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IMPACT OF THE HYDROGEL AMENDMENT AND THE DRY PERIOD DURATION ON THE GREEN ROOF RETENTION CAPACITY

Abstract: Climate changes as well as the urbanisation and economic development influence the characteristics of the stormwater runoff in the cities. The sealing of drainage basin surface leads to an increase of the runoff intensity, thereby decreasing the rainwater infiltration. This situation can lead to the risk of flooding in urban areas. Therefore, especially in great cities there is a need for application of such solutions that will support the operation of the sewage systems. The examples of such solutions are, among others, the green roofs. The paper presents the results of investigation of the water retention capacity of 4 green roof models containing following growing media: (1) the typical green roof substrate without any amendments, (2) the substrate with addition of about 1 % by weight of hydrogel (the cross-linked potassium polyacrylate), (3) the substrate containing about 0.25 % by weight of hydrogel, (4) the substrate with addition of expanded clay and perlite. The models were not vegetated in order to investigate only the water retention capacity of drainage elements and substrates. The water retention capacity of green roof models was investigated in the laboratory conditions with use of artificial precipitations simulated after diverse antecedent dry weather periods (ADWP) amounting to: 1, 2, 5, 7, and 12 days. The intensities of artificial precipitations were relatively high and ranged from 1.14 to 1.27 mm/min, whereas their durations ranged from 7.75 to 12.56 min. These values of intensities and durations corresponded to the design rainfall intensities calculated using Blaszczyk's equation for annual rain depth equal to 600 mm and the return periods ranged from 5 to 15 years. The obtained results indicate that the water retention capacity of green roof models, expressed as the volumes (or depths) of rainwater retained within their structures, increases with an increase of ADWP. Results indicate that the relation between ADWP and the amount of water retained in the layers of green roofs in the case of relatively short antecedent dry weather periods provided for the analysis (from 1 to 7 days) may be approximately linear. The results of the one-way ANOVA indicate that in the case of all models there is a statistically significant difference between the values of retention depth for specified ADWP ($p < 0.001$). During more than half of simulated precipitations, especially in the case of longer ADWPs lasting 5, 7, and 12 days the best water retention capacity had Model 3, with substrate containing about 0.25 % by weight of hydrogel. On the other hand, the results show that the weakest retention capacity had Model 2 (with substrate containing 1 % by weight of hydrogel). In the case of longer ADWPs (lasting 7 and 12 days) relatively weak water retention capacity had Model 4 (with substrate containing the addition of expanded clay and perlite). It can be concluded that too large amount of hydrogel added to the substrate can have an unfavourable impact on the water retention capacity of green roofs.

Keywords: green roofs, retention capacity, stormwater management, substrate, hydrogel

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Introduction

The increase in population and migration of people to the cities lead to the continued growth of urban areas [1]. The process of urbanisation leads to the changes in land use and to an increase of the area of impermeable surfaces. The natural areas - forests, croplands, grassland are displaced by the impervious surfaces, e.g.: streets, buildings, places [2, 3]. The persistent sealing of drainage basin surface in urbanized areas prompts the rise of runoff intensity. This can lead to an increase of threat of flood [1].

Additionally, the climate changes may lead to an increase of the frequency, duration and intensity of the extreme rainfall events [4]. Both the urbanization and climate change are major phenomena transforming natural hydrological processes in the catchments [5]. Regarding the stormwater, in the urbanized catchment the infiltration rate decreases, resulting in an increase of the surface runoff [2]. On the other hand, the increase of the surface runoff volume contributes to the decrease of time to peak, resulting in the rapid discharge of rainwater via piped drainage systems and reduction of the soil moisture replenishment and groundwater recharge [5]. This influences the surrounding urban environment and can increase the risk of flooding as well as threat of the contamination of the water resources due to the transport of pollutants from impervious surfaces [1, 2]. The traditional way to cope with excess stormwater in the urban areas is use of the sewerage systems. In many cases, especially in the great cities, these solutions no longer have the capacity to keep pace with the impacts of climate change and the progressive urbanization [6]. Therefore, in urbanized areas there is a need for application of the solutions that will support the operation of the sewerage systems [1, 3, 6]. Such solutions, that are more and more frequently used in the cities are Sustainable Urban Drainage Systems (SUDS) [7].

SUDS are developed for managing risk of floods by dealing with rainwater at the source [6-8]. They can be implemented both as a new objects and as a retrofit of existing structures [6]. SUDS include, inter alia: stormwater drainage wells [9], geocellular storage systems [10], plastic open-bottom infiltration chambers, stormwater ponds and retention-infiltration reservoirs [11, 12], grass swales [13]. Other examples of SUDS are bioretention systems (such as rain gardens), and green roofs [14].

