DOI: 10.2428/ecea.2019.26(1-2)4 ECOL CHEM ENG A. 2019;26(1–2?):37–45

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HYDRAULIC EFFICENCY OF SELECTED INTENSIVE GREEN ROOF SUBSTRATES

EFEKTYWNOŚĆ HYDRAULICZNA WYBRANYCH WYPEŁNIEŃ INTENSYWNEGO ZIELONEGO DACHU

Abstract: The rapid urbanization resulting in increased area of sealed surfaces distorts the natural water balance of urbanized ecosystems. Thus, the natural infiltration of surface water is reduced and the significant increase in volume surface runoff is being commonly observed. Water of surface runoff is usually collected and redirected by the stormwater systems to the natural surface water reservoirs, including also rivers and lakes, commonly without any treatment. So, a significant environmental threat to water quality posed by surface runoff from urbanized areas is obvious. This paper contains the attempt of numerical assessment of efficiency of six different commercially available substrates for intensive green roof. The numerical modeling of green roof efficiency was performed by the means of the finite elements modeling software FEFLOW, Wasy-DHI. The developed model reflected the cross section of the tested green roof. The required input data for modeling covered the saturated hydraulic conductivity and water retention characteristics and were based on information available in the technical descriptions of the tested substrates. The obtained results showed the diversified performance, due to different volume of retained water under the same boundary conditions, directly related to the properties of green roof filling substrates.

Keywords: green roof, sustainable stormwater management, infiltration, retention

Introduction

The recent development of cities, combined with the rapid urbanization of natural catchments, commonly related to construction of residential buildings, roads, parking lots, pavements, shopping centres and other infrastructure for different services, causes the increase in the area of sealed, impermeable surfaces. Thus, the natural water balance of catchments is alerted and the decreased infiltration and increased surface runoff are commonly observed. The increased accumulation of pollutants, including total suspended solids (*TSS*), total nitrogen (*TN*), total phosphorus (*TP*), oil derivatives, heavy

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metals etc., on the sealed surfaces and increase in their concentrations and loads in runoff water entering storm water systems and their surface receivers, posing the significant anthropopressure on the natural environment, mainly the water ecosystems are expected as result [1–6].

The goals of surface water and groundwater protection set by the Water Frame Directive [7] require the efficient management of river catchment, sustainable use of water and wide public involvement [8]. So, in order to limit the possible emissions to water, groundwater and soil, stormwater should be collected and treated on-site, as close to the source of pollution as possible. It may be performed by the systems of sustainable stormwater management, generally based on the on-site treatment, storage, infiltration and reuse, able to reduce environmental pressure caused by rainwater management [9, 10]. The green roofs, as a part of green architecture in urbanized areas, may be included to the presented group. Application of various types of green roofs, utilizing different types of porous substrates and different plants, may allow to restore the distorted water balance of urbanized catchments and to reduce the pollution of aquatic ecosystems [9–17] due to their ability to retain and reuse of precipitation water.

This paper presents the attempt of numerical assessment of efficiency of the intensive green roof utilizing six different, commercially available substrates of various particle composition, allowing to assess their hydraulic efficiency in retaining the precipitation water under the same boundary conditions.

Materials and methods

The presented research included numerical analysis of hydraulic performance and retention abilities of six commercially available substrates of different particle compositions for the intensive green roofs fillings. The particle size composition of all tested substrates is presented in Table 1.

Table 1

Particle size distribution of tested substrates

Particle size fraction	Particle content [%]					
	#1	#2	#3	#4	#5	#6
Stones (> 8mm)	61.2	4.9	31.0	1.7	13.3	12.4
Coarse gravel (8–4 mm)	28.5	34.6	19.8	16.0	23.0	19.2
Fine gravel (4–2 mm)	1.2	4.7	0.6	2.6	1.4	6.1
Very coarse sand (2–1 mm)	0.5	3.4	1.8	7.4	6.1	3.7
Coarse sand (1–0.5 mm)	0.5	12.1	2.7	21.0	16.8	4.3
Medium sand (0.5–0.25 mm)	1.3	23.6	5.9	33.9	26.0	17.0
Fine sand (0.25–0.125 mm)	1.2	11.9	6.9	13.2	10.3	12.9
Very fine sand (0.125–0.05 mm)	0.7	1.1	4.6	0.6	0.5	3.7
Silt (0.05–0.002 mm)	2.7	2.4	13.2	2.3	1.5	11.8
Clay (< 0.002 mm)	2.0	1.4	13.5	1.4	1.1	8.8

