The influence of a green roof drainage layer on retention capacity and leakage quality

Anna Baryła, Agnieszka Karczmarczyk, Andrzej Brandyk and Agnieszka Bus

ABSTRACT

The aim of the research was to determine the influence of the substrate and different drainage materials on retention capacity and runoff water quality from three green roof containers. Phosphates were chosen as the water quality indicator based on their potential adverse impact on water quality in urban rainwater collectors. The field experiment was conducted at the Warsaw University of Life Sciences Water Center meteorological station in years 2013–2015. In terms of precipitation, the monitoring period covered a wet (+147.1 mm), average (+42.7 mm) and dry (−66.3 mm) year. Leakage from the containers was recorded when the substrate moisture exceeded 20% and precipitation exceeded 3.5 mm/d for washed gravel, or 5.0 mm/d for a polypropylene mat and expanded clay. Phosphates were observed in leachates from all containers, with higher values observed in the second year of monitoring. As the result of this study, it can be concluded that the polypropylene mat and aggregates create different conditions for the formation of the leachate, in both volumes and its chemistry. The drainage layer made from a polypropylene mat is the most effective in terms of rainwater retention capacity and the resulting leachate quality.

Key words | drainage layer, green roof, runoff retention, soil substrate, water quality

INTRODUCTION

Urban growth has brought about changes in land use as well as its permeability (Berndtsson 2010). Impervious surfaces, such as roads or pavements, have become the prevailing land cover types and have increased the volume and rate of surface runoff while limiting ground water recharge. This leads to an increased flood threat in frequent storms. Green roofs are one of the measures to mitigate problems with excessive runoff in urbanized areas (Berndtsson 2010; Pęczkowski et al. 2016; Valentukevičienė & Rynkūn 2016; Szota et al. 2017). Their main advantage in comparison to infiltration ponds, absorption ditches or rain gardens, is the greater extent of available surfaces for installation since they can be installed on roofs, which cover a substantial proportion of highly urbanized areas. According to Dunnett & Kingsbury (2004), roofs account for about 40–50% of urban impervious surfaces. Apart for management of runoff quantity and quality, green roofs serve a number of functions in highly urbanised areas, such as heat island mitigation (Fang 2008), air quality improvement (Currie & Bass 2008) and reducing noise levels. They can also reduce the cost of air conditioning and heating in buildings, increase the durability of roof materials, and increase the diversity of vegetated habitats in urban areas (Nagase & Dunnett 2012).

Green roofs are most frequently multi-layer constructions, with each of the layers integral to the overall performance of the green roof. In a traditional green roof configuration, the drainage layer (in the form of a mineral aggregate layer or a polypropylene mat) is placed above a hydro-isolation layer and a protective membrane. The main function of the layer is to retain water for plant growth, and also to safely divert its excess through a drainage system. Inorganic aggregates and polypropylene mats of different physical properties are frequently used to construct the drainage layer. The selection of the drainage material can influence runoff water quality. A filter layer, which protects the under- and overlying layers against percolation of fine particles that are washed out by rainwater, is also a key component. The top layer of the green roof is a properly chosen substrate that supports vegetation.
The water balance of a green roof includes infiltration and storage of water in designed layers, evaporation and transpiration from both the canopy and the substrate, as well as subsurface runoff and in larger storms surface runoff. Abundant literature stresses the role that green roofs play in reducing runoff quantity and decreasing the ratio of runoff (Wong & Jim 2015; Sims et al. 2016). In frequent storms, it can reduce peak runoff by 60–90% as well as delaying runoff by 5 minutes to 2 hours (Burszt-Adamiak 2012; Pęczkowski et al. 2016). A vital issue is the quality of runoff from a green roof (Berndtsson 2010; Bus et al. 2016; Karczmarczyk et al. 2017). Increasingly, green roofs are expected to reduce pollution and to improve runoff quality. Berndtsson (2010) found that green roofs are capable of minimizing rainwater contamination through filtering and absorption by vegetation and the substrate layer.