Green roofs are the layered roofs covered with growing medium (substrate) and vegetation [14]. They are typically divided into three categories: intensive, simple intensive (semi-intensive), and extensive [14, 15]. Additionally, the extensive green roofs can be categorized into the single-course extensive and multi-course extensive roofs [16]. Because of costs and the building weight restrictions, the extensive green roofs are much more common than the intensive and semi-intensive roofs [17]. Due to shallow substrates, the types of plants overgrowing extensive green roofs are: succulents, grasses, herbs, mosses etc. that are extremely sun and drought tolerant [14, 18].

Extensive green roofs provide numerous ecological and economic benefits [14, 16-18] e.g. energy conservation [19, 20] and reduction of the urban heat island effect in the cities [21]. A development of artificial green zones in cities plays an important role in the preservation of biodiversity [22]. Green roofs are potential method to counteract the destruction of natural habitats for plants and animals in urban areas [17, 21, 23, 24]. However, one of the most important functions of green roofs is the stormwater management. Green roofs contribute to reduction the intensity of the stormwater runoff due to the evapotranspiration, thereby reducing the risk of flooding in urban areas [2, 25, 26].

The hydrologic performance of green roofs can be assessed, among others, in terms of stormwater retention rate and stormwater retention capacity (or water storage) [3, 26, 27]. Stormwater retention rate can be calculated as the percentage of rain water retained by green roof during a precipitation event [27]. On the other hand, the stormwater retention capacity can be, among others, estimated based on the maximum volume of water that can be retained in the layers of green roof under a certain conditions. The water retention capacity of green roofs is influenced, *inter alia*, by the climatic conditions, the roof type (intensive, semiintensive, extensive), the composition and thickness of substrate, the length of antecedent dry weather period (ADWP), the green roof slope etc. [1, 27, 28].

Substrate is a very important element of green roof. Its density should be relatively low, so as not to overload the building structure [27]. The substrate provides the physical support and supply water and nutrients (among others phosphorus) to plants [29, 30]. A very important parameter of each substrate is good permeability for both the water and air. High value of hydraulic conductivity influences the process of infiltration and rapid discharge of rainwater from the green roof surface to deeper layers, while minimizing the surface runoff that could lead to the erosion of the vegetation layer [27]. Rapid outflow of excess water from the substrate enables good aeration of plant roots, thus preventing their rotting [29]. But, on the other hand, the rapid outflow can cause the leaching of the phosphorus and other nutrients from the mineral particles used in the substrate, which can lead to the contamination of the runoff [30].

In summer, especially during hot weather, green roof substrates are exposed to drought due to their small thickness and low water capacity. The amendment of substrates with various additives may increase the availability of water for plants. This leads to the achieving favourable conditions for vegetation, as well as helps plants to survive adverse weather conditions [31].

One type of admixtures that can modify substrate properties are three-dimensional cross-linked hydrophilic polymers, also referred to as superabsorbents (SAPs) or hydrogels [31, 32]. When added to the growing medium, they play the role of "artificial humus" [33]. Examples of SAPs are, among others, polyacrylate and polyacrylamide hydrogels, *i.e.* the cross-linked potassium polyacrylate. Superabsorbents can be used as the moisture buffers. They reduce the water stress in plants and protect against loss of water soluble nutrients from the root zone [34].

Hydrogels have the ability to absorb significant amounts of water (from several to several hundred times more than their dry mass). Their water absorption depends on the depth of application and the bulk density of medium (*e.g.* substrate) covering hydrogel [34]. Young *et al.* [29] found that modifying the characteristics of substrates can significantly alter the initial growth of vegetation grown upon them and thus can improve the physiological performance of plants. They found that the addition of superabsorbent to the growing medium can improve its water holding capacity and may be useful at providing water to plants during a drought stress [29].

The focus of the research described in the paper was the investigation of the influence of the substrate amendments (cross-linked potassium polyacrylate - 1 and 0.25 % by weight, as well as expanded clay and perlite) on the water retention capacity of 4 green roof models. Substrate amended with an admixture of expanded clay and perlite was introduced into research due to investigate how a lightweight growing medium with very good water and air permeability would perform compared to models enriched with hydrogel, whose air permeability in a saturated state may be lowered. The additional focus was to analyse the

influence of ADWP duration on the water retention capacity of examined green roof models.

