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Marcin K. WIDOMSKI[1*], Anna MUSZ-POMORSKA[1] and Justyna GOŁĘBIOWSKA[1]

HYDRAULIC EFFICIENCY OF GREEN ROOF RETROFITTED WITH ADDITIONAL SAND-AGROGEL LAYER - NUMERICAL STUDIES

EFEKTYWNOŚĆ HYDRAULICZNA ZIELONEGO DACHU WYPOSAŻONEGO W DODATKOWĄ WARSTWĘ PIASKOWO-HYDROŻELOWĄ - BADANIA NUMERYCZNE

Abstract: This paper contains the attempt of numerical assessment of hydraulic efficiency of intensive green roof utilizing two different, commercially available substrates, additionally retrofitted with layer of fractioned sand 1.0-0.5 and 0.5-0.25 mm mixed in mass concentration of 0.1 % with hydrogel. The numerical modelling of green roof efficiency was performed by the means of the popular modelling software FEFLOW, Wasy-DHI. The developed model reflected the selected cross section of the tested green roof. The required input data for modelling covering the saturated hydraulic conductivity and water retention characteristics were determined under the laboratory conditions as well as were based on information available in technical descriptions of tested substrates. The applied boundary conditions were based on previously performed in-situ measurements. The obtained results of numerical modelling showed relation between porosity, saturated hydraulic conductivity, retention properties of substrate, rainfall characteristics, duration of dry period and presence of additional sand-hydrogel mixture layer and water retention efficiency of tested green roofs.

Keywords: green roofs, water balance, hydrogel, numerical modelling

Introduction

Green roofs in urbanized regions of developed, or rapidly developing, countries are nowadays very popular in restoring distorted water balance in cities as well as limiting the possible emissions of pollutants to water and groundwater [1]. Development of cites results in changes of natural water balance of catchments, mainly due to increase in area of sealed, impermeable surfaces, including roofs of different types of buildings, roads, sidewalks, parking lots etc., triggering extended, in relation to the natural ecosystems, volume of surface runoff [2, 3]. Additionally, increased surface runoff on sealed surfaces of urbanized areas accumulating various pollutants, including total suspended solids (*TSS*), total nitrogen (N_{tot}), total phosphorus (P_{tot}), as well as various oil derivatives and different metals etc., may result in flushing these pollutants, without any treatment, into stormwater systems and possible deterioration of surface water quality [4-8]. Green roofs, as part of green architecture, utilizing different plants and various porous substrates placed on already existing infrastructure, thus avoiding problems of limited available area and high pricing of land, present ability to partially collect, store and reuse rainwater, so improvement of water balance and limiting the possible pollution of aquatic ecosystems are possible [1, 9-14].

Green roofs usually consist of three main layers: vegetation, substrate and drainage [15, 16]. There are known two main types of green roofs, distinguished by thickness of

[1] Faculty of Environmental Engineering, Lublin University of Technology, ul. Nadbystrzycka 40 B, 20-618 Lublin, Poland, phone +48 81 538 44 13

[*] Corresponding author: M.Widomski@pollub.pl

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substrate layer. The extensive green roofs, sustainable and easy to maintain, possible to installation on slope roofs, up to 45 degree, have porous substrate layer thickness up to 150 mm. The other type, known as intense green roofs, of substrate thickness greater than 150 mm may be installed on surfaces inclined up to 10 degree, utilize grass as vegetation cover and require maintenance and periodical irrigation [e.g. 16]. It is stated that installation of light-weight extensive green roofs, easier and possible on greater number of surfaces, is less efficient in limiting runoff in relation to heavier and more demanding intensive green roofs [2].

Green roof, as a part of sustainable green water management utilizes plants to intercept rainfall water and to uptake water by roots from porous substrate ant to transfer it into atmosphere due to transpiration process. Substrate, as porous material of given hydraulic conductivity and water retention abilities is used to infiltrate and retain rainwater. The remaining water percolates as seepage, is collected by drainage layer and transported to stormwater management systems. Recent scientific reports suggest that green roofs, due to abilities presented above, are capable to significantly delay the peak of rainfall water runoff and reduce the total volume of runoff, even up to 50-90 % of rainwater [2, 15].