Accordingly, the research goal was to determine the degree of influence of substrates and the drainage layer on runoff quantity and quality. Retention capacities were estimated for three different drainage materials comprising a washed gravel, an expanded clay aggregate, and a polypropylene mat. Phosphates were chosen as the water quality indicator based on their potential adverse impact on water quality in rainwater collectors. The presented study period covers a wet (+147.1 mm), average (+42.7 mm) and dry (−66.3 mm) year (the values in brackets show the deviation from the multi-year average). The novelty of the study is a common analysis of the influence of a drainage layer construction material on the quality and quantity of the leachate. The practical result of the study is the determination of the minimum amount of precipitation at which leaching from various drainages occurs.

**MATERIALS AND METHODS**

The influence of the drainage layer on leakage volume was studied in a field experiment conducted at the meteorological station located at the Warsaw University of Life Sciences (WULS) in Warsaw. The three observation periods were from April 2013 to October 2013, April 2014 to October 2014 and from June 2015 to September 2015.

Three containers, each with a length, width and height of 0.5 m, 0.3 m and 0.3 m respectively, were used for the green roof trials (see Figure 1). The volume of each container was 45 L. An 8 cm layer was formed in the bottom of the first container using washed gravel and an 8 cm layer of expanded clay aggregate was formed in the second container. The third container utilized a polypropylene mat as the drainage layer (Terrafond Garden 20 L type with a thickness of 2 cm). Then, a geotextile fabric was installed on top of the drainage layer (Polypropylene geotextile Polyfelt TS 20, endurance class GRK 2, with a weight of 125 g/m²), and finally a 17 cm layer of intensive roof substrate was placed on the geotextile layer. Leachate was collected in tanks underneath each of the containers. Precipitation was recorded using a Hellman gauge, located next to the containers, while air temperature was measured at the standard height of 2 m. Based on the measurements, a relative daily retention for each container was calculated using Equation (1) (Zhang et al. 2015):

\[
R[\%] = \frac{P[mm] - H[mm]}{P[mm]} \cdot 100\%
\]

where: R = retention (%), P = precipitation (mm) and H = runoff (mm)

![Figure 1](https://iwaponline.com/wst/article-pdf/77/12/2886/371820/wst077122886.pdf)

Figure 1 | (a) A container filled with drainage material; (b) the three types of drainage used; (c) container filled with intensive substrate; (d) view of the experiment.
Reference evapotranspiration was then calculated using Hargreaves' formula as given in Equation (2) (Hargreaves & Allen 2003):

\[
ET_0 = HC \cdot R_a (T_{max} - T_{min})^{HE} \left(\frac{T_{max} - T_{min}}{2} + HT\right)
\]

(2)

where: \(ET_0\) = reference evapotranspiration (mm/d), \(HC\) = an empirical coefficient (0.0023), \(R_a\) = total radiation at upper atmospheric boundary (mm/d), \(T_{max}\) = maximum air temperature (°C), \(T_{min}\) = minimum air temperature (°C), \(HE\) = an empirical coefficient (0.5) and \(HT\) = an empirical coefficient (17.8).

The substrate moisture and temperature were measured once a day using a WET-2 probe. The correlation between the volume water content determined by the WET-2 method and the drying-weight method was determined (Janik et al. 2016).

The physical properties of selected materials were determined in accordance with the following standards: particle size distribution, PN-ISO 1277:2005; water capacity, porosity and bulk density, FLL (2008). The saturated hydraulic conductivity was estimated with a deWit apparatus. Then, the pF curve was determined by the silt block method (pF0–pF2.7) and the pressure chamber method (pF3.0–pF4.2). It was assumed that the value of pF0 represents the maximum water capacity (MWC), and pF2.0 is representative of the field capacity (FC), while the value of pF2.9 became the lower allowable limit of water content, related to water storage in a drought period, and finally pF4.2 is the wilting point (WP). The effective retention (ER) range was assumed to be between pF 1.8 and 3.7 (when 3.7 stands for moisture when plant growth terminates), and potential retention (PR) between pF 1.8 and 4.2.

The experiment was run without vegetation to eliminate the need to assess the impact of plants on phosphorus in runoff. All collected leachate and rainwater samples were filtered and analysed for PO4-P using a FiaStar analyser and the ammonium molybdate method in the range of 0.005–1 mg/L. The measurement of the volumes of the leachate and sampling were undertaken manually.

