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NUMERICAL ASSESSMENT OF INTENSIVE GREEN ROOF EFFICIENCY

NUMERYCZNA OCENA EFEKTYWNOŚCI INTENSYWNEGO ZIELONEGO DACHU

Abstract: The actual increased urbanization and increase in the area of sealed surfaces distort the natural water balance of ecosystems. As the result, the natural infiltration of surface water is limited and the significant increase in surface runoff is being commonly noted. In most cases water of surface runoff is collected and discharged by the stormwater systems to the surface water reservoirs, including rivers and lakes, commonly without any treatment, posing a significant environmental threat to water quality. This paper contains the attempt of numerical assessment of intensive green roof efficiency utilizing three different, commercially available substrates. The numerical modeling of green roof efficiency was performed by the means of the popular modeling software FEFLOW, Wasy-DHI. The developed model reflected the cross section of the tested green roof. The required input data for modeling covering the saturated hydraulic conductivity and water retention characteristics were based on information available in the technical descriptions of the tested substrates. The obtained results showed various performance, understood as 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, related to the rapid urbanization of natural catchments (the degree of urbanization in cities is assessed to reach level of 83 % in 2030) [1, 2], related to fast economic growth, results in increase in the area of sealed, impermeable surfaces, including roofs of housing and services buildings, roads, pavements and parking lots, significantly deteriorating permeability of soil surface [3]. Thus, the natural water balance of catchments is negatively alerted, the decreased infiltration due to limited permeability of catchment surface and increased surface runoff, in comparison to the natural ecosystems, triggered by sealed top layer of soil are commonly observed [4, 5]. The above also leads to increased accumulation of pollutants, including total suspended solids (*TSS*), total nitrogen (*TN*), total phosphorus (*TP*), various oil derivatives, different heavy metals etc., on the surface and resultant increase in their concentrations and loads in runoff water entering storm water systems and their surface receivers, commonly rivers, creating the significant anthropopressure on the natural environment, mainly the water ecosystems [3, 6-9].

The goals of surface water and groundwater protection set by the Water Frame Directive [10] require river catchment management, sustainable use of water and wide public involvement [11]. So, in order to limit the possible emissions, stormwater should be collected and treated on site, as close to the source of pollution as possible. It may be

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realized by the new systems of sustainable stormwater management, generally based on treatment, storage, infiltration and reuse, able to reduce environmental pressure caused by rainwater management [12, 13]. The green roofs, together with rain gardens, green walls and other bioretention systems, as a part of green architecture in urbanized areas, may be included to this group [2]. 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 [14-17]. The green roofs affect the water balance of urbanized catchment by delaying the initial wave of runoff and limiting the total volume of runoff by interception and retention (usually between 50 and 80 %, or even 90 %, of rain water) as well as slow percolation of rainfall event water [1, 4, 18]. Studies reported for Seoul, Korea [18] reported capability of green roof to limiting the total runoff by holding 10-60 % of rainfall water for different rainfall events. Moreover, green roofs may be also used as the adaptation strategy of urbanized areas in face of the possible climate change resulting in increase in the number of severe rainfall events [4]. Application of environmentally friendly green roofs could also led to up approx. 10 % decrease in heating and cooling energy demand of building as well as to improvement in air quality and enhancement of biodiversity in urbanized catchments [19, 20].

The growing popularity of green roofs in developed cities is highly related to significant area of impervious area, scarcity of free land and its high prices. On the other hands, the area of roofs, reaching even over 50 % of impervious area in the cities is ready for use [1].

Commonly the standard green roof consists of vegetation layer, substrate (porous material of different origin and particle composition) and drainage layer [1, 18, 19]. The thickness of substrate porous layer is usually used to distinguish two main types of green roofs, i.e.: 1) extensive green roofs of substrate thickness approx. 150 mm, possible to be installed on slope surfaces, up to 45 degree of inclination self-sustaining and requiring minimal maintenance, 2) intensive green roofs of substrate depth greater than 150 mm, utilizing grass as vegetation and possible to installation on slopes inclined up 10 degree, requiring maintenance and irrigation [1, 19]. However there are possible modifications of the above basic system, i.e. semi-intensive roofs being the combination of two previously mentioned [19]. The construction of light-weight extensive green roofs allow their installation on wider scope of existing roofs, even of lower load carrying capability. But their efficiency in limiting runoff may be lower, in relation to heavier intensive green roofs. There are known reports presenting reduction of annual water flow values by 65-85 % and 27-81 % for intensive and extensive roofs in Germany, respectively [4].