The hydraulic efficiency of green roofs is related to several factors including: precipitation (rainfall height, intensity and time-related distribution), duration of dry periods between rainfall, depth of substrate layer and its physical and hydraulic characteristics, mainly particle composition, saturated and unsaturated hydraulic conductivity and water retention characteristics [3, 17]. The mentioned hydraulic conductivity and water retention capabilities (holding water inside the porous media) have crucial role in delaying surface runoff by limiting seepage of gravity water (percolating downwards, hold by soil suction pressure lower than 100 cm) and assuring water availability for plants of vegetation cover. However, in case of several substrates, based mainly on stones, gravel and various fraction of sand the high saturated conductivity, large amount of gravity water and limited water retention volume, in relation to substrates containing significant share of fine particles (silt and clay fractions), the hydraulic efficiency may be reduced.

The water retention capabilities and saturated hydraulic conductivity of green roofs substrates may be improved by absorbent hydrogels, known also as agrogels, unique materials, mainly hydrophilic polymers, presenting ability to absorb and sustain large amount of water, even under unfavourable conditions, i.e. under significant pressure [18, 19]. Hydrogels have large industrial application, including water purification and agriculture [20]. Hydrogels are used to improve water retention of soils in arid and semiarid regions, especially for sandy soils of high saturated conductivity and insufficient retention as well as for plants with shallow root zone and high water demand [20, 21]. Thus, application of hydrogel, or hydrogel-soil mixture, to green roof construction may increase the water holding capabilities, decrease saturated and unsaturated hydraulic conductivity and reduce volume of percolated water, thus, improvement of hydraulic efficiency of green roof substrate may be possible, especially during prolonged dry periods between subsequent rainfall events [21]. Additionally, application of hydrogel may slow nitrogen loss by sandy soils caused by high infiltration and seepage resulted from significant precipitation [18].

This paper presents numerical assessment of hydraulic efficiency of intensive green roof utilizing two different, commercially available substrates, additionally retrofitted with layer of fractioned sand 0.25-0.5 mm and 0.5-1.0 mm mixed in mass concentration of 0.1 % with agrogel. The presented numerical calculations were performed for two different rainfall events and for two assumed various initial conditions, reflecting different length of dry periods between precipitation.

Materials and methods

The present studies covered numerical calculations performed in FEFLOW, Wasy-DHI, Germany [22] to determine the influence of retrofitting the standard substrate layer of intensive green roof with the additional layer of sand mixed with agrogel on hydraulic and retention capabilities of two green roofs utilizing commercially available substrates. The substrates tested in our research were in agreement with two popular European guidelines for green roofs designing and maintenance i.e. German Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) and UK Green Roof Organization (GRO) [23, 24]. The particle compositions of selected substrates, presented in Table 1, as well as hydraulic characteristics, including coefficient of saturated hydraulic conductivity, porosity and water retention curve data, were obtained directly form the technical data provided by the manufacturers.

Table 1

Particle size distribution of tested substrates

	Particle content [mass %]	
Particle size fraction	**Substrate #1**	**Substrate #2**
Stones (> 8 mm)	31.0	13.3
Coarse gravel (8-4 mm)	19.8	23.0
Fine gravel (4-2 mm)	0.6	1.4
Very coarse sand (2-1 mm)	1.8	6.1
Coarse sand (1-0.5 mm)	2.7	16.8
Medium sand (0.5-0.25 mm)	5.9	26.0
Fine sand (0.25-0.125 mm)	6.9	10.3
Very fine sand (0.125-0.05 mm)	4.6	0.5
Silt (0.05-0.002 mm)	13.2	1.5
Clay (< 0.002 mm)	13.5	1.1

The additional drainage layer introduced to construction of intensive green roof to improve the retention capabilities utilized locally available quartz sand, fractioned to 1.0-0.5 mm and 0.5-0.25 mm, fractions mixed with commercially available agrogel in mass concentration 0.1 %. The hydraulic characteristics of two developed mixtures were measured under laboratory conditions. The values of coefficient of saturated hydraulic conductivity for both mixtures were determined by the falling head method in HM-5891A permeameter by Humboldt Mfg. Co., USA. The water retention characteristics in range 0-15 bar were determined utilizing sandbox (0-100 cm) by former IMUZ, Poland and pressure extraction chambers with ceramic plates (1-15 bar) by Soil Moisture, USA.

