprint of: Hydrological behaviour of rain gardens and plant suitability: A study in the Veneto plain (north-eastern Italy) conditions. *Urban Forestry & Urban Greening*, 37, 74-86. doi: 10.1016/j.ufug.2018.07.003.

[7] Burszta-Adamiak, E., Biniak-Pieróg, M., Dąbek, P.B., & Sternik, A. (2023). Rain garden hydrological performance – responses to real rainfall events. *Science of The Total Environment*, 887, article number 164153. doi: 10.1016/j.scitotenv.2023.164153.

[8] DSTU B V.2.1-23:2009. (2009). *Bases and foundations of buildings and structures. Soils. Methods of laboratory determination of the filtration coefficient*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=25933.

[9] Goh, H.W., Lem, K.S., Azizan, N.A., Chang, C.K., Talei, A., Leow, C.S., & Zakaria, N.A. (2019). A review of bioretention components and nutrient removal under different climates – future directions for tropics. *Environmental Science and Pollution Research*, 26, 14904-14919. doi: 10.1007/s11356-019-05041-0.

[10] Hallam, J., & Hodson, M.E. (2020). Impact of different earthworm ecotypes on water stable aggregates and soil water holding capacity. *Biology and Fertility of Soils*, 56, 607-617. doi: 10.1007/s00374-020-01432-5.

[11] Hoban, A., & Gambirazio, C. (2021). Bioretention performance: A review of field studies. *Australasian Journal of Water Resources*, 25(2), 202-210. doi: 10.1080/13241583.2021.1984190.

[12] Jiang, C., Li, J., Li, H., & Li, Y. (2019). An improved approach to design bioretention system media. *Ecological Engineering*, 136, 125-133. doi: 10.1016/j.ecoleng.2019.06.014.

[13] Kim, J., Baek, J., Kim, B., & Kwon, S. (2023). Analysis of outflow reduction effect of bioretention in small watersheds during short-term rainfall. *Journal of Korea Water Resources Association*, 56(12), 855-869. doi: 10.3741/JKWRA.2023.56.12.855.

[14] Kravchenko, M., Trach, Y., Trach, R., Tkachenko, T., & Mileikovskyi, V. (2024a). Improving the efficiency and environmental friendliness of urban stormwater management by enhancing the water filtration model in rain gardens. *Water*, 16(10), article number 1316. doi: 10.3390/w16101316.

[15] Kravchenko, M., Trach, Y., Trach, R., Tkachenko, T., & Mileikovskyi, V. (2024b). Behaviour and peculiarities of oil hydrocarbon removal from rain garden structures. *Water*, 16(13), article number 1802. doi: 10.3390/w16131802.

[16] Kravchenko, M., Tkachenko, T., & Mileikovskyi, V. (2024c). Study of the influence of the main parameters of the rain garden on its hydrological parameters by modeling. *Collection of Scientific Papers of Admiral Makarov National University of Shipbuilding*, 1, 166-176. doi: 10.15589/znp2024.1(494).23.

[17] Lee, J., Bae, S., Lee, W.H., & Gil, K. (2022). Effect of surface area to catchment area ratio on pollutant removal efficiency in vegetation-type facilities. *Ecological Engineering*, 179, article number 106609. doi: 10.1016/j.ecoleng.2022.106609.

[18] Li, G., Xiong, J., Zhu, J., Liu, Y., & Dzakpasu, M. (2021). Design influence and evaluation model of bioretention in rainwater treatment: A review. *Science of The Total Environment*, 787, article number 147592. doi: 10.1016/j.scitotenv.2021.147592.

[19] Libohova, Z., Seybold, C., Wysocki, D., Wills, S., Schoeneberger, P., Williams, C., Lindbo, D., Stott, D., & Owens, P.R. (2018). Reevaluating the effects of soil organic matter and other properties on available water-holding capacity using the national cooperative soil survey characterization database. *Journal of Soil and Water Conservation*, 73(4), 411-421. doi: 10.2489/jswc.73.4.411.

[20] Lisenbee, W., Hathaway, J., Negm, L., Youssef, M., & Winston, R. (2020). Enhanced bioretention cell modeling with DRAINMOD-Urban: Moving from water balances to hydrograph production. *Journal of Hydrology*, 582, article number 124491. doi: 10.1016/j.jhydrol.2019.124491.

