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The effect of the substrate depth on hydrological performance of a vegetation roof: Laboratory study

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There are increasing demands in cities to reduce the amount of impermeable areas and mitigate water runoff from extreme rainfall. Vegetated roofs are a promising nature-based solution for stormwater management in urban areas. In this study, the retention of rainwater on a roof substrate with different depths and during different rainfall intensities was evaluated. An experiment was conducted in laboratory conditions using a small rainfall simulator. A commercial roof substrate was tested, where by 3 different depths of a substrate were chosen (7, 10, and 14 cm) then, a 15-minute rainfall with 3 intensities (1.3; 2.7, and 3.8 mm min^{-1}) was applied. The study revealed variations in higher rainfall intensities of 2.7 mm and 3.8 mm min^{-1}. A comparison was made using substrate with a depth of 7–10 cm, indicating an 8–16% increase in water retention capacity. The roof substrate with a depth of 10–14 cm increased its retention capacity by 12%. The water retention results can be considered as the maximum limit of possible retention for a 15-minute duration of rainfall at specific 3 intensities. This experiment showed that a longer duration of rain is needed to determine the peak discharge attenuation rate.

KEY WORDS: extensive vegetated roof, roof substrate, rainfall, runoff reduction, retention

Introduction

Considering possible threats posed by climate change, urbanised areas are nowadays forced to incorporate blue-green infrastructures. The definition of a blue-green infrastructure is a network of water-related, green elements located in urban areas. It aims to ensure the proper management of stormwater, the greening of street spaces, improvement of the air, and the reduction of heat islands in cities. A blue-green infrastructure cannot prevent abrupt changes in the local climate, but it can significantly mitigate the impact of climate change through appropriately designed and combined adaptation measures. In the past few years, we have been experiencing more and more frequent droughts, so it is necessary to think about the best ways to use and supply rainwater. The problem in urbanised areas is not only droughts with high temperatures but also extreme precipitation events with high intensities. Intense precipitation over a short period of time results in a high amount of rainfall, which can cause insufficient infiltration into the soil. Streets and other public areas are generally made of impervious materials (concrete, asphalt). Combinations of intense short-term precipitation and impervious surfaces cause rapid surface runoff. Rapid surface runoff leads to flood activity (flooding of public areas, roads, and pavements). Stormwater runoff is also another major problem. The elements of blue-green infrastructure can help to prevent undesirable effects. The basic elements are green areas, e.g., green/vegetated roofs or vegetated walls (vertical gardens) (Zaťovičová and Majorošová, 2023). Due to their hydrological function, they can significantly reduce stormwater runoff, which supports sustainable urban drainage systems. Runoff can be used as a supplementary source of water through its accumulation. Water accumulation is achieved by a drainage layer and a substrate that contains a larger pore volume. As a result of the accumulation of water, the runoff of uninfiltrated water is significantly slowed down, thereby significantly reducing flow and volume (Uhl and Schiedt, 2008).

Urban development needs to take into consideration social and demographic changes and processes, and technological developments, as well as the impact of climate change, including the occurrence of extreme events, from the perspective of sustainable development. To mitigate the impact of climate change, cities are incorporating adaptation measures that seek to eliminate paved and impermeable surfaces and increase green spaces. This is due not only to the need for rainwater drainage but also to the overheating of these areas and the consequent radiation of heat into the environment and an increase in people's body temperature. Strategically designed green spaces in cities can achieve a reduction in temperature differences and the gradual absorption of rainwater. Various measures can be used to minimize the issue, which include vegetated roofs. The composition of a vegetated roof structure consists of several layers, such as roof sheathing layers and vegetation layers (protection, drainage, and filtration layers, substrate, and vegetation) (Burian et al., 2022). The positive effects of vegetated roofs are manifold. They provide natural cooling or possibly heat retention in living spaces (Getter and Rowe, 2006) and create spaces for recreation and relaxation for residents of public/residential developments. Their ability to influence runoff is considered to be their greatest positive characteristic, as they can temporarily retain rainfall volume (Sailor and Hagos, 2011). This has the effect of delaying peak flows into the stormwater conveyance system. With the evaporation from the substrate surface and transpiration from vegetation, vegetated roofs are able to significantly reduce runoff (Schultz et al., 2018).