To identify environmental factors that may have an important role in green roof stormwater retention performance, multiple linear regression (MLR) was adopted for the statistical analysis. Three types of parameters were examined as explanatory variables to green-roof stormwater retention: rainfall, evapotranspiration, and soil moisture condition. Scatter plots and correlations were examined between explanatory and dependent variables to identify their correlation. Next, MLR was conducted to examine the explanatory power between potential factors and retention. Statistical analyses were carried out in the STATGRAPHICS Centurion XVI program.

### Properties of drainage materials

In the experiment, two types of aggregates were tested for the drainage layer, namely, a washed gravel, which is a natural aggregate, and an expanded clay aggregate (which is a man-made product of a mineral origin created in Poland through an industrial process of clay thermal conditioning and burning, which is usually applied to clay loam). A polypropylene drainage mat was used as the third drainage layer. The bulk density of the analysed aggregates was 1,100 (kg/m³) for the expanded clay aggregate, and 1,500 (kg/m³) for the washed gravel. Grain diameters for the gravel ranged from 16 mm to 32 mm, and for the expanded clay aggregate from 8 mm to 16 mm respectively (see Table 1). For a drainage layer material, the grain size is an important determinant of the water holding capacity (Beattie & Berghage 2004). The ability to permanently absorb water, i.e., the absorbability, was also analyzed. From the point of view of the green roof, the absorbability was more efficient with the expanded clay aggregate (15%),

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Unit</th>
<th>Washed gravel</th>
<th>Expanded clay aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size</td>
<td>mm</td>
<td>16–32</td>
<td>8–16</td>
</tr>
<tr>
<td>Compactability</td>
<td>%</td>
<td>10–15</td>
<td>10–15</td>
</tr>
<tr>
<td>Subsidence</td>
<td>%</td>
<td>&lt;3</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Powder density (dry matter)</td>
<td>kg/m³</td>
<td>1,500</td>
<td>1,100</td>
</tr>
<tr>
<td>Density at maximum saturation</td>
<td>kg/m³</td>
<td>1,800</td>
<td>1,300</td>
</tr>
<tr>
<td>Porosity</td>
<td>%</td>
<td>40</td>
<td>52</td>
</tr>
<tr>
<td>Maximum water holding capacity</td>
<td>%</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Air entry value</td>
<td>%</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Absorbability</td>
<td>%</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Conductivity</td>
<td>mm/min</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Organic matter content</td>
<td>% weight</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Foreign matter</td>
<td>% weight</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
while the gravel was very low at only 1% (Gwóźdź et al. 2016). The ratio of dry mass water content to optimum water content was 2.6% for the expanded clay aggregate and 0.3% for the washed gravel. In the case of some aggregates, as for the washed gravel analyzed herein, water molecules tend to gather in small, dry pores, which causes flow under unsaturated conditions (Stovin et al. 2012). In the case of LECA (expanded clay), an inner-aggregate specific porosity exists, which may restrict water availability for the plants. The retention capacity of the drainage mat was 5.2 L/m².

**Physical properties of the substrate**

The substrate (intensive type) was composed of washed sand, chalcedony, clay, low peat and compost. The characteristics of the soil substrate are given in Table 2.

Comparing the water content of the substrate samples at certain pF values using the FLL (2008) guidelines, it was found that the maximum water holding capacity (pF0) was appropriate for the analysed substrate type. Air content was satisfactory as well, because moisture values at pF1.8 exceeded the accepted limit of 20% of the volume. A vital parameter from the viewpoint of the plant water requirement is the PR, which represents the water available to plants, and the ER, which is a measure of the amount of water utilized by plants for biological processes (Bogacz et al.). The PR was 16.8% on average, while the ER reached 15.2%. Water content of the substrate at maximum capacity, for pF0,0, averaged 55.0%, while the field capacity (pF2.0) was 21.2% and the wilting point (pF4.2) reached 8.0%. Basing on the available water range (pF2.0−pF4.2) and the substrate thickness of 17 cm, the maximum retention value calculated for the layer was 22.44 L per 1 m². However, it should be stressed that the value is based on the testing of substrates sampled in 2013. In 2014, the substrate in each container was subject to 2 cm subsidence. Taking that into account, the substrate retention reduced to 19.80 L per 1 m².