The obtained results of water retention characteristics for tested mixtures were fitted to the standard and popular model of water retention curve presented by van Genuchten [22]:

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

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, $m = 1 - n^{-1}$.

Table 2

Water retention curve characteristics of tested substrates

Substrate	Saturated vol. water content	Saturated hydraulic conductivity	Water retention curve fitting parameters	
			A	n
-	[$m^3 \cdot m^{-3}$]	[$m \cdot s^{-1}$]	[m^{-1}]	[-]
#1	0.527	$1.17 \cdot 10^{-4}$	1.36	1.329
#2	0.620	$7.50 \cdot 10^{-4}$	1.95	1.667
Sand 1.0-0.5 mm + agrogel	0.207	$2.49 \cdot 10^{-4}$	40.131	1.292
Sand 0.5-0.25 mm + agrogel	0.292	$8.95 \cdot 10^{-5}$	6.114	1.253

Water retention curves of all tested specimens, including both tested sand-agrogel mixtures are presented in Figure 1.

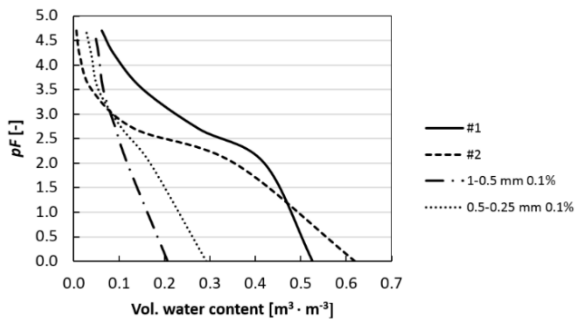

Fig. 1. Water retention curves for two tested substrates and two sand-hydrogel mixtures applied to modelling, where $pF = \log h$, h - suction pressure head [cm]

The numerical modelling of water infiltration, retention and seepage in FEFLOW software was based on standard forms of Darcy and Richards equations [25, 26]. There were two modelling domains developed, reflecting 3 m long section of intensive green roof of thickness equal 0.30 m, as well as section of the same length but retrofitted with 5 cm thick drainage layer consisting of sand mixed with aerogel in mass concentration of 0.1 %. The developed models, presented in Figure 2 consisted of 3014 nodes and 1633 elements as well as 2860 elements and 1545 nodes, respectively. The assumed time duration of simulation was equal 7 days, with the rainfall event present during the first day of calculations.

The efficiency of modelled intensive green roofs, also retrofitted with sand-agrogel, was tested for two different rainfall events observed in Lublin, Poland in July, 2011 [27]. The total height of applied rainfall events was equal 11.4 and 23.4 mm. The time related distribution of rainfall events applied to our calculations is presented in Figure 3. The hourly height of precipitation reduced by assumed interception [28] was directly assigned as the time-related top boundary conduction to the developed model to reflect the infiltration of rainfall water into green roof substrate profile.