Materials and methods

The investigations were conducted from 5/04/2016 to 1/06/2016 in the laboratory conditions with use of 4 green roof models placed on the garden trays. In the right lower corner of each tray a hole was drilled and a plastic flexible PVC hose was installed in order that the excess of water would outflow from the green roof model. The slope of model bottoms amounted to 5 %. On the bottoms of trays were placed the drainage elements Floradrain FD 25 (docked for the internal tray dimensions at the bottom, amounted to about 55.7×55.7 cm) and filter sheets SF (70×70 cm). 10 dm^3 of properly prepared commercial available substrate "Roof garden" produced by ZinCo (without modifications and amended with hydrogel or expanded clay and perlite) was placed on the surface of filter sheet on each model. The substrate "Roof garden" consisted of the high-quality crushed brick, other mineral aggregates (i.a. expanded clay), wood chips, sandy soil enriched with compost and fibre materials, etc. The structures (cross-sections) of the models are described in the Figure 1 (on the base of [35]). The amounts of the hydrogel admixtures (0.25 and 1 % by weight) were assumed to be close, but not the same to the amounts reported in the literature [32]. The amounts of expanded clay and perlite were assumed arbitrary. The bulk density of the air dry substrate (unmodified as well as amended with hydrogel) amounted to $1212 \pm 12 \text{ kg/m}^3$. The bulk density of the substrate with admixture of expanded clay and perlite (used in Model 4) was equal to $762 \pm 41 \text{ kg/m}^3$. The average moisture of air dry substrates was equal to 4.86 ± 1.57 % by weight. The substrate moisture was not additionally measured during investigations. The average area of substrate surface in each green roof model amounted to $3213.3 \pm 17.2 \text{ cm}^2$, and the average thickness of substrate amounted to about 32 ± 1 mm. The models did not contain the vegetation layer in order to investigate only the water retention capacity of drainage layers and substrates. The test stand was located under the roof skylight so that the substrate surfaces would be appropriately sun-filled.

Fig. 1. The cross-sections of the models: 1 - the garden tray bottom, 2 - the drainage element Floradrain FD 25 (height: 25 mm), 3 - the filter sheet SF, 4 - the substrate "Roof garden" without additions (weight: 12.12 kg), 5 - the substrate "Roof garden" (12.00 kg) with addition of 1 % by weight of hydrogel (0.12 kg), 6 - the substrate "Roof garden" (12.09 kg) with addition of 0.25 % by weight of hydrogel (0.03 kg), 7 - the substrate "Roof garden" (6.63 kg) with addition of 7.82 % by weight of expanded clay (0.597 kg), and 5.21 % by weight of perlite (0.398 kg)

A suitable volume of water (the rain volume) was evenly spilled on the substrate surface of each model. The water was spilled using the 500 cm^3 bottles with caps with apertures. The initially predetermined rain intensity was equal to about $200 \text{ dm}^3/(\text{s} \cdot \text{ha})$. To achieve this required rain intensity each 500 cm^3 of water (1 bottle) was evenly spilled on the model substrate surface during the time of about 78 seconds. Additionally, the actual

duration of spill of each 500 cm³ of water was registered due to calculate the actual average rain rates (Table 1).

The water drained through the outflow pipe from each model (water that was not retained within the structures of models) was collected to determine its volume. The amount of water retained within the layers of each model was established based on the difference between the volumes of artificial precipitation and runoff. The durations of the assumed antecedent dry weather periods (ADWPs) amounted to: 1, 2, 5, 7, and 12 days. In the case of ADWPs amounting to 1, 2, 5, and 7 days the experiments were repeated three times. In the case of ADWP amounting to 12 days the experiment was performed once only, because it was not possible to continue the investigation for this ADWP under the similar atmospheric conditions. Therefore, the results obtained for precipitation simulated after 12 dry days were not included in the analysis of the impact of ADWP on the water retention capacity of green roofs as well as the one-way ANOVA. The properties of simulated (artificial) precipitations are given in Table 1. The maximum and minimum values of the air temperature and relative humidity prevailing in the laboratory during ADWPs were recorded with the use of the digital thermometer/hygrometer. The data presented in the Table 1 show that the intensities of rains were similar and relatively high, and they ranged from $190 \pm 12 \text{ dm}^3/(\text{s} \cdot \text{ha})$ to $211.9 \pm 2.4 \text{ dm}^3/(\text{s} \cdot \text{ha})$.