**RESULTS AND DISCUSSION**

**Meteorological conditions during the research period**

The rainfall depth, along with its spatiotemporal variability, is an important factor in the performance of green roofs. The precipitation was recorded during the three monitoring periods with a total of 162 rainy days observed, giving a total precipitation of 984.3 mm. Daily precipitation lower than 5 mm (p < 5 mm) constituted 63.5% of all recorded daily totals, while daily totals between 5 mm and 10 mm and between 10 mm and 20 mm each represented 14.8% of the readings. Daily totals between 20 mm and 30 mm constituted 5.6% of readings while daily totals greater than 30 mm represented 1.2% of all readings (see Figure 2).

In 2013, during the measurement period from April to October, the precipitation was considerably higher than the average values recorded for the period 1960–2009 (Majewski et al. 2010). The highest monthly total of 113.5 mm was recorded in May 2013 (a very wet month), while the highest daily value of 55.7 mm was observed on 10th August 2013. July was the month with the lowest total precipitation of only 22.3 mm (extremely dry). Moreover, in 2013 precipitation observed within a 6 day period exceeded 20 mm. In 2014 the highest monthly total of 100.1 mm was recorded in July 2014 (a wet month) while the highest daily value of 26.6 mm was observed on 14th August 2014. September was an extremely dry month in 2014, with a monthly total of only 7.0 mm. Precipitation readings in 2015 were generally lower than the long term average, with a highest daily value of 21.2 mm. The lowest monthly total of 11 mm was recorded in August 2015 (in comparison to the long term monthly average of 63.7 mm; however, the highest value occurred in September in that year.

Contemporary research on the role of evapotranspiration in urbanized areas has identified environmental benefits related to the mitigation of flash floods (Stovin et al. 2012). Monthly evapotranspiration totals were analysed as well (Table 3). They were utilized to calculate the rainfall deficit (P−E), which reached a maximum in August 2015 (~95.9 mm). During the research period, there were only four months where the precipitation was higher than the evapotranspiration (April 2013, May 2013, September

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Unit</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size &lt;0.063 mm</td>
<td>(% w/w)</td>
<td>2.0</td>
</tr>
<tr>
<td>Median particle size, d50</td>
<td>mm</td>
<td>1.5</td>
</tr>
<tr>
<td>Bulk density</td>
<td>kg/m³</td>
<td>1,500</td>
</tr>
<tr>
<td>Total pore volume</td>
<td>%</td>
<td>55</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>mm/min</td>
<td>11−33</td>
</tr>
<tr>
<td>Organic matter content</td>
<td>% weight</td>
<td>1.7</td>
</tr>
</tbody>
</table>
2013 and April 2015) (see Figure 3). In this respect, the air temperature seems to be an indicator, which averaged 20.4 °C in 2013 (the average for the substrate equal to 23 °C) and 20.5 °C in 2014 (average substrate temperature of 24.5 °C), amounting to 22.2 °C in 2015 (with the substrate average equal to 25.3 °C). An insight into temperature differences between the air and 5-cm substrate indicated a 12 °C maximum in August 2013. It was also evident, that the highest temperature differences occurred in summer months (see Figure 3).

Retention capacity

During the monitoring period, the retention capacities of the experimental units ranged from 8.9–100% in the case of washed gravel used as a drainage layer, 27.5–100% for the model equipped with the drainage mat and 13.6–100% for the expanded clay aggregate. Nonetheless, different retention ranges were observed for each unit. The highest range was noted during the rainfall (14.2 mm) on 27th May 2014. The differences represent the diverse water storage capacities for the whole roof profile due to different drainage layers.