On the other hand, it should be noted that the quoted variable green roofs efficiency in limiting stormwater runoff is directly related to the precipitation patters, understood as rainfall event intensity (height and time), as well as to duration of dry periods between consecutive rainfalls and depth of substrate layer [5]. The hydraulic and heat saving efficiency of green roofs is, on the other hand, directly related to material and particle composition of the applied substrate [20]. Thus, the selection of substrate, as the most important element of green roofs construction, providing retained water, nutrients and base for plants of vegetation cover, is the critical issue [21]. The water-physical characteristics of substrate as porous media, its saturated and unsaturated hydraulic conductivity as well as water retention characteristics, described commonly by water retention curve (WRC), directly affect delay of stormwater runoff peak, volume of retained water and availability of water for plants. The ratio of infiltration process is triggered by saturated and unsaturated hydraulic conductivity, the higher conductivity the faster infiltration occurs. Shape of water retention curve, dependent to porous material particle composition and distribution of micro-, meso- and macropores, directly affects volume of gravity water (below matric suction pressure 100 cm H_2O) percolating to the drainage layer and amount of retained water, available for vegetation cover and allowing its undisturbed growth.

This paper presents attempt of numerical assessment of intensive green roof efficiency utilizing three different, commercially available substrates, allowing to assess their hydraulic efficiency in retaining the precipitation water during the assumed duration of warm half of the hydrologic year.

Materials and methods

The presented studies covered numerical determination of retention abilities and hydraulic performance, understood as ability to retain infiltration water inside voids of porous medium, of three commercially available substrates for the intensive green roofs fillings. The modeling calculations used in this study were performed by the commercial modeling software FEFLOW, Wasy-DHI, Germany, based on the finite elements method. The numerical model of water infiltration and retention in FEFLOW was based on the standard forms of Darcy's and Richards' equations [22, 23]:

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

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

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

The water retention curve model assumed to the presented calculations was based on the most popular formula presented by van Genuchten [24]:

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

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

Hydraulic conductivity coefficient of unsaturated soils K was calculated in the presented model according to van Genuchten's formula [24]:

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

where: K_s - coefficient of saturated conductivity [$m \cdot s^{-1}$], l - fitting parameter, $l = 0.5$ [24], S_e - dimensionless effective saturation defined as:

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

Our studies were based on the three selected substrates, successfully meeting demands of two the most popular European guidelines for green roof design, operation and maintenance, i.e. German FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.) and UK GRO (Green Roof Organization) [25, 26]. The substrates selection was determined by availability of the necessary input data for modeling, covering the physical and water retention characteristics, which were provided by the manufacturer. The particle size compositions of all tested substrates, presented in Table 1, were obtained directly from the official technical documentation of green roofs filling provided by their manufacturer. As it is visible in Table 1, the different particle composition of three studied substrates may trigger different hydraulic properties. Substrate #1 contains mainly stones and coarse gravel fractions, while specimen #2, beside stones and gravels, additionally contains significant share of various sands. So high saturated conductivity and low water retention capabilities may be expected for substrates #1 and #2. On the other hand, material #3 contains significant share of fine particles (silt and clay) mixed with coarse fractions. In this case, fine fractions may cause decrease in value of saturated hydraulic conductivity coefficient and increase in water retention capabilities of discussed porous medium.

Table 1

Particle size distribution of tested substrates

	Particle content [%]		
Particle size fraction	**Substrate #1**	**Substrate #2**	**Substrate #3**
Stones (> 8 mm)	61.2	4.9	31.0
Coarse gravel (8-4 mm)	28.5	34.6	19.8
Fine gravel (4-2 mm)	1.2	4.7	0.6
Very coarse sand (2-1 mm)	0.5	3.4	1.8
Coarse sand (1-0.5 mm)	0.5	12.1	2.7
Medium sand (0.5-0.25 mm)	1.3	23.6	5.9
Fine sand (0.25-0.125 mm)	1.2	11.9	6.9
Very fine sand (0.125-0.05 mm)	0.7	1.1	4.6
Silt (0.05-0.002 mm)	2.7	2.4	13.2
Clay (< 0.002 mm)	2.0	1.4	13.5

The determined hydraulic characteristics of the applied substrates, recalculated from available data, are presented in Table 2, while their water retention curves, presented as $pF = \log h$ are shown in Figure 1.

