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ROLE OF EXTENSIVE GREEN ROOFS IN WATER MANAGEMENT IN URBAN DRAINAGE SYSTEMS

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Abstract

Roof areas represent a significant part of the surfaces in city centers, where space for new drainage infrastructure (channels, storage tanks etc.) is limited. In these areas, green roofs have become a popular technique for implementation of sustainable urbanism concept. Green roofs are used the most common for stormwater mitigation but there are other benefits: reduce energy consumption and air pollution, decrease urban heat island effect, increase biodiversity and roof life. The paper is focused on characteristics of green roofs in the quantitative management of storm water: the reduction of the runoff volume, the peak attenuation and delay at the rainfall event. There are many factors affecting the hydrological performance of green roofs: local climate conditions, substrate depth and composition, drainage layer, type of vegetation cover, rainfall pattern, thus the influence on the drainage infrastructure is uncertain.. The results of numerous hydrodynamic simulations showed a significant impact of the use of green roofs on the performance of drainage infrastructure (storage tanks and channels).

***Keywords**: Water protection, Storm water retention, Vegetation, Sustainable urbanism*

Introduction

Conventional solutions used so far to involving direct discharge of stormwater by direct discharge of the stormwater through sewerage systems to water bodies (rivers, streams and lakes) are becoming insufficient in the dynamically developing and expanding urban areas. Increased runoff changes stream hydrology and worsen water quality resulting in reduced habitat quality. The amount of impervious areas cover within a catchment has many adverse effects on the health of the stream. The current development of urban drainage systems is shaped to maintain the natural hydrology cycle by use of the site layout and integrated control measures. Natural hydrology refers to practices and systems that use natural processes, including infiltration, evapotranspiration and retention to keep site's water balance of pre-development conditions. The roof areas represent from 35% to even 50% of the surfaces of in cities where no space is available for new drainage infrastructure (channels, storage tanks etc.). In these areas, green roofs have become a technical solution that enables effective rainwater management. Green roofs, as a form of SUDS (Sustainable Urban Drainage Systems), manage stormwater at the source, reducing runoff volumes and peak flows [1]. Green roofs have been shown to effectively retain stormwater depending on their construction and the climate in which they are located [2]. Reduction of stormwater runoff is especially important in areas equipped with combined sewer systems. Overflows through the combined sewer overflows (CSO) occurs during wet weather and are mix of industrial, commercial and domestic wastewater with

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stormwater. The discharges contains pathogens, organic substances and toxic substances and has been identified as a serious contributor to natural water pollution and negative human health impacts. Green roofs increase retention capacity at the site and improve the CSO performance by reduction of volumes, frequency and pollution loads of overflows. Apart for management of rainfalls, green roofs serve a number of advantages in other fields:

- improved energy efficiency - the insulating effects of added layers reduces energy losses during winter and the penetration of summer heat (direct savings may reach over 4kWh/m^2 per year),
- mitigate heat island effects,
- improve air quality by trapping particulates and dissolving pollutants,
- reduces ambient noise outside and inside the building,
- increase aesthetics of the building,
- creates additional fire-resistant layer,
- increases biodiversity and wild life protection.

The most common classification of green roofs is based on the characteristics of the vegetation layer and substrate layer:

- extensive - uses shallow substrate depth of less than 15cm and drought-resistant vegetation cover (mosses, grasses, herbaceous plants, or succulents), minimum maintenance needs. Unit weight varies from 50 to 140kg/m^2.
- intensive - possibility of using a variety of plant species, from grasses to trees of plants and even tree species, supported on substrate depth from 15cm to 50cm, placed on structures designed to bear additional weight (from 200 to even 500kg/m^2). High maintenance needs with respect to fertilization and irrigation of plants.
- semi-intensive - system between extensive and intensive systems with plant species that grow on 12 to 25cm substrate (unit weight 120 to 200kg/m^2), usually require artificial irrigation systems.

Extensive roofs are generally preferred because they require less structural support and can often be added to the existing roofs to decrease the building's impervious footprint of a building. Green roofs are multilayer systems and typically consists of following layers (Fig. 1): vegetation composed of different biological species, engineered soil (substrate), filter layer (usually geotextile), drainage layer, waterproof membranes, thermal insulation layer, anti-root barrier and roofing membrane. Each of these layers has a different function to keep the plants alive and to protect the structure of the building.