Table 1

Properties of artificial precipitations

No.	Anteced. dry period	Rain volume	Rain depth	Min. air tempera- ture	Max. air tempera- ture	Min. air humidity	Max. air humidity	Rain intensity
	[d]	[cm ³]	[mm]	[°C]	[°C]	[%]	[%]	[dm ³ /(s·ha)]
1	1	3000 ±15	9.3 ±0.1	22.1 ±0.1	29.6 ±0.1	28 ±1	39 ±1	199.3 ±5.4
2	1	3000 ±15	9.3 ±0.1	20.6 ±0.1	25.0 ±0.1	33 ±1	44 ±1	200.9 ±9.3
3	1	3000 ±15	9.3 ±0.1	27.5 ±0.1	32.0 ±0.1	37 ±1	58 ±1	205.2 ±3.6
4	2	4000 ±20	12.4 ±0.2	22.0 ±0.1	29.9 ±0.1	33 ±1	50 ±1	190 ±12
5	2	4000 ±20	12.4 ±0.2	21.1 ±0.1	28.4 ±0.1	32 ±1	44 ±1	199.4 ±6.3
6	2	4000 ±20	12.4 ±0.2	25.1 ±0.1	33.7 ±0.1	30 ±1	50 ±1	206.7 ±4.9
7	5	4000 ±20	12.4 ±0.2	20.5 ±0.1	29.3 ±0.1	55 ±1	40 ±1	193.1 ±7.3
8	5	4000 ±20	12.4 ±0.2	22.1 ±0.1	31.6 ±0.1	29 ±1	43 ±1	198.9 ±2.4
9	5	5000 ±25	15.6 ±0.2	24.3 ±0.1	33.7 ±0.1	28 ±1	48 ±1	207.9 ±2.3
10	7	4000 ±20	12.4 ±0.2	19.9 ±0.1	27.5 ±0.1	35 ±1	57 ±1	206.3 ±3.2
11	7	5000 ±25	15.6 ±0.2	21.0 ±0.1	32.0 ±0.1	31 ±1	51 ±1	211.9 ±2.4
12	7	5000 ±25	15.6 ±0.2	21.3 ±0.1	34.0 ±0.1	28 ±1	51 ±1	207.0 ±3.1
13	12	5000 ±25	15.6 ±0.3	22.5 ±0.1	36.7 ±0.1	25 ±1	53 ±1	208.4 ±1.8

The rain volumes spilled during simulated precipitations no. 9 and 10 (Table 1) were different than for the rest of tests with the same ADWPs. Generally, it was not a problem, because in the majority of analyses described in this article the relevant parameters were the volumes (or depths) of rainwater retained in the structures of green roofs (the retention), and not the volumes of rainfalls. These simulated precipitations should have had the enough volumes to completely saturate all layers of green roof models and to obtain the sufficient volumes of runoff. These volumes were dependent on the durations of ADWPs as well as the air temperatures prevailing in the laboratory during ADWPs. An exception is the stormwater retention rate, which value depends on the volume of precipitation falling on the model (see Equation (2) and Table 3). Therefore, in the case of this parameter, only the

values obtained for different models during a specific rainfall can be compared with each other. Thus, no further statistical calculations were performed for the stormwater retention rates.

Figure 2 presents the intensity-duration-frequency (IDF) curves showing the relationships between duration (in min) and intensity (in mm/min) of simulated precipitations for different return periods ($C = 1, 2, 5, 10$, and 15 years) established based on the simplified Blaszczyk's equation for calculation of the design rainfall intensity for the average annual precipitation depth in Poland $H = 600$ mm [36, 37]:

$$q = \frac{470 \cdot \sqrt[3]{C}}{t^{0.67}} \quad (1)$$

where q is the design rainfall intensity in [$\text{dm}^3/(\text{s} \cdot \text{ha})$], C is the return period in [years], and t is duration of rain in [min].

Fig. 2. The rainfall intensity and duration, t , of simulated precipitations compared to the intensity-duration-frequency curves (IDF curves) calculated based on Blaszczyk's equation for return periods C amounted to: 1, 2, 5, 10, and 15 years and the annual precipitation depth $H = 600$ mm

Despite serious questions to the theoretical fundamentals and both limited and outdated data, Blaszczyk's formula is still in use for design of sewerage systems in Poland [37]. The IDF curves presented in Figure 2 are compared to the points showing the relationships between intensity and duration of simulated precipitations. Presented results show that the intensities of all simulated precipitations were relatively high and approximate (1.14-1.27 mm/min). Results show that the points corresponding to the precipitation depth of 9.3 ± 0.1 mm lie near the IDF curve for $C = 5$ years (the precipitation durations amounted to 7.75-7.78 min). The points corresponding to the precipitation depth of 12.4 ± 0.2 mm are situated between IDF curves for $C = 5$ and $C = 10$ years (precipitation durations amounted to 10-10.88 min). The points corresponding to the precipitation depth of 15.6 ± 0.2 mm lie near the IDF curve for $C = 15$ years (the precipitation durations amounted to 12.27-12.56 min). Assuming, it should be noted that all of the simulated precipitations were equal to or exceeding the design rainfall intensities calculated using the Blaszczyk's equation for annual depth $H = 600$ mm and the return period $C = 5$ years. Such high depths and intensities of simulated precipitations were necessary to exceed the water retention capacity of each green roof model under certain conditions (after specified ADWP) and

thus to obtain the runoff. It was necessary to perform an analysis of the impact of ADWP on the retention capacity of green roofs.