[21] Lisenbee, W.A., Hathaway, J.M., & Winston, R.J. (2022). Modeling bioretention hydrology: Quantifying the performance of DRAINMOD-Urban and the SWMM LID module. *Journal of Hydrology*, 612, article number 128179. doi: 10.1016/j.jhydrol.2022.128179.

[22] Liu, R., & Fassman-Beck, E. (2018). Pore structure and unsaturated hydraulic conductivity of engineered media for living roofs and bioretention based on water retention data. *Journal of Hydrologic Engineering*, 23(3), article number 04017065. doi: 10.1061/(ASCE)HE.1943-5584.0001621.

[23] Nelson, J.T., Adjuik, T.A., Moore, E.B., VanLoocke, A.D., Ramirez Reyes, A., & McDaniel, M.D. (2024). A simple, affordable, do-it-yourself method for measuring soil maximum water holding capacity. *Communications in Soil Science and Plant Analysis*, 55(8), 1190-1204. doi: 10.1080/00103624.2023.2296988.

[24] Nichols, W., Welker, A., Traver, R., & Tu, M.-C. (2021). “Peter” modeling seasonal performance of operational urban rain garden using HYDRUS-1D. *Journal of Sustainable Water in the Built Environment*, 7(3), article number 04021005. doi: 10.1061/JSWBAY.0000941.

[25] Nuruddin, M., & Moghal, A.A.B. (2024). State-of-the-art review on the geotechnical and geoenvironmental feasibility of select biochars. *Indian Geotechnical Journal*, 54, 1073-1094. doi: 10.1007/s40098-023-00788-3.

[26] Putri, F.K., Hidayah, E., & Ma’ruf, M.F. (2023). Enhancing stormwater management with low impact development (LID): A review of the rain barrel, bioretention, and permeable pavement applicability in Indonesia. *Water Science & Technology*, 87(9), 2345-2361. doi: 10.2166/wst.2023.095.

[27] Rain gardens. (2023). Retrieved from https://www.instagram.com/p/CngYDIatE1B/?img_index=1.

[28] Rain garden and bioretention literature review: An assessment of functional parameters, BMPs and landowner perspectives. (2017). Retrieved from https://www.ezview.wa.gov/Portals/_1962/Documents/SAM/RainGarden-Bioretention%20Literature%20Review%202017.pdf.

[29] Rinchumphu, D., Suriyanon, N., Phichetkunbodee, N., Munlikawong, S., Wanitchayapaisit, C., & Sitthikankun, S. (2023). Economics and cost effectiveness of a rain garden for flood-resistant urban design. *Global Journal of Environmental Science and Management*, 10(1), 1-12. doi: 10.22034/gjesm.2024.01.01.

[30] Sittisom, P., Tangsongsuwan, R., Munlikawong, S., Wongsapai, W., Sitthikankun, S., & Rinchumphu, D. (2022). The determination of soil infiltration rate of urban bioretention design process in Chiang Mai, Thailand. *Nakhara: Journal of Environmental Design and Planning*, 21(3), article number 228. doi: 10.54028/NJ202221228.

[31] Ellis, L., & Bettin, K. (2022). Stormwater management: Rain gardens to bioretention areas. *Journal of Opinions, Ideas & Essays*, 5, article number 1.

[32] Takaijudin, H., Abdurrashed, A.S., Osman, M., Sholagberu, A.T., Yusof, W.K., & Ab Ghani, A. (2019). The influence of soil characteristics on hydraulic performance in bioretention system. *Platform: A Journal of Science and Technology*, 2(1), 12-22. doi: 10.61762/pjstvol2iss1art4587.

[33] Técher, D., & Berthier, E. (2023). Supporting evidences for vegetation-enhanced stormwater infiltration in bioretention systems: A comprehensive review. *Environmental Science and Pollution Research*, 30, 19705-19724. doi: 10.1007/s11356-023-25333-w.

[34] Verheijen, F.G.A., Zhuravel, A., Silva, F.C., Amaro, A., Ben-Hur, M., & Keizer, J.J. (2019). The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. *Geoderma*, 347, 194-202. doi: 10.1016/j.geoderma.2019.03.044.