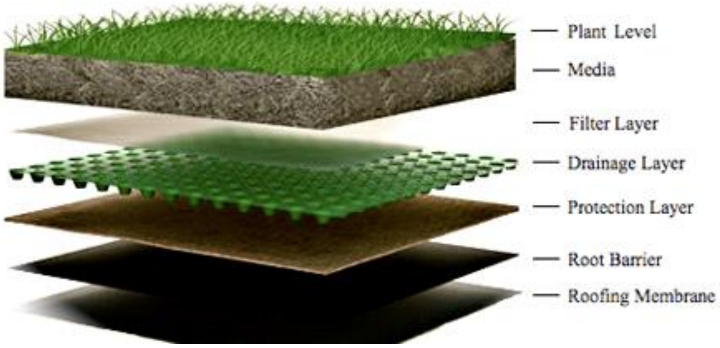

Fig. 1. Typical construction of extensive green roof

Retention performance of extensive green roofs

Green roofs improve the management of stormwater runoff, by retention and evaporation, minimizing the risk of flooding, and are considered an important instrument in its prevention and control. In practice the retention capacity of green roofs is affected by many factors:

- type of vegetation cover – plants retains the water through interception by leaves, evapotranspiration and water uptake by root system. Plant species with bigger diameter, larger root biomass and taller height would increase the stormwater retention capacity of a green roof.
- type of substrate and drainage layer (composition and depth) has a key influence on water retention capacity of green roof.
- rainfall characteristics and seasonal climate – numerous studies show an inverse relationship between the reduction of stormwater runoff and both rainfall depth and rainfall intensity.
- slope of the roof – generally runoff retention decreases as the roof slope increases but in some studies found no correlation between roof slope and runoff retention.
- age of green roof – retention capacity may vary over time due to chemical, physical and biological processes changes the substrates (i.e. washout of dissolvable substances, loss of soil particle, changes of soil porosity due to roots development) - but there is no clear dependency between age of a green roof and retention capacity.

The factors listed above have a varying effect on the ability of a green roof to reduce rainwater runoff, therefore the influence of green roofs on the performance of drainage infrastructure is uncertain [3, 4]. Design parameters for green roofs including type and depth of substrate and drainage layer, plant species, position of the roof to wind and sunlight are summarized by Czemiel-Berndtsson [5]. Reported retention performance in different field studies shows significant variation of retention capacity due to different composition of green roofs layers, but probably most important are local climate conditions: precipitation characteristics (depth, intensities, dry periods) and evapotranspiration (temperatures, wind). The studies conducted in Germany showed that a green roof with a substrate depth of up to 5cm with a vegetation cover composed of sedum and mosses can retain 39 to 46% of the annual precipitation [6]. These values are increasing to 60% when the depth of the substrate is between 10cm to 15cm and the vegetation layer is a mixture of herbs, sedum and grasses.

The research conducted by *Burszta-Adamiak et al.* [7] in Wroclaw showed that a green roof can retain up to 100% of the rainfall event, however, the percentage of the stormwater retained dropped from 33% to 75% depending on time between storm events. Similar results were found by Rowe et al. [8] – extensive green roofs can retain on average 60% of total rainfall. Uhl and Schiedt [9] present the data that suggest a maximum retention of 40mm in a 100mm substrate, that implies retention of up to 40% of substrate depth. *Kolb* [10] reported reduction of the annual runoff by 30–57% depending on roof construction, while Moran et al. [11] reported 62% total rainfall retention and an 85% reduction of maximum outflow rates. Many publications emphasize influence of seasonal effects on hydrological performance of green roofs – during winter months efficiency of water retention is lower than during summer months.

The experiments conducted in Czestochowa (Poland) by *Sobczyk and Mrowiec* [12] showed a significant influence of the antecedent dry period (ADP) on runoff coefficient (fig. 2a). For ADP=1 day runoff coefficient was in range 0.03-0.19 (depending on green roof construction) while for ADP=10 days the runoff coefficient grows to even 0.60. Figure 2b shows the outflow hydrographs from five models of green roofs for ADP = 1 day and ADP = 10 days. According to the these results, it is clear that reduction of runoff from green roofs is highly dependent on the intensity and volume of rainfall as well as duration of dry periods.

Field studies described in many papers reflect the hydrological performance of a specific type of green roof and specific location, therefore cannot be used for predictions to other regions/countries. For this reason, numerical models (i.e. physically-based models) are developed for the purpose of estimating the green roof hydrological performance.