The purpose of a vegetated roof is to bring more greenery into an existing urbanised area. A properly designed vegetated roof promotes retention during increasingly frequent short precipitation events and can cool rooftop apartments. They encourage the development of biodiversity (the occurrence of local plants to attract pollinators). The right choice of vegetation can reduce dust particles and CO_2 in the air of an urbanised area. A vegetated roof has a beneficial effect on the psychological state of a person. It creates a place for relaxing, and common activities (community gardens). In addition to the beneficial effects, we also must consider the negative aspects of vegetated roofs. Before designing roofs, we must also take into account the maintenance intensity factor, which varies depending on the type of roof. The maintenance of a vegetated roof varies depending on the type of vegetated roof type and the structure's difficulty. Extensive vegetated roofs are classified as roofs that do not require frequent and demanding maintenance. Maintenance is carried out 2–3 times a year. On the contrary, intensive vegetated roofs are classified as one of the most demanding roofs to maintain. It consists of a varied composition of vegetation types (perennials, shrubs, trees). Due to the diversity of vegetation, these roofs require a regular irrigation system. The maintenance is carried out 4 to 8 times a year. It is very important to take into consideration the loading of the roof structure by the vegetated roof layers. A vegetated roof is not designed for every roof. Conventional roofs have not been designed for such loads. Before any renovation, the roof must be subjected to a static test. The test will demonstrate whether it is appropriate to use a vegetated roof on the existing roof and what type of vegetated roof is appropriate. The cost of construction depends on the type of vegetation roof that has been selected. An extensive vegetation roof is cheap compared to an intensive vegetation roof. The final price depends on the condition of the original roof, the dimensioning of the roof after a static test, the size of the area, the choice of material, the depth of the substrate, the type of vegetation and, last but not least, the technical elements used (photovoltaics, irrigation) (Burian et al., 2022).

In general, it is known that intensive roofs with a substrate depth of more than 15 cm can mitigate surface runoff compared to extensive roofs, which have a substrate depth of up to 15 cm, regardless of the typology of the region (Zheng et al., 2021).

Roof substrate

Vegetated roofs are capable of retaining and infiltrating rainwater based on certain rainfall characteristics. Stormwater that has been infiltrated can be retained by the soil and storage layer of a vegetated roof. Studies by Villarreal et al. (2004) and Šurda et al. (2023) delineate their observation of the occurrence of surface runoff. The runoff starts at the point when the rainfall intensity is greater than the soil's hydraulic conductivity. Compaction of the component is important when the soil is used on a vegetated roof. Too much compaction can affect the thermal properties of the substrate and can also lead to a lack of oxygen in the root system, which can affect the healthy growth of the plants (Sailor and Hagos, 2011).

One of the most important components of a vegetated roof is the roof substrate. With the right choice of substrate composition, we can avoid too much weight on the building structure. This can permit us to use a thicker layer of roof substrate, which will allow us to expand the range of different plant taxa. The ideal composition of the substrate should provide and retain the necessary nutrients for the proper development of vegetation. Substrates for vegetated roofs vary in their materials and amounts, they mostly contain organic matter and lightweight mineral aggregate to meet the required properties. Aggregate is the most commonly used in vegetated roofs. After aggregate, sand is the most widely used component; it represents 30–40% of the volume of the mixture. Substrates may include pumice, zeolite, vermiculite, perlite, peat, and crushed brick. Sailor and Hagos (2011) tested soil containing expanded clay, porous silica, and expanded slate. The study showed that soils based on silica were able to retain more moisture. The results of the study indicate that silica components can retain moisture during dry periods. Several studies have focused on investigating the reduction of water velocity by the use of additives such as biochar. The results have shown that biochar helps to increase the saturated hydraulic conductivity of the soil (Toková et al., 2023). There is a large variety of roofing substrates on the market, that are usually typical of regions and countries. Their selection is important due to the variety of weather conditions, the type of cover, and the limiting load on the roof. Countries that do not have access to commercial substrates are forced to use local substrates. These substrates have low water retention capacity, place significant loads on the structure, promote weed growth, wash away nutrients, and harden the substrate quickly (Dvorak and Volder, 2010). A German manual suggests that the substrate should contain 4–8% organic material for extensive roofs and 6–12% for intensive roofs (Landscape Development and landscaping research society e.V. – FLL, 2018). According to Vijayaraghavan (2016), an ideal substrate should include a minimum amount of organic material, high water-holding capacity, a high degree of hydraulic conductivity, less leaching and high sorption capacity, good aeration and movement of soil water. The weight (lightweight), cost, local availability, and stability under different conditions are also important.

When vegetated roofs are designed, the most important part of stormwater management is the reduction of the total runoff volume, the reduction of peak flow, and the overall delay of any runoff. Several studies address stormwater management during extreme precipitation events, as well as the factor of substrate depth. From a rational aspect, it appears that the deeper the substrate, the better the retention capacity. However, some studies show evidence, to the contrary, e.g., Voyde et al. (2010), who in a study of extensive vegetated roofs in New Zealand, did not find a significant difference in water retention in roof substrates with 5 and 7 cm depths. Fassman-Beck et al. (2013) came to a similar conclusion in experimental measurements. A study conducted in Beijing investigated retention on 6 modular vegetation canopies with different substrate heights. Simulations have shown that the retention performance of vegetated roofs decreases with increasing frequency of extreme storms, but improves with increasing substrate depth. However, there is a critical substrate depth beyond which further increases in depth do not significantly improve retention performance. (Zhang et al., 2021).