Generally, rainfall volume is the most important weather factor that determines the retention capacity of green roofs. In our study, the depths of rainfall and the runoff retention rates shown a significant negative relationship ($P < 0.01$) (see Figure 4(a)). No leakage was observed for the unit with washed gravel until the rainfall intensity exceeded 3.5 mm/d; however, for the units with the expanded clay aggregate and the drainage mat, no leakage was observed until the rainfall intensity exceeded 5 mm/d (see Figure 4(a)). Research on green roof retention undertaken for the conditions of the Wroclaw city

### Table 3

<table>
<thead>
<tr>
<th>Years (s)</th>
<th>April P</th>
<th>E</th>
<th>May P</th>
<th>E</th>
<th>June P</th>
<th>E</th>
<th>July P</th>
<th>E</th>
<th>August P</th>
<th>E</th>
<th>Sept. P</th>
<th>E</th>
<th>Apr-Sept. P</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960–2009</td>
<td>35.3</td>
<td></td>
<td>56.4</td>
<td></td>
<td>66.4</td>
<td></td>
<td>75.3</td>
<td></td>
<td>63.7</td>
<td></td>
<td>46.4</td>
<td></td>
<td>343.5</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>65.6</td>
<td></td>
<td>53.9</td>
<td></td>
<td>113.5</td>
<td>85.0</td>
<td>98.6</td>
<td>105.8</td>
<td>22.3</td>
<td>109.2</td>
<td>92.1</td>
<td>111.1</td>
<td>98.5</td>
<td>53.0</td>
</tr>
<tr>
<td>2014</td>
<td>63.9</td>
<td></td>
<td>63.4</td>
<td></td>
<td>80.6</td>
<td>91.6</td>
<td>63.8</td>
<td>100.6</td>
<td>100.1</td>
<td>111.0</td>
<td>70.8</td>
<td>84.1</td>
<td>7.0</td>
<td>54.7</td>
</tr>
<tr>
<td>2015</td>
<td>31.4</td>
<td>62.3</td>
<td>57.7</td>
<td>80.0</td>
<td>37.5</td>
<td>107.3</td>
<td>66.2</td>
<td>115.1</td>
<td>11.3</td>
<td>106.9</td>
<td>73.1</td>
<td>52.5</td>
<td>277.2</td>
<td>524.1</td>
</tr>
</tbody>
</table>

*Majewski et al. (2010); P = precipitation; E = evapotranspiration.
Burszta-Adamiak (2012) showed no leakage formation until rainfall exceeded 5 mm for the green roofs underlined with a polypropylene mat and gravel drainage. For the roofs with inner-substrate drainage and a storage-type drainage system, leakage occurred when the rainfall exceeded 8 mm and 10 mm, respectively.

Figure 3 | Precipitation, reference evapotranspiration, air temperature, substrate temperature, substrate moisture content, and runoff (leakage) between (a) 25th April 2013 to 30th September 2013 and (b) 25th April 2014 to 30th September 2014 (L – Expanded clay; M – Polypropylene mat; WG – Washed gravel).
The obtained results confirmed that the retention capacity of green roofs is limited in the case of intensive rain events, especially if they occur in high amount and in a short time. In this study, it was observed on 25th May 2013 (47.9 mm) and 12th August 2013 (50.2 mm) (see Figures 3 and 4(a)). Limited retention capacity was also observed in the case of small rains following one after another. It was observed in two periods: from 26th May to 4th June 2013 and 23rd May to 3rd June 2014 (see Figures 3 and 4(a)). This is due to the construction of the green roofs and retention capacity limited to the pore structure of the substrate and drainage layer. Retention capacity of green roofs tested in this study also showed seasonal variability. For example, in September 2013, when air temperature and evapotranspiration were lower than in summer time, the retention capacity of the green roof was also limited. This was, however, not observed in 2014, as it was a very dry month.

As shown in Figure 4(b), leakage was observed if the moisture content of the substrate exceeded 20%, while the field capacity (FC, pF 2.0) amounted to 21.2%. In five terms, leakage was observed with moisture levels below 20%.