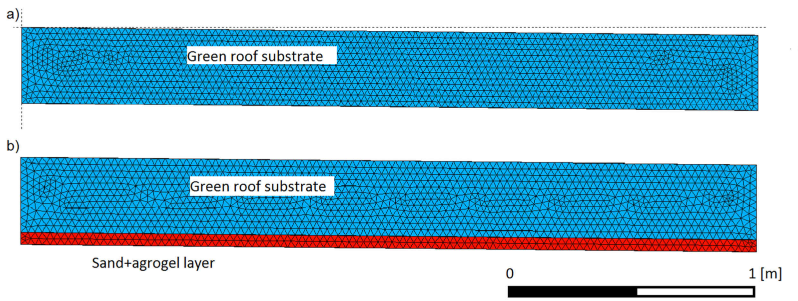

Fig. 2. Developed models of green roofs: a) sole substrate, b) substrate with additional sand-hydrogel drainage layer

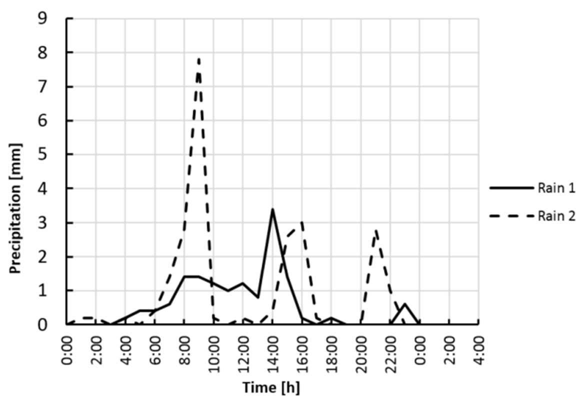

Fig. 3. Rainfall events assumed to numerical calculations

The gradient type of Neumann condition was assumed as the bottom boundary condition, with the value equal to the coefficient of saturated hydraulic conductivity of porous medium at the boundary. This type of bottom boundary condition reflects the free, undisturbed gravity flow of water to lower drainage layers or drainage pipes [22].

Two values of initial conditions, dimensionless degree of saturation, S equal 0.2 and 0.4, were assumed to our modelling to allow comparison of green roof efficiency during different rainfalls and various initial water content. The assumed various values of initial saturation led to different distribution of initial soil pressure due to variable shapes of water retention curves (see Fig. 1) for all tested substrates and sand-agrogel mixtures. The assumed initial values of soil pressure were as follows: –89.3 and –56.4 kPa as well as –116.0 and –18.8 kPa for two substrates and two values of initial saturation, respectively.

Results

The obtained results of numerical calculations allowing to assess hydraulic efficiency of two tested intensive green roof substrates additionally retrofitted with drainage layer consisting of sand-agrogel mixture covered volume of retained water, as part of substrate water balance, and percentage precipitation water retention efficiency.

Figure 4 shows comparison of total calculated volume of retained water for both substrates, two sand-agrogel mixtures, two rainfall events and two different initial conditions, saturation equal 0.2 and 0.4, reflecting different duration of dry period before the simulated rainfall.

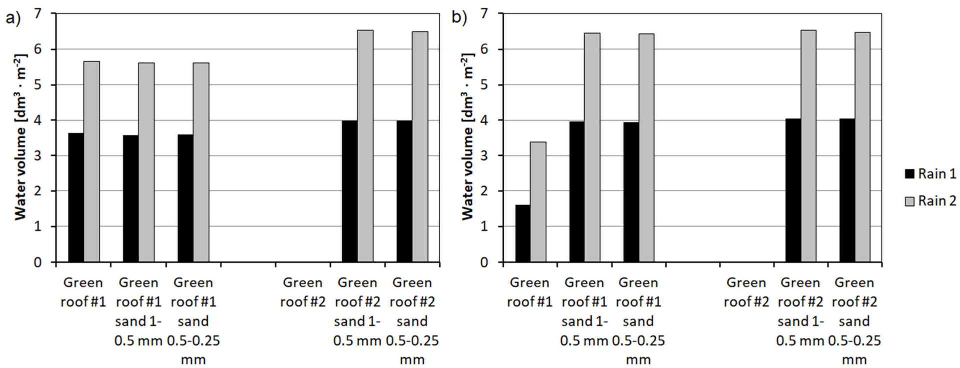

Fig. 4. Calculated volume of retained water for tested green roofs with different initial degree of saturation: a) $S = 0.2$, b) $S = 0.4$