[35] Wang, J., Chua, L.H.C., & Shanahan, P. (2019). Hydrological modeling and field validation of a bioretention basin. *Journal of Environmental Management*, 240, 149-159. doi: 10.1016/j.jenvman.2019.03.090.

[36] Williams, A., Jordan, N.R., Smith, R.G., Hunter, M.C., Kammerer, M., Kane, D.A., Koide, R.T., & Davis, A.S. (2018). A regionally-adapted implementation of conservation agriculture delivers rapid improvements to soil properties associated with crop yield stability. *Scientific Reports*, 8, article number 8467. doi: 10.1038/s41598-018-26896-2.

[37] Zhang, B., Li, J., & Li, Y. (2020). Simulation and optimization of rain gardens via DRAINMOD model and response surface methodology. *Ecohydrology & Hydrobiology*, 20(3), 413-423. doi: 10.1016/j.ecohyd.2020.03.002.

[38] Zhang, L., Ye, Z., & Shibata, S. (2020). Assessment of rain garden effects for the management of urban storm runoff in Japan. *Sustainability*, 12(23), article number 9982. doi: 10.3390/su12239982.

Моделювання інфільтраційних процесів у дощових садах: вплив параметрів дизайну на гідрологічну ефективність

Марина Кравченко

Кандидат технічних наук, доцент
Київський національний університет будівництва і архітектури
03037, просп. Повітряних Сил, 31, м. Київ, Україна
https://orcid.org/0000-0003-0428-6440

Тетяна Ткаченко

Доктор технічних наук, професор
Київський національний університет будівництва і архітектури
03037, просп. Повітряних Сил, 31, м. Київ, Україна
https://orcid.org/0000-0003-2105-5951

Віктор Мілейковський

Доктор технічних наук, професор
Київський національний університет будівництва і архітектури
03037, просп. Повітряних Сил, 31, м. Київ, Україна
https://orcid.org/0000-0001-8543-1800

Анотація. Дощовий сад – це конструкція для управління дощовими водами на місці. Недосконалий дизайн дощового саду може погіршити його гідрологічні властивості під час експлуатації, що вимагає розробки та апробації відповідної математичної моделі для інженерного розрахунку й оцінки конструкції. Метою цього дослідження було моделювання процесу інфільтрації у дощовому саду на основі математичної моделі, яка враховує висоту стовпа води (ВСВ) на поверхні конструкції та коефіцієнт фільтрації ґрунтових матеріалів, імітуючи реакцію системи під час екстремальної дощової події (36 мм/год). Використовуючи розроблену модель, отримано розрахункові криві, що описують продуктивність дощового саду залежно від параметрів його дизайну: глибини конструкції, співвідношення площі водозбірного басейну до площі дощового саду, коефіцієнта фільтрації та водоутримувальної здатності (ВУЗ). Основні параметри ґрунтових матеріалів визначалися експериментальним шляхом у лабораторних умовах. Інфільтраційна продуктивність конструкції оцінювалася за зміною часу проникнення та насичення всіх шарів, а також заповненням водою дощового саду в результаті коригування його параметрів і змін ВСВ на поверхні. Результати моделювання показали, що основними параметрами, які визначають прогнозований час повного заповнення системи водою і формування ВСВ, є співвідношення площ та коефіцієнт фільтрації. ВУЗ ґрунтових матеріалів і глибина шарів конструкції суттєво впливають на час повного насичення і заповнення системи водою, але майже не впливають на ВСВ на поверхні. Показано, що конструкція глибиною 1,2 м, при співвідношенні площ 15 та з коефіцієнтом фільтрації 100-200 см/год ефективно функціонує при критичній інтенсивності дощових опадів. Розроблена модель і отримані результати, надаючи точні розрахунки та рекомендації щодо параметрів конструкції, можуть бути використані інженерами та проєктувальниками для вдосконалення дизайну дощових садів, що сприятиме підвищенню ефективності управління зливовими водами

Ключові слова: управління зливовими водами; коефіцієнт фільтрації; водоутримувальна здатність; співвідношення площ; висота водяного стовпа