Results and discussion

Table 2 shows the volumes of rainwater retained within the layers of examined green roof models (the water retention capacity) during simulated precipitations which occurred after 1, 2, 5, 7, and 12 antecedent dry days. The maximum values of the water retention capacity obtained during the specified simulated rainfalls were set in bold type.

Table 2
Volumes of water retained within the layers of green roof models

No.	Antecedent dry days [d]	Volume of water retained on the models (the retention capacity)			
		[cm ³]			
		Model 1	Model 2	Model 3	Model 4
1	1	492 ±30	520 ±29	519 ±29	489 ±30
2	1	382 ±31	310 ±31	407 ±30	362 ±30
3	1	627 ±29	879 ±27	585 ±29	695 ±28
4	2	970 ±36	904 ±36	1063 ±36	1104 ±36
5	2	821 ±37	770 ±37	815 ±37	778 ±37
6	2	974 ±36	1010 ±35	1084 ±36	1122 ±36
7	5	1372 ±36	1421 ±35	1454 ±35	1407 ±35
8	5	2028 ±29	1690 ±33	2062 ±29	1853 ±32
9	5	2164 ±41	1962 ±41	2176 ±41	2140 ±40
10	7	1808 ±32	1802 ±32	1828 ±32	1773 ±32
11	7	2592 ±39	2172 ±41	2893 ±37	2326 ±41
12	7	2480 ±40	2088 ±41	2508 ±39	2230 ±40
13	12	3870 ±32	3280 ±35	4287 ±31	3245 ±36

The obtained results indicate that in most cases, especially for ADWPs amounted to 5, 7, and 12 days, Model 3 (with substrate containing 0.25 % by weight of hydrogel) exhibited the best water retention capacity. In more than half of cases, especially after longer ADWPs, the weakest retention capacity had Model 2 (with substrate containing 1 % by weight of hydrogel). In the case of longer ADWPs (lasting 7 and 12 days) relatively weak retention capacity had Model 4 (with lightweight, good permeable substrate containing the admixture of expanded clay and perlite). But it should be noted that Model 4 exhibited relatively good retention capacity in the case of ADWP equal to 2 days, especially at higher air temperatures. But, nevertheless, it should be emphasized that the results of the one-way analysis of variance (ANOVA) show that the statistically significant difference does not exist between the groups of the water retention capacity values for four models ($p > 0.05$; $F_{\text{crit}} = 4.07$). Calculated values of $F_{3,8}$ amounted to: 0.091 (for ADWP = 1 day); 0.384 (for ADWP = 2 days); 0.308 (for ADWP = 5 days); 2.824 (for ADWP = 7 days). Such results of ANOVA were obtained due to the fact that in the case of specified ADWP, the different volumes of water were retained on specified model during separate artificial precipitations, depending on the air temperature and humidity prevailing in the laboratory during experiments.

Table 3 presents the calculated values of stormwater retention rates, expressed as percentages of the relations between the volumes of water retained within the layers of

models and the volumes of simulated precipitations falling on the model surface (Equation (2)):

$$S_r = \frac{V_r}{V_p} \cdot 100 \quad (2)$$

where S_r is the stormwater retention rate [%], V_r is the volume of water retained within the model [cm^3], and V_p is the volume of the precipitation falling on the model surface [cm^3].

The maximum values of stormwater retention rates were set in bold type.

Table 3

Calculated stormwater retention rates

No.	Antecedent dry days	Stormwater retention rate			
	[d]	[%]			
		Model 1	Model 2	Model 3	Model 4
1	1	16.4 ±1.1	17.3 ±1.1	17.3 ±1.1	16.3 ±1.1
2	1	12.7 ±1.1	10.3 ±1.1	13.6 ±1.1	12.1 ±1.1
3	1	20.9 ±1.1	29.3 ±1.1	19.5 ±1.1	23.2 ±1.1
4	2	24.3 ±1.1	22.6 ±1.1	26.6 ±1.1	27.6 ±1.1
5	2	20.5 ±1.1	19.3 ±1.1	20.4 ±1.1	19.5 ±1.1
6	2	24.4 ±1.1	25.3 ±1.1	27.1 ±1.1	28.1 ±1.1
7	5	34.3 ±1.1	35.5 ±1.1	36.4 ±1.1	35.2 ±1.1
8	5	50.7 ±1.0	42.3 ±1.1	51.6 ±1.0	46.3 ±1.1
9	5	43.3 ±1.1	39.2 ±1.1	43.5 ±1.1	42.8 ±1.1
10	7	45.2 ±1.1	45.1 ±1.1	45.7 ±1.1	44.3 ±1.1
11	7	51.8 ±1.1	43.4 ±1.1	57.9 ±1.1	46.5 ±1.1
12	7	49.6 ±1.1	41.8 ±1.1	50.2 ±1.1	44.6 ±1.1
13	12	77.4 ±1.1	65.6 ±1.1	85.7 ±1.1	64.9 ±1.1