The brief analysis of data concerning particle distribution of studied substrates presented in Table 1 shows the possible variable hydraulic characteristics of discussed specimens. Substrate #1 consists mainly of stones and gravel, specimens #2, #4 and #5 besides the huge share of gravel, contain significant share of sands, from fine to coarse. On the contrary, specimens #3 and #6 present significant addition of silt and clay fractions, which may trigger changes in their hydraulic capabilities. Thus, the high saturated conductivity and low retention abilities may be expected for specimens based mainly on gravel and carious fractions of sand. On the other hand, presence of significant share of fine particles (silt + clay) should allow the lower saturated and unsaturated hydraulic conductivity and the better retention capabilities.

The modeling calculations used in this study were performed by the commercial finite element method modeling software FEFLOW, Wasy-DHI, Germany. The developed model of water infiltration into the green roof substrate in FEFLOW computing software was based on the standard forms of Darcy's and Richards' equations [18, 19]:

$$\boldsymbol{q}_i = \boldsymbol{K}_{ij} \frac{\partial h}{\partial x_j} \tag{1}$$

$$\frac{\partial h}{\partial t} = -\frac{\partial \boldsymbol{q}_i}{\partial x_i} \mp Q \tag{2}$$

where: $\boldsymbol{q}_i$ – water flux vector $[\mathrm{m} \cdot \mathrm{s}^{-1}]$;
h – hydraulic pressure head [m];
t – time [s];
$\boldsymbol{K}_{ij}$ – tensor of hydraulic conductivity, $i, j = 1, 2$;
Q – sink or source term $[\mathrm{s}^{-1}]$.

The water retention curve model assumed to the presented calculations was based on the most popular formula presented by van Genuchten [20]:

$$\theta = \frac{\theta_s - \theta_r}{[1 + (Ah)^n]^m} + \theta_r \tag{3}$$

where: θ_s – saturated volumetric water content $[\mathrm{m}^3 \cdot \mathrm{m}^{-3}]$;
θ_r – residual volumetric water content $[\mathrm{m}^3 \cdot \mathrm{m}^{-3}]$, $\theta_r = 0\ \mathrm{m}^3 \cdot \mathrm{m}^{-3}$;
h – pressure head [m];
A – fitting parameter $[\mathrm{m}^{-1}]$;
n, m – dimensionless fitting parameters, $m = 1 - n^{-1}$.

Hydraulic conductivity of unsaturated soil K was calculated in the presented model according to van Genuchten's formula [20]:

$$K = K_S S_e^l [1 - (1 - S_e^{\frac{1}{m}})^m]^2 \tag{4}$$

where: K_s – saturated conductivity $[\mathrm{m} \cdot \mathrm{s}^{-1}]$;
l – fitting parameter, $l = 0.5$ [20];
S_e – dimensionless effective saturation defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{5}$$

The determined hydraulic characteristics of the applied substrates are presented in Table 2, while their water retention curves, presented as $pF = \log_{10} h$ are shown in Figure 1.