Table 2

Water retention curve characteristics of tested substrates

Substrate	**Saturated volumetric water content**	**Saturated hydraulic conductivity coefficient**	**Water retention curve fitting parameters**	
-	$[\mathrm{m^3 \cdot m^{-3}}]$	$[\mathrm{m \cdot s^{-1}}]$	A	n
			$[\mathrm{m^{-1}}]$	[-]
#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

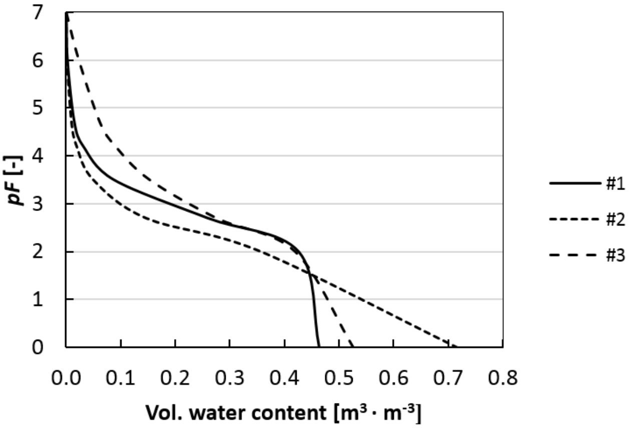

Fig. 1. Water retention curves of tested intensive green roof substrates

The developed numerical model, presented in Figure 2, allowing to assess the hydraulic performance of three tested green roofs filling porous materials represented cross section of substrate filling of intensive green roof for public building with dimensions 22.8 and 0.3 m. The model prepared in FEFLOW consisted of 5896 nodes and 10595 elements. Time duration of simulation covered the warm half of year, 184 days.

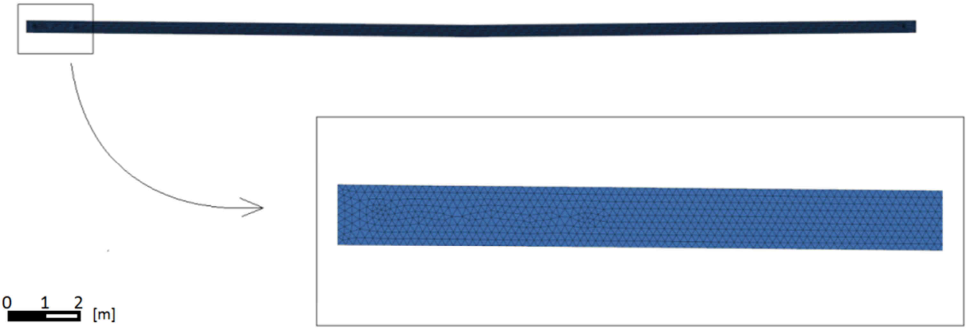

Fig. 2. Developed numerical model of intensive green roof substrate filling

Initial conditions for water flow modeling covered the degree of soil saturation assumed as 0.2 for the layer of modeled substrate for each applied variant. The top boundary condition reflecting rainwater infiltration, presented in Figure 3, was assumed as the 2nd type (Neumann type) condition reflecting mean daily flux of water inflow or outflow through the top boundary. The values of assumed top boundary were based on measurements and calculations of the several components of water balance, including precipitation, interception and evapotranspiration of grass cover in Rastorf, near Kiel, Germany [27]. The bottom boundary condition was assumed as the gradient type of Neumann condition, of the value equal to the determined coefficient of saturated hydraulic conductivity. This type of bottom boundary condition reflects the free, undisturbed gravity flow of water to lower drainage layers, finally to groundwater or drainage pipes [24].