The results presented in Table 3 show that green roofs can play a significant role in the reduction of surface runoff and thus the reduction of volume of water that discharges to the stormwater sewers. The values of the stormwater retention rate ranged from 10.3 ±1.1 % to 85.7 ±1.1 %. The highest value of the stormwater retention rate (85.7 ±1.1 %) was obtained after ADWP equal to 12 days in the case of Model 3 (substrate with addition of 0.25 % by weight of hydrogel). However, it should be emphasized that the reliability of this particular research result is limited due to the small number of measurements (only 1 trial for ADWP equal to 12 days). The results presented in Table 3 show that in the case of longer ADWPs (lasting 5, 7 and 12 days) Model 3 exhibited the best stormwater retention rate. It should be noted that the thickness of each substrate was very low and amounted to about 32 mm ±1 mm. Additionally, it should be highlighted that the depths and intensities of simulated rains were relatively high (Fig. 2) due to irrigate all green roof model layers completely and thus to obtain the sufficiently high runoff volumes.

The plots presented in Figure 3 show the relationships between the values of ADWP (with maximal value of 7 days) and the retention (S) expressed as the depth of rainfall retained within the layers of models. The values of retention (expressed in mm) were calculated as ratio of the volumes of retained water (Table 2) and the averaged area of each model amounting to 3213.3 ±17.2 cm^2 . The error bars show the values of absolute errors of individual S estimated using the logarithmic derivatives.

Fig. 3. The relationships between ADWP and retention depth (S) for ADWP in the range 1 to 7 days: a) Model 1, b) Model 2, c) Model 3, d) Model 4

The results presented in Figure 3 reveal that in the case of research described in the paper the duration of ADWP influences the retention capacity of green roofs (in this case not vegetated) expressed in terms of the depth of rainfall retained within structures of green roof models (S). The values of S are positively correlated to ADWP indicating on an increasing trend between these parameters. The results indicate the good match between the linear equations and the relationships between ADWP (in the range from 1 to 7 days) and S . The values of determination coefficients (R^2) range from 0.87 (for Model 4) to 0.90 (for Model 2). The results of the one-way ANOVA show that in the case of each model there is a statistically significant difference between the values of retention depths for specified ADWP ($p < 0.001$; $F_{\text{crit}} = 15.83$). Calculated values of $F_{3,8}$ are: 21.4 (for Model 1); 26.3 (for Model 2); 18.9 (for Model 3); 22.1 (for Model 4).

Obtained results indicate that the longer the ADWP, the more time for drainage elements and substrates to dry out leaving more capacity in pores and voids of growing medium (and in troughs of drainage element) to retain water from next precipitation. Razzaghmanesh and Beecham [38] came to a very similar conclusion. They reported that long ADWPs may lead to retentions of nearly 100 %. But it should be emphasized that their investigations were conducted under natural weather conditions with use of the natural precipitations, in most cases having lower depth and intensity [38]. Schultz et al. [39] reported that both the ADWP and the precipitation depth influence the amount of water retained within green roof during individual rain event. Baryla et al. [40] found that both ADWP and the antecedent volumetric moisture content are the parameters that influence the preceding moisture level in the substrate and thus the retention depth. On the other hand, however, they reported not statistically significant correlation between ADWP and retention, but their research was conducted in natural conditions and they have taken into

account all precipitations having diversified depths and intensities [40]. In another publication Baryla [41] found that the volume of precipitation, the initial moisture substrate, and ADWP have a significant effect on green roof retention. But she reported the higher correlation of retention with moisture content than with the ADWP.