Table 2

Water retention curve characteristics of tested substrates

Substrate	Saturated vol. water content	Saturated hydraulic conductivity	Water retention curve fitting parameters	
			A	n
	$[\mathrm{m}^3 \cdot \mathrm{m}^{-3}]$	$[\mathrm{m} \cdot \mathrm{s}^{-1}]$	$[\mathrm{m}^{-1}]$	[-]
#1	0.464	$8.00 \cdot 10^{-4}$	0.42	1.644
#2	0.718	$3.55 \cdot 10^{-3}$	2.95	1.589
#3	0.527	$1.17 \cdot 10^{-4}$	1.36	1.329
#4	0.719	$2.52 \cdot 10^{-3}$	2.05	2.013
#5	0.620	$7.50 \cdot 10^{-4}$	1.95	1.667
#6	0.593	$7.17 \cdot 10^{-4}$	2.55	1.386

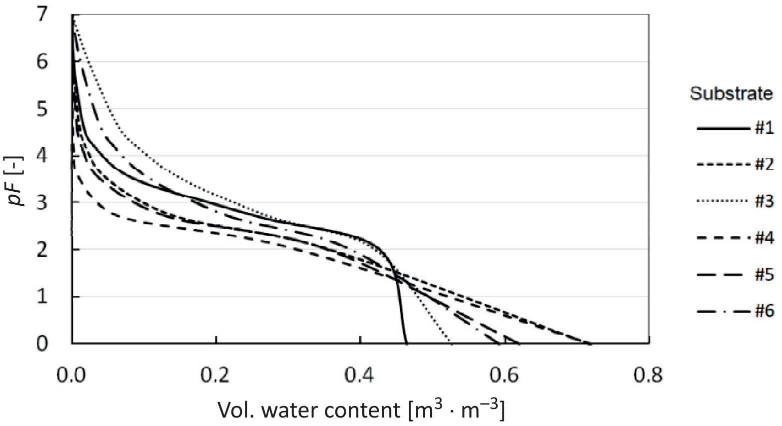

Fig. 1. Water retention curves of six tested intensive green roof substrates

The developed model, presented in Fig. 2, represented cross section of substrate filling of intensive green roof for public building with dimensions 22.8 m and 0.3 m. The prepared model consisted of 5896 nodes and 10595 elements. The assumed time duration of simulation covered the warm half of year, 184 days.

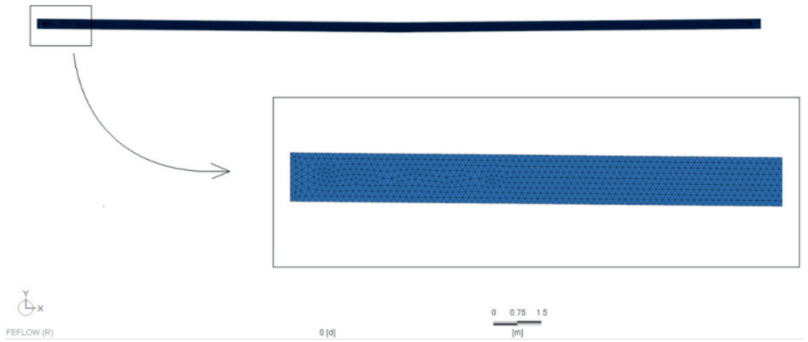

Fig. 2 Developed numerical model of intensive green roof substrate filling

The applied initial conditions for water flow modeling covered the degree of porous medium saturation assumed as 0.2 for the layer of modeled substrate. The top boundary condition for rainwater infiltration, presented in Fig. 3, was assumed as the 2nd type (Neumann type) condition reflecting mean daily flux of water inflow or outflow through the top boundary. The assumed values were based on previously performed measurements and calculations of the several components of water balance, including precipitation, interception and evapotranspiration of grass cover in Kiel, Germany [21]. The gradient type of Neumann (2nd type) condition of the value equal to the determined coefficient of saturated hydraulic conductivity was assumed as the bottom boundary condition to reflect the free, undisturbed gravity flow to lower drainage layers [20].