When designing a vegetated roof, the depth of the substrate is a key factor, but the relationship between increasing depths and increasing retention does not appear to be clear. Substrates for vegetated roofs should have unique properties to achieve the desired requirements (Bollman et al., 2019). They should mainly, have low bulk density, high water retention capacity to reduce runoff from rainfall, proper organic matter content for vegetation growth (Vandegrift et al., 2019), and high sorption for a lower risk of water pollution (Vandegrift et al., 2019). It is not easy to find a single material that can meet all of these desired properties. A good substrate consists of components, each of which will deliver a given property; their ratio and grain size composition also important. It is usually a mix of materials including organic matter, sand, and lightweight mineral aggregates (Bollman et al., 2019). A variety of commercial substrates are used to construct vegetated roofs in regions where locally available materials are used to produce substrates and make vegetated roofs more efficient (Gong et al., 2019). The amount, of the precipitation and intensity, and the duration of any previous dry season have an important role in predicting the effectiveness of a vegetated roof. Voyde et al. (2010) found that water retention by a vegetation roof decreases during wetter days and also when precipitation events occur in succession over a short period. Carson et al. (2013) demonstrated a seasonal effect on runoff for precipitation events of 10–40 mm. Similar results were reached by Spolek (2008) on research in Portland, where the difference in summer and winter in the effectiveness of runoff reduction on a vegetated roof was 30%.

The substrate layer acts as a major factor influencing the quality of runoff from vegetated roofs and can filter and absorb stormwater, thereby potentially reducing the concentrations and loading of pollutants and nutrients in stormwater (Gong et al. 2019). When a vegetated roof is fertilized or impacted by atmospheric deposition, the vegetated roof becomes a source of certain pollutants. Therefore, the concentration of these pollutants in runoff will increase dramatically compared to runoff from a conventional roof (NR) (Razzaghmanesh and Beecham, 2014; Vijayaraghavan et al., 2016). Several studies, on the other hand, have shown that runoff from vegetated roofs contains heavy metals in the composition of copper (Cu), iron (Fe), zinc (Zn), and aluminum (Al). The roofs with less organic material have a better effect on the heavy metal content of water (Razzaghmanesh and Beecham, 2014).

The aim of this article is to demonstrate the importance of choosing a roof substrate when establishing vegetated roofs. Specifically, we have focused on the effect of the depth of the roof substrate. In general, an increased substrate depth results in a better retention capacity. However, some studies indicate evidence to the contrary, e.g. (Voyde et al., 2010).

For this reason, a change in the runoff regime was detected for the selected depth range of the commercial substrate that is widely used in our country. The retention capacity of the substrate is also affected by the duration and intensity of the stormwater. The following question is also related to this: In the event of a higher intensity of precipitation, does the runoff volume change? This study is based on experimental measurements of different rainfall intensities and substrate depths. The results should answer the question about the retention capacity of the selected substrate under different conditions.

Material and methods

Experimental setup

The main equipment of the experiment was a rainfall simulator with other important accessories such as a hygrometer, a stopwatch, and a sampling cylinder. Specifically, a small portable rainfall simulator Eijkelkamp was used with a storage capacity of 2.3 l and an area of 0.0625 m^2. For the above experiment, a roof substrate set-up was constructed consisting of two plastic containers. The top container had a perforated bottom to simulate the natural conditions in a vegetated roof´s composition and allow subsurface runoff to occur. The top container had a slope of approximately 2%. The stormwater runoff was subsequently captured in the bottom container (Fig. 1).

A Bratislava roof substrate was used with depths of 7 cm, 10 cm, and 14 cm, which was slightly compacted to achieve the natural conditions of its facilitation. To ensure the same conditions of the roof substrate, a different sample was used each time; it generally had about the same initial moisture condition (max. 5%) as well as the actual placement of the substrate. Moisture content was measured with the HH2 Moisture Meter from Delta-T Devices.

The experiment studied the effect of the intensity of a rainfall on the storage capacity of the roof substrate. Rainfall simulations were performed at an intensity of

1.3 mm min^{-1}, 2.7 mm min^{-1}, and 3.8 mm min^{-1}. The duration of the simulation was identical for all the rainfall experiments, i.e., 15 min. In this case, it was an intermittent 15-minute rainfall with a constant intensity. The intermittent rainfall and the actual measurements were carried out at various times (3, 6, 9, 12, and 15 min) to obtain detailed runoff production and information on the change in the moisture content. The reason for the interruption was also the necessity to refill the water in the simulator tank, which has a volume of 2.3 liters. The duration of the subsurface runoff production was measured using a stopwatch in parallel with the start of the rainfall simulator; this was the time at which water flowed through the substrate through the small drainfall holes drilled into the empty bottom container. The holes are 5 mm in size and formed in a triangular grid (Fig. 2). After 3 minutes, the simulation was stopped, and the runoff and substrate moisture were measured in the shortest time possible. Each experiment lasted 15 minutes. It was assumed that the influence of rainfall intensity and different thickness of the substrate is detected in this duration.