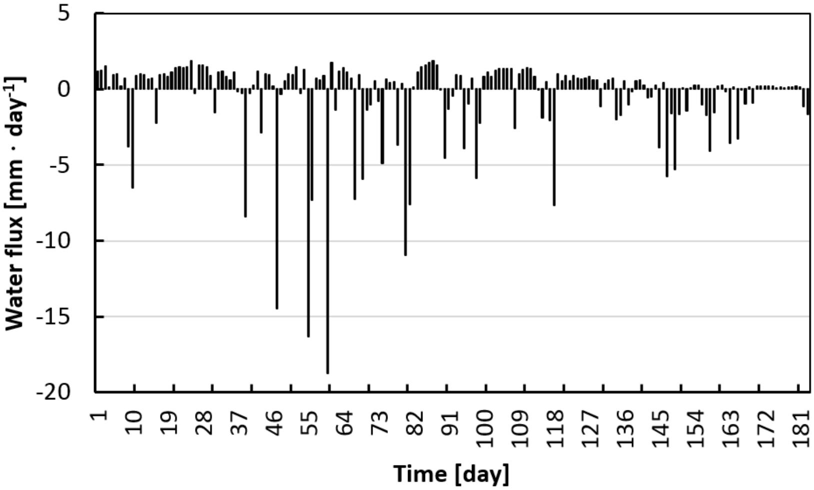

Fig. 3. Top boundary condition assumed to modeling (positive values - evapotranspiration, negative values - infiltration), modified after [27]

Results and discussion

Figure 4 presents determined retention capabilities of the three tested substrates, calculated directly from their water retention curves (see Fig. 1). It is visible that all the tested materials present comparable, 0.33-0.40 $m^3 \cdot m^{-3}$, amount of available water for plants (*pF* 2.0-4.7) and slightly variable, between 0.14 and 0.21 $m^3 \cdot m^{-3}$, content of easily available water. The most distinctive difference resulting from the water retention curves of all substrates is the different amount of gravity water, the highest value equal 0.35 $m^3 \cdot m^{-3}$ was determined for substrate #2, while the lowest, 0.04 $m^3 \cdot m^{-3}$, for substrate #1.

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

It is visible in Figure 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/from the modeled domain determined by the assumed top boundary condition. However, in both cases, substrate #3 presented the highest mean daily degree of saturation and volume of retained water. The above is significantly related to the shape of water retention curve (*n* fitting parameter) and the resultant retention capabilities, including easily available water and the full range of available water. Additionally, the #2 substrate was characterized by the highest value of coefficient of saturated hydraulic conductivity, higher by one order of magnitude then values shown by the remaining substrates.