Elliott et al. [42] in research conducted in New York City analysed the influence of seasonal weather conditions and thickness of the substrate on the potential evapotranspiration and on the relationship between ADWP and retention depth. They found that the impact of ADWP on the retention depth depends on the weather conditions as well as on the substrate depth [42]. They underlined that in the case of the investigations conducted under natural conditions, the saturation of substrate during the previous precipitation, predated ADWP, may have an impact on the available retention capacity and thus on the hydrologic performance of green roof [42]. Akther et al. [27] emphasized that longer ADWP allows the substrate to dry out through the process of evapotranspiration. As a result, the green roof has more capacity to retain the precipitation water during the next rainfall event. Burszta-Adamiak et al. [43] in their research conducted in Wrocław (Poland) found that short ADWP contributes to reduced retention on green roofs and, on the other hand, longer ADWP may result in higher retention. They established that in Wrocław conditions, the green roof platforms used in the experiments recovered their water retention capacity after ADWP equal to 3 days [43]. In the case of investigations described in the current article the time of recovery of maximal retention capacity was longer due to the laboratory conditions (lower air temperatures, lack of the direct solar radiation, lack of the air movement).

Figure 4 presents the box-whisker plots showing the values of retention depth per day (S_d) for four models, calculated as the ratio of the retention depth (S) to the corresponding ADWP duration.

Fig. 4. Non-parametric distribution of the retention depth per day (S_d) calculated as the ratio of the retention depth (S) to the corresponding ADWP duration; the boxes represent 1st, 2nd and 3rd quartiles (Q_1 , Q_2 and Q_3 , respectively); the whiskers represent the range of data (exception: the upper whisker in the case of Model 2 represents the maximum value in the data $Q_3 + 1.5IQR$ (where: IQR - the interquartile range - the range between Q_1 and Q_3); $\times$ - medium values; $\circ$ - outlier; $n = 13$

Taking into account all results, the widest range of the values of retention depth per day was obtained in the case of Model 2. It should be noted that the outlier ($S_d = 2.7$ mm) corresponds to the rainfall that occurred after ADWP equal to 1 day. During this period the temperature prevailing in the laboratory was relatively high (see Table 1, rain no. 3). Disregarding the outlier, the range of remaining results obtained in the case of Model 2 was relatively narrow. Simultaneously, Model 2 had the lowest retention capacity taking into

account the interquartile range IQR (the range between 1st and 3rd quartiles). On the other hand, the greatest retention capacity, taking into account IQR was obtained in the case of Model 3. Results indicate that the smaller addition of the hydrogel (0.25 % by weight) may have a positive influence on the retention capacity of green roof. The greater addition of the hydrogel (1 % by weight) predominantly may have negative influence on the retention depth, but under certain conditions (at high temperature) may have positive impact on the retention. It should be emphasized that in the case of Model 4, containing lightweight, good permeable substrate, the range of values of S_d was relatively wide, compared with Model 3 (regarding all results) as well as Model 1 (especially taking into account the interquartile range IQR). However, the results of one-way ANOVA reveal that the statistically significant difference does not exist between the groups of S_d values for four models ($p > 0.05$; $F_{3,48} = 0.084$; $F_{crit} = 2.81$). This is probably due to the different conditions (especially air temperatures) prevailing in the laboratory during ADWPs. Table 4 presents the linear regression equations describing the influence of the minimal and maximal temperatures prevailing in the laboratory during ADWPs ($T_{min.}$ and $T_{max.}$, respectively) on the values of S_d .

Table 4
The linear regression equations describing the influence of minimal and maximal air temperatures prevailing in the laboratory ($T_{min.}$ and $T_{max.}$, respectively) on the retention depth per day (S_d) for ADWP ranging from 1 to 12 days

Model	$T_{min.}$ vs. S_d		$T_{max.}$ vs. S_d	
	Formula	R^2	Formula	R^2
1	$S_d = 0.12(T_{min.}) - 1.37$	0.66	$S_d = 0.01(T_{max.}) + 0.86$	0.02
2	$S_d = 0.21(T_{min.}) - 3.36$	0.72	$S_d = 0.02(T_{max.}) + 0.73$	0.01
3	$S_d = 0.11(T_{min.}) - 1.06$	0.56	$S_d = 0.02(T_{max.}) + 0.83$	0.03
4	$S_d = 0.16(T_{min.}) - 2.22$	0.66	$S_d = 0.01(T_{max.}) + 0.93$	0.01

The regression analysis shows that the values of S_d (in the range of ADWP from 1 to 12 days) are positively correlated to the minimal air temperature prevailing in the laboratory which in turn can be relatively good correlated to the average temperature. The values of R^2 range from 0.56 (for Model 3) to 0.72 (for Model 2). The S_d values were weak correlated or no correlated with the values of maximal temperatures prevailing in the laboratory rarely, only during the most intense solar radiation ($R^2 = 0.01$ -0.03).