Bratislava substrate

The Bratislava substrate is composed of a large amount of particles of various materials in different proportions. The most common substrate components are brick rubble, lava, and compost. The chemical and physical properties of the substrate are given in Table 1. In the construction of vegetated roofs, it is used with a layer depth of 6 cm and can be placed on flat and sloped roofs. The weight of the substrate in its dry state is low at 1 m^3=0.95 t and at 1 m^3=1.39 t in the wet state (Roof substrate, 2021), which represents a weight increase of approximately 30%.

The high water absorption of the substrate has several advantages. It helps the vegetation to create optimum conditions for growth. There is a reduction in costs for the roof drainage and air conditioning of buildings. However, a high retention rate can be problematic for the static load of the roof. The roof must be designed and constructed to bear such static load. When we identify soil, we primarily focus on its basic physical properties, which include the specific gravity (ρ_s), bulk density (unreduced ρ_W, reduced ρ_d), porosity, texture, and structure. These properties are important in any mixture and substrate. The soil texture (aggregate sizes 5–10 mm) influences the flow of the water and air in the soil. The texture is categorized as fine soil (particles smaller than 2 mm, e.g., sand, dust, clay) and skeletal (particles larger than 2 mm, e.g., gravel, stone).

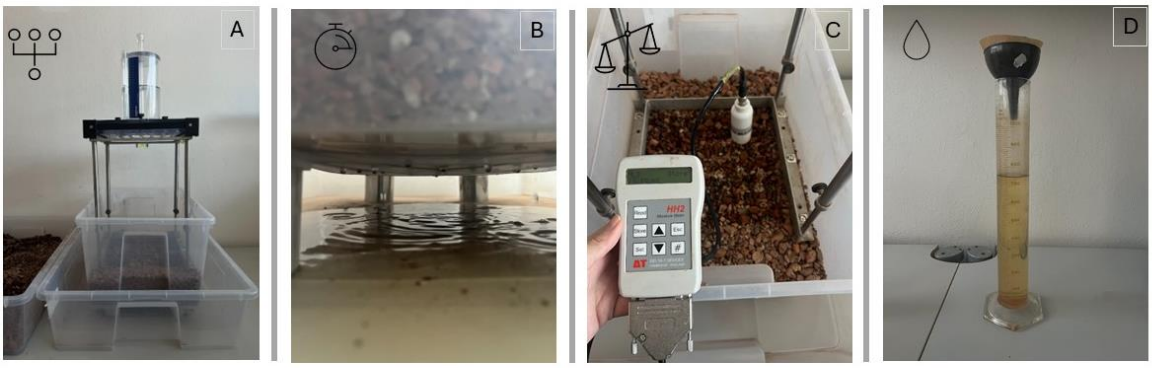

Fig. 1. A – Experimental set-up, B – Runoff from the substrate, C – Substrate moisture measurements, D – Graduated cylinder with runoff water.

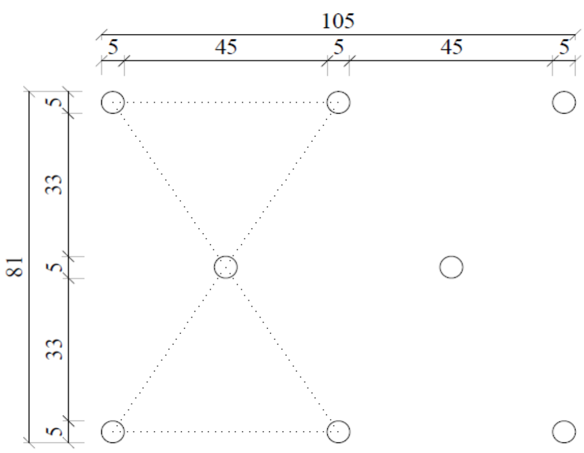

Fig. 2. Perforation distance of the plastic container.

The grain size of the Bratislava roof substrate was detected by standard sieving through sieves on a 200-gram sample. From the grain size analysis, approximately half of the substrate is in the 2–5 mm grain size range; grains of 5–10 mm make up 14%; and grains of 10–20 mm make up 27%. Smaller percentages consist of grain sizes of 0.01–0.25 mm (1%), 0.25–0.5 mm (2%), 0.5–1 mm (3%), and 1–2 mm (4%). In the case of the roofing substrate tested, the skeleton is 90% skeleton, with approximately 80% being brick rubble (Fig. 3).