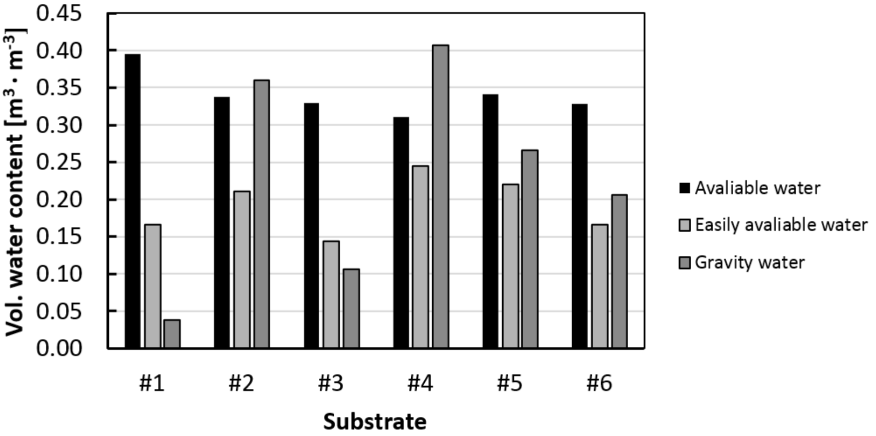

Fig. 4. Retention characteristics of tested substrates

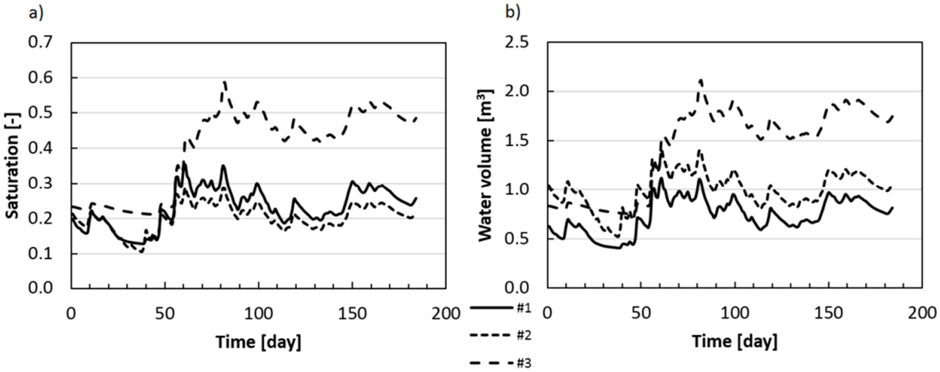

Fig. 5. a) Daily mean saturation, b) volume of retained water for tested substrates

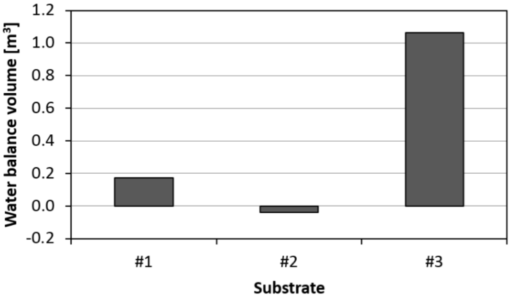

Fig. 6. Water balance calculated for green roofs utilizing tested substrates

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 Figure 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 smallest calculated, negative value of water balance for substrate #2 is related to 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. Thus, the particle composition of the tested substrates, affecting their saturated hydraulic conductivity and retention capabilities seems to have the significant meaning. The best hydraulic performance, understood as ability to retain the greatest volume of water inside the voids of green roof filling, was presented by specimen containing the significant share of fine particles (silt and clay), i.e. 26.7 %.

Summary and conclusions

Our studies allowed to assess the hydraulic efficiency of three tested substrates under the same initial and boundary conditions. The obtained results showed that water retention characteristics and permeability 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 substrate presenting the lowest values of saturated hydraulic conductivity and *n* fitting parameter of water retention curve, as pore size distribution index, affecting the shape of water retention curve. 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, should be avoided. Our studies should be continued for the greater number of substrates and different initial and boundary conditions.

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NUMERYCZNA OCENA EFEKTYWNOŚCI INTENSYWNEGO ZIELONEGO DACHU

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Abstrakt: Zauważalna aktualnie wzmożona urbanizacja i wzrost udziału powierzchni uszczelnionych zaburzają naturalny bilans wodny ekosystemów. W rezultacie naturalna infiltracja wód opadowych zostaje ograniczona, a zdecydowanie wzrasta objętość spływu powierzchniowego. W większości przypadków wody spływu powierzchniowego są zbierane przez układy kanalizacji deszczowej i kierowane do odbiorników, zazwyczaj bez żadnego oczyszczania, stwarzając poważne zagrożenie środowiskowe dla jakości wody. Prezentowana praca zawiera numeryczną próbę oceny efektywności hydraulicznej zielonego dachu wykorzystującego trzy zróżnicowane komercyjnie dostępne substraty warstwy retencyjnej. Modelowanie numeryczne efektywności zielonego dachu zostało przeprowadzone za pomocą popularnego pakietu symulacyjnego FEFLOW, Wasy-DHI. Opracowany model odzwierciedlał wybrany przekrój badanego zielonego dachu. Niezbędne dane wejściowe do obliczeń modelowych, obejmujące współczynniki filtracji oraz charakterystyki retencyjne badanych materiałów porowatych, uzyskano z materiałów technicznych wybranych substratów. Otrzymane wyniki obliczeń numerycznych wykazały zróżnicowaną efektywność badanych substratów, rozumianą jako objętość retencjonowanej wody przy zastosowaniu tych samych warunków brzegowych, bezpośrednio zależną od właściwości hydraulicznych badanych wypełnień zielonego dachu.

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