The results agreed with the previous, well-understood, inverse relationship between retention and precipitation values. Researchers including Teemusk & Mander (2007), Stovin et al. (2012) and Zhang et al. (2015) have reported that green roof retention decreases with increases in rainfall. As shown on Figure 5, all units retained 94–96% of rainfall in small events (<10.0 mm), 66–81% in medium rainfall events (10 mm–24.9 mm), 40–75% in large rainfall events (25.0 mm–49.9 mm), and 22–28% in storm events greater than 50 mm. These results are similar to those obtained by Carter & Rasmussen (2006) in Athens, Georgia. In small storms (<25.4 mm), 88% of the rainfall was retained; in medium storms (25.4 mm–76.2 mm), more than 54% of the rainfall was retained, while in large storms (>76.2 mm) 48% was retained.

![Figure 4](https://iwaponline.com/wst/article-pdf/77/12/2886/371820/wst077122886.pdf)  
(a) Relationship between retention rate R [%] and daily precipitation P (mm) and (b) retention rate R [%] and moisture content θ (%) (L – Expanded clay; M – Polypropylene mat; WG – Washed gravel).

![Figure 5](https://iwaponline.com/wst/article-pdf/77/12/2886/371820/wst077122886.pdf)  
The relationships between runoff retention and rainfall depths (L – Expanded clay; M – Polypropylene mat; WG – Washed gravel).
This investigation focuses on developing a statistically valid model that can provide simple and meaningful interpretation on important salient environmental factors that may enhance understanding of retention in the green roofs. MLR identified that the combination of rainfall depth, evapotranspiration and soil moisture in expanded clay aggregates significantly explained storm water retention, $F(3,92) = 23.74$, $p < 0.001$, with only rainfall and soil moisture contributing significantly to the model (see Table 4). The adjusted $R^2$ was 0.43, indicating that about 43% of the variance in retention can be explained by this model. Similar results were found in the cases of polypropylene mat and washed gravel ($F(3,92) = 15.01$; $p < 0.001$; $R^2 = 0.33$ and $F(3,92) = 22.05$; $p < 0.001$; $R^2 = 41\%$ respectively). Both correlation and MLRs analyses indicate that rainfall depth relate strongly to percent retention. These findings concur with prior studies that the total rainfall depth can exert strong influence on retention (Carter & Rasmussen 2006; Stovin et al. 2012).

### Leachate quality

The $PO_4$-P concentration (volume-weighted mean) in collected rainwater samples was 0.018 mg PO$_4$-P/L in 2013 and 0.012 mg PO$_4$-P/L in 2014 and ranged from 0 ÷ 0.229 mg PO$_4$-P/L and 0 ÷ 0.281 mg PO$_4$-P/L in 2013 and 2014 respectively. In both seasons, most of the leachate from all units was polluted with phosphates. The volume-weighted mean PO$_4$-P concentration was lower in the first year of operation than in the second year in the case of all units (see Table 5). In 2013, the highest phosphate concentration was noted for the substrate with gravel drainage, while in 2014 it was observed for substrate with the expanded clay. Despite two events when the highest concentrations observed in the monitoring period were noted in leachate from the container with polypropylene mat drainage (2nd July, 0.806 mgPO$_4$-P/L and 21st July, 0.461 mg PO$_4$-P/L), the volume-weighted means calculated for this container were the lowest in both years. Also the volumes of leachate from this container were lower than the other types of drainage used. What was also observed was that only 50% of leachates from the substrate with the polypropylene mat were polluted with phosphates (in 2014), while the proportion of polluted leachates in the total number of recorded leachate events from gravel and expanded clay drainage were 67% and 76% respectively. It is concluded that the polypropylene mat and aggregates create different conditions for the formation of the leachate, in terms of both volumes and chemistry. Due to the very dry summer in 2015, leachate was not collected during the period of monitoring.

Higher phosphate concentrations observed in leachates from substrates underlain with washed gravel and expanded clay can be a result of leaching of phosphates from aggregates. According to our previous studies (Karczmarczyk et al. 2017), expanded clay and gravel contain similar amount of $P$. The third drainage material used in the study, the polypropylene mat, should not release phosphates during washing with rainwater. The presented results should increase interest in less-noticeable sources of urban water.