Retention and detention functions of rainfall water

The water retention and detention functions of the roof substrate were quantified using four hydrological indicators, according to Zhangh et al. (2021). The hydrological indices are a water retention rate of the rainfall (D_r), peak discharge attenuation rate (D_{pr}), and time delays in both runoff generations (ΔT_r). From the rainfall-runoff measurements of the roof substrate, those indices could be determined by the following formulae:

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

where:
P – rainfall depth [mm],
R – the depth of runoff from substrate [mm],
D_r – water retention rate of the rainfall.

$$D_{pr} = \frac{I_{max}-D_p}{I_{max}} \times 100\% \quad (2)$$

where:
I_{max} – the peak rainfall intensity [mm min^{-1}],
D_p – the peak runoff from substrate [mm min^{-1}],
D_{pr} – peak discharge attenuation rate.

$$\Delta T_r = T_{rR} - T_{rP} \quad (3)$$

where:
T_{rR} – the runoff starting time [min],
T_{rP} – the rainfall starting time [min],
ΔT_r – time delays in both runoff generations.

Results and discussion

The results of the simulated rainfall runoff from the roof substrate are presented in Fig. 4. The substrate infiltration (black dashed line) and runoff volumes (blue area) were measured in the experimental modules (substrate depths of 7 cm, 10 cm, and 14 cm). To exclude any uncertainty of the results, 3 repetitions of the measurements were performed. A simulated rainfall with a duration of 15 minutes at a constant intensity (1.3 mm min^{-1}, 2.7 mm min^{-1}, and 3.8 mm min^{-1}) for all the substrate depths tested was used. Fig. 4 shows the mean of the three replicates for each combination. A total of 27 simulations were performed.

The highest increase in the runoff volume was after 9 minutes in all the cases. The influence of the depth of the substrate was demonstrated, as can be seen from the visualization of the results. The intensity of the rainfall also had a significant impact (Fig. 4). The following table shows the basic hydrological parameters related to the water retention rate of the rainfall, and the time delay in the runoff generation and substrate moisture (Table 2). The cumulative runoff shows (Fig. 4) that the peak runoff from the simulated rainfall was not detected. For this reason, the peak discharge attenuation characteristics are not shown in Table 2.

Table 1. Chemical and physical properties by supplier

Properties	Value
Moisture content in % by weight	max. 10
Content of combustible substances in dry matter % by weight	min. 3
Nitrogen content as N in % of dry substances	min. 0.07
Phosphorus content as P_2O_5 in % of dry substances	min. 0.1
Potassium content as K_2O in % of dry substances	min. 0.3
El. conductivity in s cm^{-1}	max 1.2
pH value	6.5–8.5
Grain size above 20 mm	0

< 1 mm 3–5 mm 5–10 mm 10–20 mm

Fig. 3. The grain size analysis of the Bratislava roof substrate.