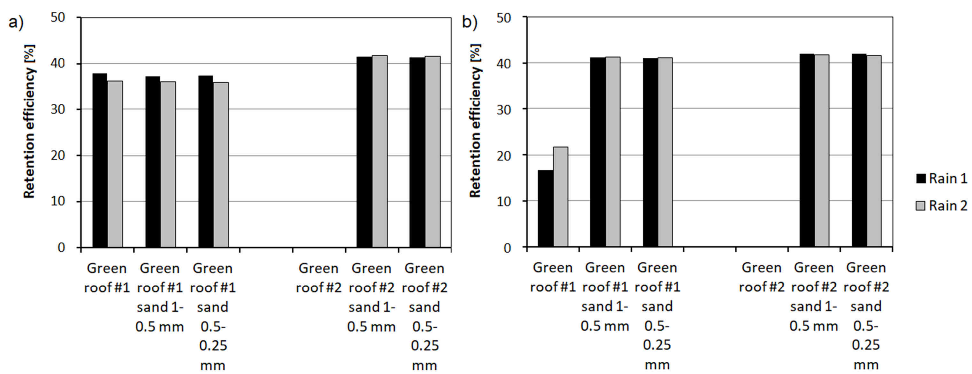

Fig. 5. Calculated retention efficiency for tested green roofs with different initial degree of saturation: a) $S = 0.2$, b) $S = 0.4$

Figure 4 presenting total volume of retained water by two tested green roof substrates shows that retention depends to particle composition of substrate, characteristics of rainfall event as well as length of dry period affecting substrate moisture before rainfall water infiltration. Application of additional sand-agrogel layer in case of green roof utilizing substrate #1 showed no effect in case of longer dry period, in all cases volume of retained water was observed at the same level, for both applied rainfall events. However, the same modelled green roofs based on substrate #1 performed differently in case of higher initial moisture content. Application of additional sand-agrogel drainage layer caused increase in volume of retained water from approx. 1.6 to 3.9 $dm^3 \cdot m^{-2}$ and 3.4 to 6.4 $dm^3 \cdot m^{-2}$ for both applied rainfalls, respectively. Figures 4 and 5 show also that independently to the assumed initial conditions greater volume of water was retained by the studied green roofs utilizing substrate #1 for Rain 2, of higher rainfall event height.

The second tested green roof, based on substrate #2, without additional drainage layer, showed zero retention ability for both applied rainfall events, no matter the value of soil saturation set as initial conditions. Thus, all infiltration water entering the tested profile, left it as a seepage water during the assumed time duration of simulation. The situation changes dramatically after application of additional sand-agrogel drainage layer, utilizing two fractions of sand. The modelled volume of retained water for both tested drainage layers for both applied initial substrate moisture conditions reached value of approx. 4.0 and 6.5 $dm^3 \cdot m^{-2}$ for both applied rainfall events, respectively. Thus, in case of substrate #2 the assumed initial conditions of different length of dry period resulting in various profile degree of saturation had negligible effect, in relation to height and intensity of applied precipitation, on calculated volume of retained water.

The determined numerically values of percentage retention efficiency, presented in Figure 5, allowed similar observations. In case of substrate #1 retention efficiency was influenced by assumed values of initial conditions as well as of height and intensity of rainfall event. Substrate #1 during calculations with initial saturation 0.2 showed comparable efficiency for Rain 1 than for Rain 2, with and without additional sand-agrogel drainage layers, approx. 37-38 vs. 36 %, respectively. The results were different for higher initial saturation of green roof substrate, i.e. $S = 0.4$. In this case retention efficiency of sole substrate roof, for both applied rainfall events was significantly lower than for roofs equipped with the additional drainage sand-agrogel mixture layer, i.e. 17 vs. 41 % and 22 vs. 41 %, respectively. Green roof utilizing substrate #2, without additional drainage layer, showed zero retention efficiency. However, application of drainage layer utilizing 0.1 % mixture of hydrogel and fractioned sand 1.0-0.5 and 0.5-0.25 mm allowed infiltration water holding ability reaching level of approx. 41-42 % for both tested initial values of saturation and both applied rainfall events.