### Table 4

<p>| Summary of multiple regression explaining percent retention (R) using rainfall depth (P), evapotranspiration (E), volumetric moisture content ($\theta$) (N = 162) |
|---------------------------------|---|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SEB</th>
<th>$P$-value</th>
<th>Equation of the fitted model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expanded clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>-1.08</td>
<td>0.16</td>
<td>0.000</td>
<td>$R = 101.83 + 0.586E - 1.078P - 0.167\theta$</td>
</tr>
<tr>
<td>$E$</td>
<td>0.59</td>
<td>1.57</td>
<td>0.709</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>-0.17</td>
<td>0.16</td>
<td>0.308</td>
<td></td>
</tr>
<tr>
<td>Polypropylene mat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>-0.73</td>
<td>0.15</td>
<td>0.000</td>
<td>$R = 100.36 + 1.728E - 0.727P - 0.239\theta$</td>
</tr>
<tr>
<td>$E$</td>
<td>1.73</td>
<td>1.50</td>
<td>0.252</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>-0.24</td>
<td>0.14</td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td>Washed gravel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>-1.29</td>
<td>0.19</td>
<td>0.000</td>
<td>$R = 107.45 - 1.290E - 1.285P - 0.250\theta$</td>
</tr>
<tr>
<td>$E$</td>
<td>-1.29</td>
<td>1.97</td>
<td>0.514</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>-0.25</td>
<td>0.16</td>
<td>0.164</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5

The concentration (mgPO$_4$-P /L) and the range of PO$_4$-P concentrations observed in leachate collected from each unit during April–September 2013 and April–September 2014

<table>
<thead>
<tr>
<th>Drainage type</th>
<th>April–September 2013</th>
<th>April–September 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume-weighted mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded clay</td>
<td>0.035</td>
<td>0.135</td>
</tr>
<tr>
<td>Polypropylene mat</td>
<td>0.006</td>
<td>0.029</td>
</tr>
<tr>
<td>Washed gravel</td>
<td>0.075</td>
<td>0.090</td>
</tr>
<tr>
<td>Range</td>
<td>0 ÷ 0.143</td>
<td>0 ÷ 0.223</td>
</tr>
<tr>
<td></td>
<td>0 ÷ 0.122</td>
<td>0 ÷ 0.806</td>
</tr>
<tr>
<td></td>
<td>0 ÷ 0.229</td>
<td>0 ÷ 0.281</td>
</tr>
</tbody>
</table>
pollution, like green roof runoff, and strive to create legislative conditions to promote use of low P emission materials in green roof construction.

CONCLUSIONS

Green roofs are one of the measures to mitigate problems with excessive runoff in urbanized areas. Their main advantage in comparison to infiltration ponds, absorption ditches or rain gardens, is the greater extent of available surfaces for installation since they can be installed on roofs, which cover a substantial proportion of highly urbanized areas. Apart for management of runoff quantity and quality, green roofs serve a number of functions in highly urbanised areas, such as heat island mitigation, air quality improvement and reducing noise levels. The research goal was to determine the degree of influence of substrates and the drainage layer on runoff quality. Retention capacities were also estimated for three different drainage materials comprising a washed gravel, an expanded clay aggregate, and a polypropylene mat. Phosphates were chosen as the water quality indicator based on their potential adverse impact on water quality in rainwater collectors.

Examining the 162 recorded rainfall events, it was found that the retention rate ranged from 8.9% to 100% (for washed gravel), 27.5% to 100% (for a polypropylene mat) to 13.6% to 100% (for expanded clay). The average retention over the monitoring period in 2013 and 2014 was 62.7% (for washed gravel), 80.0% (for polypropylene mat) and 67.5% (for expanded clay). The monthly runoff retention rates of the green roof units were lower in May and September in 2013 than in June, July and August, because of the larger amount of rainfall in May and October and the higher temperatures in June, July and August.

The leachates from each model contained phosphates. Since no plants were grown in the units nor irrigation or fertilization applied, the possible sources of phosphates in the leachate were precipitation, the substrate and the drainage material. In terms of volume-weighted phosphate concentrations, the values observed in the unit with the polypropylene mat were lower than in the units with drainage layers made of aggregates. Based on the results, it can be concluded that a drainage layer made from a polypropylene mat is the most effective in terms of rainwater retention capacity and the resulting leachate quality.

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