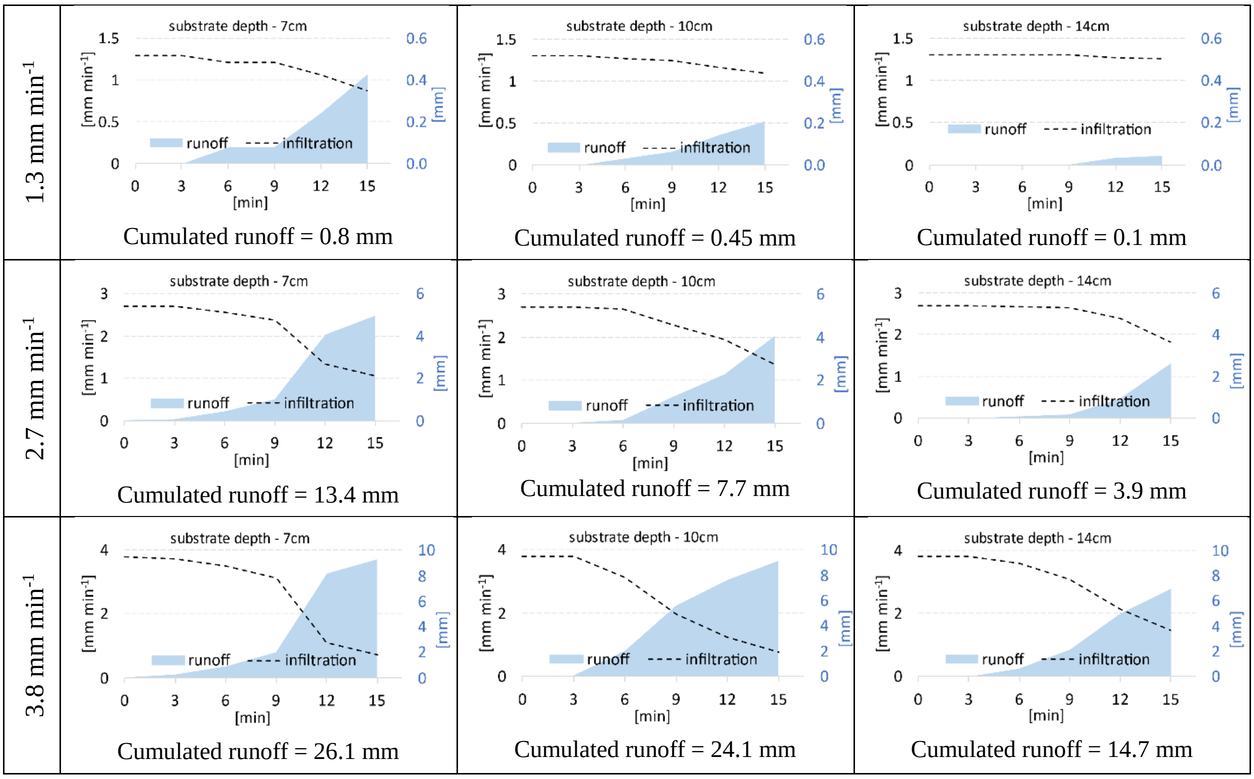

Fig. 4. Substrate infiltration and runoff rates/cumulative runoff volumes (mean of three replicates) measured in the experimental modules (substrate depth 7 cm, 10 cm, and 14 cm) after a simulated rainfall of a duration of 15 minutes (constant intensity 1.3 mm/min, 2.7 mm min^{-1} *and 3.8* mm min^{-1}*).*

Table 2. Hydrological variables were measured in the experimental modules after the simulated rainfalls

Substrate depth [cm]	Rainfall depth [mm]	Runoff depth [mm]	Water retention rate of rainfall (1) [%]	Time delay in runoff generation (3) [min]	Substrate moisture [%]	
					Before measurement	After measurement
7	19.5	0.83	95.77	5.00	1.9	19.4
10	19.5	0.36	98.15	5.80	0.7	20.2
14	19.5	0.06	99.67	12	1.4	21.7
7	37.5	13.58	63.78	2.6	2.1	22.8
10	37.5	7.80	79.31	3.2	0.7	20.2
14	37.5	3.30	91.21	5	1.6	22.6
7	57	26.78	53.01	0.55	2.1	22.8
10	57	22.10	61.23	1.26	2.1	21.4
14	57	14.75	74.12	1.7	1.4	21.6

The results show that the runoff was minimal, with an intensity of 1.3 mm min^{-1} and a rainfall duration of 15 min (a total rainfall of 19.5 mm). The effect of the substrate depth (7, 10, and 14 cm) was not significant (Fig. 4). The initial moisture content of the substrate before the measurement was below 5%. The final moisture content at the end of the measurements varied from 19–22% (Fig. 5). According to Zhang et al. (2022), the vegetated roofs generated hardly any runoff under light rainfall events (<10 mm), which was also indirectly confirmed in this study.

However, at higher intensities (2.7 and 3.8 mm min^{-1}) substantial differences in runoff were found. There was an increase in substrate retention capacity of 8–16% (comparing the depths of 7 and 10 cm). In a comparison of the cumulative runoff from the substrate depths of 10 and 14 cm, retention increased by 12%.

The time delay in the runoff formation was evident at low rainfall intensities, i.e., 5–12 min. No significant time delay between the substrate depths was recorded at

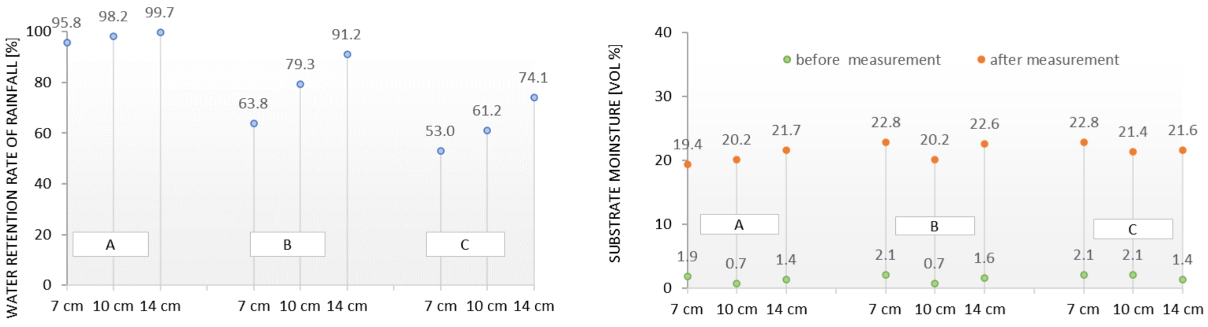

Fig. 5. A water retention rate of the substrate at different depths during the 27 simulated rainfall events (A – intensity rainfall 1.3 mm min^{-1}, B – 2.7 mm min^{-1}, C – 3.8 mm min^{-1}), substrate moisture before and after simulation rainfall.