The investigations described in the current paper were the continuation and supplement of the previous research conducted on the same green roof models (described in [35]). The primary goal of the research characterized in this article was to investigate the relationship between ADWP and the water retention capacity (such analysis was not performed in [35]). The results of these two articles cannot be directly compared, because in most cases the assumed ADWPs were different and the investigations were not conducted under identical atmospheric conditions. Nevertheless, taking into account the values of retention per day (S_d) calculated based on the retention depths and ADWPs it should be emphasized that the average retention capacity of all green roof models has decreased over a period of approximately one year (results of such analysis are not included in the current paper). The smallest decrease in the average retention capacity occurred in the case of Model 1 (without any amendments) and Model 4 (containing admixture of expanded clay and perlite), while the largest decrease was observed in the case of Model 2 (with addition of 1 % by weight of hydrogel). A significant decrease in the average retention capacity was also observed in the case of Model 3. One of the reasons for the

decrease in the water retention capacity of green roof models may be the difference in an average outdoor air temperature which influenced the temperature prevailing in the laboratory during experiments (with higher average temperature during investigations described in [35]). The second reason for the lowering of the water retention capacity of Models 2 and 3 may be the reduction of the hydrogel efficacy.

In this regard it should be emphasized, that there is a need to continue research on the impact of hydrogel amendment on the water retention capacity of green roofs. The further investigations should be conducted on vegetated models under natural weather conditions, with use of new and older models, and focus on the influence of atmospheric conditions on the retention depth per day for specified ADWP durations.

Conclusion

The results of the conducted research allow to formulate the following conclusions:

1. The green roofs may have a positive effect on the stormwater management, particularly in the urban areas. The stormwater retention rate of green roof models used in the experiments ranged from 10.3 ± 1.1 % to 85.7 ± 1.1 %. It should be emphasized that the intensities and durations of simulated precipitations were relatively high and approximated the design precipitation intensities calculated for time from 5 to 15 min and the return periods from 5 to 15 years. Additionally, it should be stressed that the thicknesses of models were relatively low (32 ± 1 mm).
2. The results of investigations indicate that in most cases, especially for ADWPs amounted to 5, 7, and 12 days, the best retention capacity was exhibited by Model 3, with substrate layer containing 0.25 % by weight of hydrogel. The highest volume of water retained in the layers of this model (after ADWP equal to 12 days) amounted to 4287 ± 31 cm³, which corresponded to the retention depth equal to 13.3 mm. But it should be noted that the reliability of research result for ADWP equal to 12 days is limited due to the small number of measurements.

In more than half of cases the lowest water retention capacity was exhibited by Model 2, with substrate layer containing 1 % by weight of hydrogel. Results indicate that the greater addition of the hydrogel (1 % by weight) predominantly may have negative influence on the retention depth. Besides, after longer ADWPs lasting 7 and 12 days, the relatively low retention capacity, compared to other models, was exhibited by Model 4, containing lightweight, good permeable substrate with admixture of expanded clay and perlite. But, on the other hand, Model 4 has relatively good retention capacity in the case of ADWP equal to 2 days, especially in comparison with the models containing substrate amended with hydrogel. It could be derived from the good permeability of substrate amended with expanded clay and perlite and as a result better ventilation and faster evaporation of water retained in the layers of Model 4.

3. Nevertheless, the results of the one-way ANOVA performed for specific ADWPs did not prove any statistically significant impact of the tested model type on the water retention capacity. This was caused by the fact that the volumes of water retained on specific models after similar ADWPs were different among others due to diversified values of air temperature prevailing in the laboratory during experiments.
4. The obtained results reveal that in the case of research described in the paper and in the analysed range of ADWPs (1 to 7 days) the duration of ADWP affects the retention capacity of green roofs expressed in terms of the retention depth (S).

The values of S are positively correlated to ADWP and indicate on an increasing linear trend between these parameters (the values of R^2 ranged from 0.87 to 0.90). However, it should be emphasized that for longer antecedent dry weather periods the relationship between ADWP and S should be not linear, because the retention capacity of green roof is limited and can reach its maximal value after sufficiently long ADWP. The results of the one-way ANOVA indicate that in the case of analysed models (and for the ADWP range from 1 to 7 days) there is a statistically significant difference between the values of retention depths for specified ADWP ($p < 0.001$).

5. It should be emphasized that good correlation between ADWP and S resulted from the fact that the investigations were carried out under relatively stable laboratory conditions. It should be noted that all of the simulated precipitations included in the analysis, both preceding and following the ADWP, exceeded the retention capacity of the green roof models causing the runoff.
6. Comparison of obtained results with the results of previously conducted investigations [35] indicates that the efficiency of the hydrogel may decrease over time (especially in the case of the substrate with higher superabsorbent content).
7. The further research should include the studies on the effect of atmospheric conditions (e.g. air temperature and humidity) on the hydrological performance of green roofs containing substrates amended with superabsorbent and other admixtures.

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