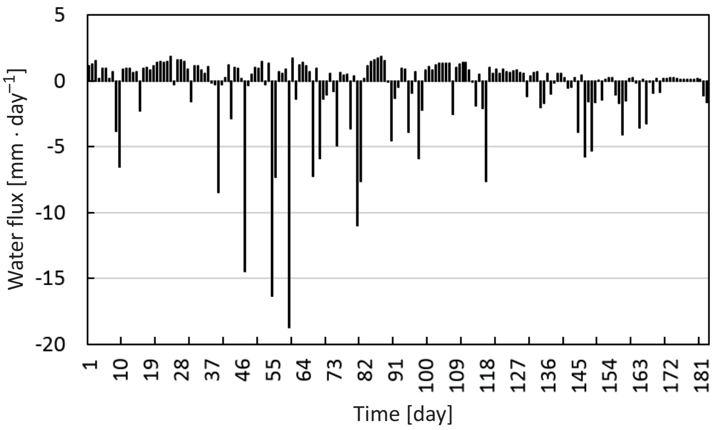

Fig. 3. Top boundary condition assumed to modeling (positive values – evapotranspiration, negative values – infiltration), modified after [21]

Results and discussion

Figure 4 presents determined retention capabilities of the six tested substrates, calculated directly from their water retention curves. It is visible that all the tested

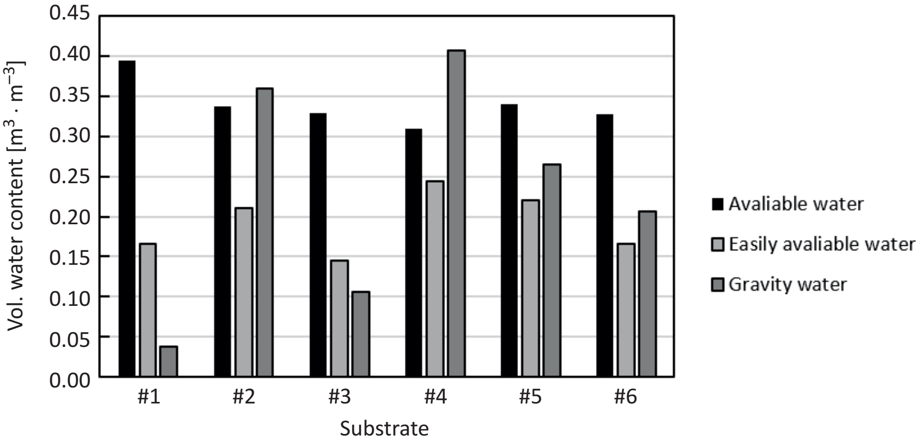

Fig. 4. Retention characteristics of tested substrates

materials present comparable, 0.33–0.40 m^3 · m^{-3}, amount of available water for plants (*pF*: 2.0–4.7) and slightly variable, between 0.14 and 0.24 m^3 · m^{-3}, content of easily available water. The different amount of gravity water was the most distinctive difference resulting from the water retention curves of all substrates. The highest values of gravity water content equal 0.36 and 0.41 m^3 · m^{-3} were determined for substrates #2 and #4, respectively. These specimens were characterized by relatively high content of gravel and different types of sand (see Table 1).

Figure 5 presents comparison of daily mean degree of saturation and volume of retained water for the whole time duration of simulation and all the tested substrates.

It is visible in Fig. 5 that the values of calculated saturation and water volume are different, despite the fact that the plotted curves have similar shape and generally reflect the variability of inflow and outflow of water to the modeled domain determined by the assumed top boundary condition. However, in both cases, substrates #3 and #6 presented the highest mean daily degree of saturation and volume of retained water. In our opinion this observation is significantly related to particle size distribution of these substrates, containing approx. 20 % of summarized content of silt and clay fraction. The significant silt and clay contents affect the shape of water retention curve and the resultant retention capabilities, including easily available water and the full range of available water. Additionally, the #2 and #4 substrates, presenting the lowest saturation degree and retained water content, were characterized by the highest value of coefficient of saturated hydraulic conductivity, higher by one order of magnitude then values shown by the remaining substrates.