Summary and conclusion

The performed numerical calculations of retention efficiency for two commercially available substrates, additionally supported by drainage layer utilizing 0.1 % mass mixture of fractioned sand (1.0-0.5 and 0.5-0.25 mm) showed that holding water ability may depend to particle composition of substrate, presence of additional sand-agrogel layer, characteristics of rainfall event as well as to assumed values of initial saturation at the beginning of precipitation. The modelled hydraulic performance of two tested substrates was significantly different. Substrate #1 containing significant amount of fine particles fraction (silt and clay) show retaining capability, up to approx. 37 %, dependant mostly to value of assumed initial saturation; the higher initial saturation, the lower retention efficiency was observed. Application of additional sand-agrogel layer increased its hydraulic efficiency, especially in case of higher initial saturation (shorter dry period).

On the other hand, intensive green roof utilizing substrate #2, containing mainly stones, gravel and different fraction of sand showed zero retention ability when applied alone, for both tested precipitation events. In all tested cases, for various characteristics of rainfall event and different initial conditions, application of additional 0.1 % mixture of fractioned sand and agrogel allowed significant modelled increase of volume of retained water as well as retention efficiency of green roof.

Thus, according to results of our calculations, application of additional sand-agrogel significantly increases retention abilities of substrate consisting mainly of stones, gravel and several fraction of sand which presented high water saturated hydraulic conductivity, and significant volume of gravity water (*pF* form range 0-2.0, suction pressure 0-100 cm) allowing quick and large seepage of infiltration water. On the other hand, in case of substrate consisting significant share of fine particles fraction (including silt and clay) mixed with stones, gravel as well as medium and fine sands implementation of additional drainage layer does not affect retention abilities of tested intensive green roofs.

Our numerical studies focused on influence of additional 0.1 % sand - agrogel mixture drainage layer on retention abilities and water balance of intensive green roofs substrates should be continued with application of greater types of substrates and different rainfall events as well as various saturation initial conditions reflecting different length of dry period between precipitation.

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EFEKTYWNOŚĆ HYDRAULICZNA ZIELONEGO DACHU WYPOSAŻONEGO W DODATKOWĄ WARSTWĘ PIASKOWO-HYDROŻELOWĄ - BADANIA NUMERYCZNE

Wydział Inżynierii Środowiska, Politechnika Lubelska, Lublin

Abstrakt: W pracy przedstawiono próbę numerycznej oceny efektywności hydraulicznej intensywnego zielonego dachu wykorzystującego dwa różne, dostępne komercyjnie, wypełnienia, dodatkowo wzbogacone warstwą frakcjonowanego piasku, 1,0-0,5 i 0,5-0,25 mm, zmieszanego w stężeniu masowym 0,1 % z hydrożelem. Obliczenia numeryczne efektywności badanego zielonego dachu zostały przeprowadzone za pomocą programu obliczeniowego FEFLOW, Wasy-DHI. Opracowany model odzwierciedlał wybrany przekrój poprzeczny przez badany zielony dach. Wymagane dane wejściowe do obliczeń modelowych, obejmujące współczynnik filtracji oraz charakterystykę retencyjną badanych materiałów porowatych, określono w czasie drogą badań laboratoryjnych oraz oparto o upublicznione opisy techniczne wykorzystanych wypełnień. Zastosowane warunki brzegowe wykorzystały poprzednio przeprowadzone pomiary terenowe. Wyniki obliczeń modelowych wykazały związek pomiędzy porowatością, współczynnikiem filtracji, właściwościami retencyjnymi wypełnienia oraz charakterystyką opadu, długością okresu suchego i obecnością dodatkowej warstwy mieszaniny piasku z hydrożelem a efektywności zielonego dachu.

Słowa kluczowe: zielone dachy, bilans wodny, hydrożel, modelowanie numeryczne