the higher rainfall totals (Table 2). The water retention results can be considered as the maximum limit of possible retention for a 15-minute duration of rain at specific 3 intensities. This experiment showed that a longer duration of rainfall is needed to determine the peak runoff. Recently, extreme rainfall intensities (more than 4 mm min^{-1}) were identically simulated, and a duration of 15 minutes was sufficient for this purpose. It can be concluded that the intensity and duration of rainfall are very important in the formation of runoff.

This experimental study is focused on testing the Bratislava substrate and, therefore, does not correspond to the requirements of a real vegetated roof. Initial measurements will focus on the analysis of a substrate to see how the substrate material (80% crushed brick) will behave during a 15-minute rainfall event.

Because these presented retention rates are not total ones, just retention rates after 15 minutes. Future laboratory measurements will investigate substrate performance during a 30-minute rainfall event. And it will be very important to measure the base with all the necessary components of the vegetation roof.

Conclusion

The aim of the study was to demonstrate the effect of the substrate in a vegetated roof on any reduction in stormwater runoff. This was based on experimental measurements in the form of different rainfall intensities and substrate depths.

Identical initial conditions were set up for all the measurements. The substrate moisture content varied up to a maximum of 3% (Fig. 5). During the measure ments, three repetitions were performed, and the same combinations of rainfall events were tested. The effect of the height of the substrate was not manifested at low intensities. The differences in the substrate water retentions were higher for the intense rainfalls, and the effect of the substrate´s height was also demonstrated.

From the results of the time duration of the formation of the runoff from the rainfall, the highest increase in the volume of the runoff can be seen after 9 minutes (Fig. 4). The results from the higher intensity rainfalls (2.7 and 3.8 mm min^{-1}) show that differences in runoff were found. There was an increase in the retention capacity of the substrate of 8–16% (comparing the depth substrates of 7 and 10 cm). From a comparison of the cumulative runoff from the substrate depths of 10 and 14 cm, the retention increased by 12%. The effect of the depth of the substrate at the low intensities of the rainfall was not found to have a significant difference. The water retention results can be considered as the maximum limit of possible retention for a 15-minute duration of rainfall at specific 3 intensities. This experiment showed that a longer duration of rainfall is needed to determine the peak runoff.

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References

Bollman, M. A., DeSantis, G. E., DuChanois, R. M., Etten-Bohm, M., Olszyk, D. M., Lambrinos, J. G., Mayer, P. M. (2019): A framework for optimizing hydrologic performance of green roof media, Ecological Engineering, 140(Aug.), p. 105589. Available at: https://doi.org/10.1016/j.ecoleng.2019.105589.

Burian, S., Dostálová, J., Dubský, M. (2022): Vegetačné súvrstvie zelených striech: Štandardy pre navrhovanie, realizáciu a údržbu [Vegetation cover of green roofs: standards for design, implementation and maintenance] (1. 34 pp.). (in Slovak)

Carson, T. B., Marasco, D. E., Culligan, P. J., McGillis, W. R. (2013): Hydrological performance of extensive green roofs in New York City: Observations and multi-year modeling of three full-scale systems, Environmental Research Letters, 8(2). Available at: https://doi.org/10.1088/1748-9326/8/2/024036.

Dvorak, B., Volder, A. (2010): Green roof vegetation for North American ecoregions: A literature review,