The determined water balance for all tested cases, covering the differences between the volume of water infiltration into the modeled profile and volume of seepage through the bottom boundary of the model, is presented in Fig. 6. It is visible that the best performance was presented by substrate #3 with the highest volume of annually retained water, exceeding 1 m^3 for the tested area of 22.8 m^2. The second result, 0.67 m^3 of

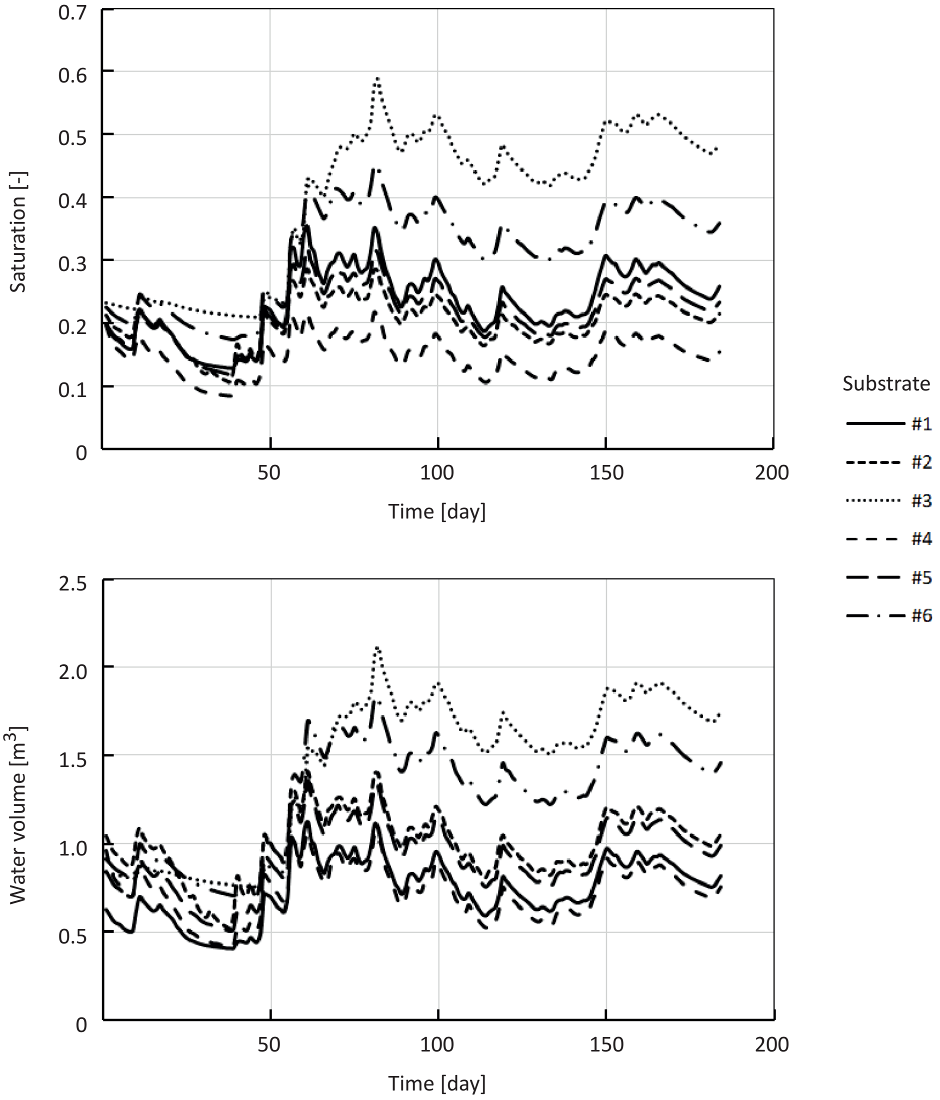

Fig. 5. a) Daily mean saturation, b) volume of retained water for tested substrates

retained water, was achieved by substrate #6, presenting, similarly as #3 significant share of silt and clay particles.

The smallest calculated, negative value of water balance for substrate #4 and #2 is related to their particle composition (dominant share of gravel and sand particles), high value of coefficient of saturated hydraulic conductivity, the shape of its water retention curve, a very high value of impossible to retain gravity water (*pF*: 0–2.0) and to the applied initial conditions.

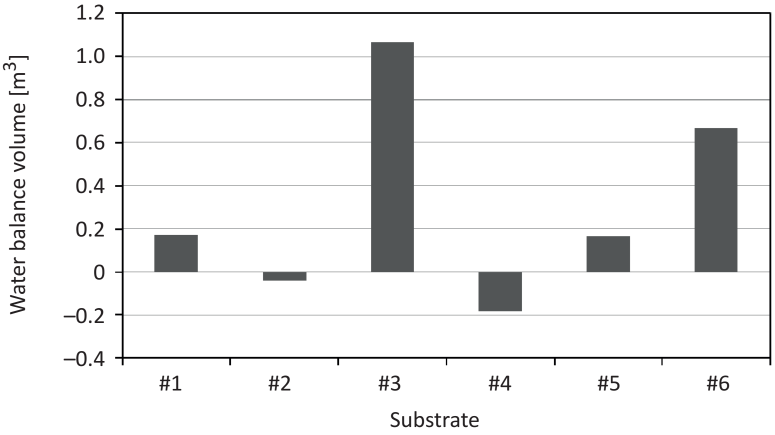

Fig. 6. Water balance calculated for green roofs utilizing tested substrates

Summary and conclusion

Our numerical modeling studies allowed to assess the hydraulic efficiency of six tested substrates of different particle compositions under the same initial and boundary conditions. The obtained results showed that water retention characteristics and permeability, directly related to particle composition, of the applied substrates significantly affect the hydraulic performance of the intensive green roof filling. The best retention efficiency of annual water balance, as well as the mean daily saturation and the daily volume of retained water, were shown by substrates containing significant share of silt and clay particles and presenting the lowest values of saturated hydraulic conductivity, *n* fitting parameter of water retention curve, as pore size distribution index, affecting the shape of water retention curve. On the other hand, the weakest retention capabilities were observed for substrates based mainly on gravel and different and characterized by the highest values of coefficient of saturated hydraulic conductivity. In our opinion, to avoid increased water outflow and to improve the water balance of the green roof, substrates of high gravity water content, below water field capacity *pF:* 0–2.0, based mainly on gravel and coarse sand should be avoided. Our studies should be continued for the greater number of substrates of variable compositions and different initial and boundary conditions.

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EFEKTYWNOŚĆ HYDRAULICZNA WYBRANYCH WYPEŁNIEŃ INTENSYWNEGO ZIELONEGO DACHU

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Abstrakt: Gwałtowna urbanizacja prowadząca do wzrostu areału powierzchni uszczelnionych zaburza naturalny bilans wodny zurbanizowanych ekosystemów. Powyższe zazwyczaj prowadzi do obniżenia naturalnej infiltracji wód opadowych i znacznego wzrostu objętości spływu powierzchniowego. Wody spływu powierzchniowego są zazwyczaj ujmowane i przekierowywane, bardzo często bez żadnego oczyszczania, przez układy kanalizacji deszczowej bezpośrednio do odbiorników, czyli do wód powierzchniowych. Oczywistym jest zatem znaczne zagrożenie środowiskowe stwarzane jakości wód powierzchniowych poprzez zrzut nieoczyszczonych wód deszczowych z obszarów zurbanizowanych. Niniejsza praca przedstawia próbę numerycznej oceny efektywności hydraulicznej sześciu różnych dostępnych na rynku substratów wypełnień intensywnych zielonych dachów. Obliczenia numeryczne efektywności zielonego dachu zostały przeprowadzone w komercyjnym pakiecie FEFLOW, Wasy-DHI. Opracowany model odzwierciedlał przekrój poprzeczny wybranego dachu. Wymagane dane wejściowe do modelowania obejmujące przewodnictwo hydrauliczne w stanie nasyconym oraz charakterystyki retencyjne zastosowanych materiałów zostały wyznaczone w oparciu o ogólnodostępne informacje techniczne badanych wypełnień. Uzyskane wyniki obliczeń wykazały zróżnicowaną efektywność hydrauliczną badanych materiałów, szacowaną na podstawie zawartości retencjonowanej wody przy tych samych warunkach brzegowych, wynikającą bezpośrednio z właściwości hydraulicznych substratów objętych analizami.

Słowa kluczowe: zielony dach, zrównoważone zarządzanie wodami opadowymi, infiltracja, retencja