Landscape and Urban Planning. Elsevier, pp. 197–213. Available at: https://doi.org/10.1016/j.landurbplan.2010.04.009.
Fassman-Beck, E., Voyde, E. Simcock, R., Hong, Y. S. (2013): 4 Living roofs in 3 locations: Does configuration affect runoff mitigation? Journal of Hydrology, 490, pp. 11–20. Available at: https://doi.org/10.1016/j.jhydrol.2013.03.004.
Getter, K., Rowe, B. D. (2006): The Role of Extensive Green Roofs in Sustainable Development, HortScience HortSci, 41(5), 1276–1285. Available at: https://doi.org/10.21273/HORTSCI.41.5.1276
Gong, Y., Yin, D., Li, J., Zhang, X., Wang, W., Fang, X., Shi, H., Wang, Q. (2019): Performance assessment of extensive green roof runoff flow and quality control capacity based on pilot experiments, Science of the Total Environment, 687, 505–515. Available at: https://doi.org/10.1016/j.scitotenv.2019.06.100.
Landscape Development and Landscaping Research Society e.V. - FLL (2018): Green Roof Guidelines - Guidelines for the planning, construction and maintenance of Green Roofs, USA, p. 158. Available at: https://commons.bcit.ca/greenroof/files/2019/01/FLL_greenroofguidelines_2018.pdf.
Razzaghmanesh, M., Beecham, S. (2014): The hydrological behaviour of extensive and intensive green roofs in a dry climate. Science of the Total Environment [online]. 2014, year 499, n. 1, pp. 284–296. ISSN 18791026. Available at: doi:10.1016/j.scitotenv.2014.08.046
Sailor, D.J., Hagos, M. (2011): An updated and expanded set of thermal property data for green roof growing media, Energy and Buildings, 43(9), pp. 2298–2303. Available at: https://doi.org/10.1016/j.enbuild.2011.05.014.
Schultz, I., Sailor, D. J., Starry, O. (2018): Effects of substrate depth and precipitation characteristics on stormwater retention by two green roofs in Portland OR. Journal of Hydrology: Regional Studies 2018, vol. 18, 110–118. Available at: https://doi.org/10.1016/j.ejrh.2018.06.008
Spolek, G. (2008): Performance monitoring of three ecoroofs in Portland, Oregon, Urban Ecosystems, 11(4), pp. 349–359. Available at: https://doi.org/10.1007/s11252-008-0061-z.
Roof substrate [Strešné substráty] (2021): Bratislavský substrát extenzívny [Bratislava extensive substrate]. [online] [cit. 2024-3-14]. Available at: https://stresnesubstraty.sk/sortiment-spolocnosti/bratislavsky-substrat-extenzivny
Šurda, P., Vitková, J., Zvala, A., Lichner, Ľ. (2023): Analyzing fire-induced water repellency and runoff in forest soil from beech forest: A controlled laboratory experiment, Acta Hydrologica Slovaca, 24(2), 205–213. Available at: https://doi.org/10.31577/ahs-2023-0024.02.0023.
Toková, L., Botková, N., Vitková, J., Botyanszká, L., Skic, K., Gryta, A. (2023): Impact of the biochar fraction sizes on the selected hydrophysical properties of silty loam soil. Acta Hydrologica Slovaca. 2023, year 24, n. 1, 9–13. ISSN 26444690. Available at: doi:10.31577/ahs-2023-0024.01.0002
Uhl, M., Schiedt, L. (2008): Green roof storm water retention–monitoring results, 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, (2006), 1–10. Available at: http://www.ecotelhado.com.br/Informacoes Interna/Green Roof Storm Water Retention.pdf.
Vandegrift, D. A., Rowe, D. B., Cregg, B. M., Liang, D. (2019): Effect of substrate depth on plant community development on a Michigan green roof, Ecological Engineering, 138(July), 264–273. Available at: https://doi.org/10.1016/j.ecoleng.2019.07.032.
Vijayaraghavan, K. (2016): Green roofs: A critical review on the role of components, benefits, limitations and trends, Renewable and Sustainable Energy Reviews, 57, 740–752. Available at: https://doi.org/10.1016/j.rser.2015.12.119.
Villarreal, E. L., Semadeni-Davies, A., Bengtsson, L. (2004): Inner city stormwater control using a combination of best management practices, Ecological Engineering, 22(4–5), 279–298. Available at: https://doi.org/10.1016/j.ecoleng.2004.06.007.
Voyde, E. Fassman, E., Simcock, R., Wells, J. (2010): Quantifying Evapotranspiration Rates for New Zealand Green Roofs, Journal of Hydrologic Engineering, 15(6), 395–403. Available at: https://doi.org/10.1061/(asce)he.1943-5584.0000141.
Zaťovičová, M., Majorošová, M. (2023): The Use of Vertical Gardens as a Network of Urban Navigation Elements with a Positive Impact on Biodiversity and Microclimate in a Dense Urban Environment, Slovak Journal of Civil Engineering, 31(4), 47–56. Available at: https://doi.org/10.2478/sjce-2023-0027.
Zhang, S., Lin, Z., Zang, S., Ge, D. (2021): Stormwater retention and detention performance of green roofs with different substrates: Observational data and hydrological simulations, Journal of Environmental Management, 291(May). Available at: https://doi.org/10.1016/j.jenvman.2021.112682.
Zheng, X., Zou, Y., Lounsbury, A. W., Wang, C., Wang, R. (2021): Green roofs for stormwater runoff retention: A global quantitative synthesis of the performance, Resources, Conservation and Recycling, 170(October 2020), p. 105577. Available at: https://doi.org/10.1016/j.resconrec.2021.105577.

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