Green roofs have no means of infiltration and therefore rely completely on evapotranspiration for retention recovery. In warm climates the evapotranspiration is high, so retention capacity can be restored faster, resulting in better storage availability at the start of a rain event.

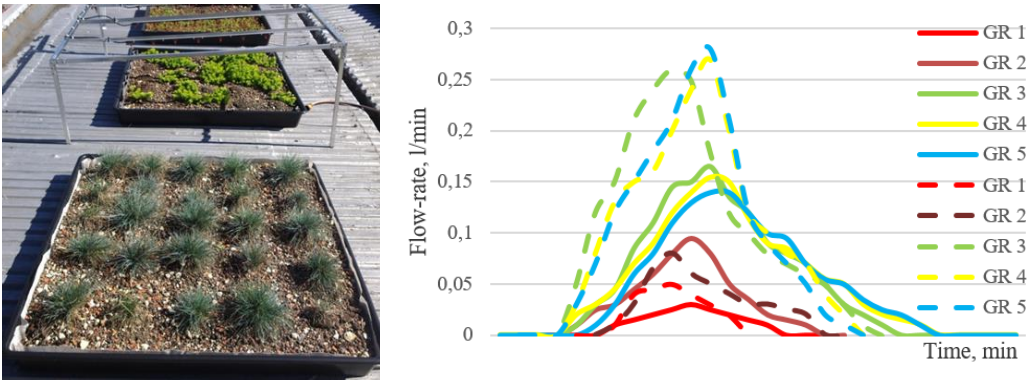

Fig. 2. a) Test sites of green roof located on the roof at Institute of Environmental Engineering (Czestochowa, Poland), b) outflow hydrographs from green roofs (ADP = 1 day – solid lines; ADP = 10 days – dashed lines) [12]

Climatic parameters are crucial in their performance and explain the great temporal variability in the runoff reduction reported in many studies. Recent studies have questioned the influence of vegetation cover on retention capacity of the green roof, because plant species are characterized by very low evapotranspiration rates, to enhance their survival in dry periods. Evapotranspiration rate of green roofs are affected by small scale, vegetation cover heterogeneity, properties of engineered soil (thickness of the layer), and uncertain moisture availability [13-15]. In this paper, the authors analyzed the scenario of green roof application in combination with storage tanks on relief of urban drainage systems - assuming the green roof covers half of the catchment area.

Methods

The research was focused on the efficiency of extensive green roofs to reduce volume and peak flows of runoffs and their influence on the performance of urban drainage systems (Fig. 3). Two variants were considered: a) direct discharge to drainage system, b) outflow regulated by storage tank (different values of outflow-rate q_0). Commercial large-surface area in the Czestochowa city (Poland) was selected to create an a hydrodynamic model. The total catchment area is 2.05ha, including roof (1.02ha), car park, roads, sidewalks (1.04ha), green areas can be ignored (around 0.1ha).

Stormwater Management Model (SWMM) was used to create the hydrodynamic model of the catchment. It is capable of representing the long-term behavior of green roofs through a hundreds of rainfall events and antecedent dry periods by applying continuous simulation. SWMM provides an assessment tool to predict the hydrologic performance of a green roof and its hydraulic influence on the drainage system. The catchment was divided into 12 subcatchments (6 for roof, 6 for parking lots and roads). The main parameters for subcatchment: - width determined by the shape and size of the subcatchment, - depression storage 1.2mm, - Manning coefficient 0.015, - slope 0.015÷0.03), The model of drainage network contains 14 links of diameter 0.3 to 0.6m linked to street collector of diameter 1.0m. The model was calibrated in the existing state (traditional roof, no storage tank) using rainfall data and flow-rates recorded in 2017 (June to September). Precipitation was measured by tipping bucket rain gauge SEBA RG50 (resolution of 0.1mm, 2min intervals) located 300m from the catchment. Flow-rate was measured at the outlet of the drainage system in a circular pipe (diameter of 600mm). Area-velocity flowmeter (PCM4 by Nivus) was used to measure and record the fluid level and mean velocity (time step 2min). The measuring campaign covered a total of 14 rainfall events (depths from 7.9mm to 29.7mm). The reliability of the calibration results was evaluated using the following goodness-of-fit tests: absolute relative error (8.7% for volume and 11.2% for peak flows) and Nash–Sutcliffe coefficient (0.952 for volume and 0.971 for peak flow). The obtained goodness-of-fit results allow considering the model as well- calibrated for estimating the runoff and peak flows for the reference scenario (conventional roof).

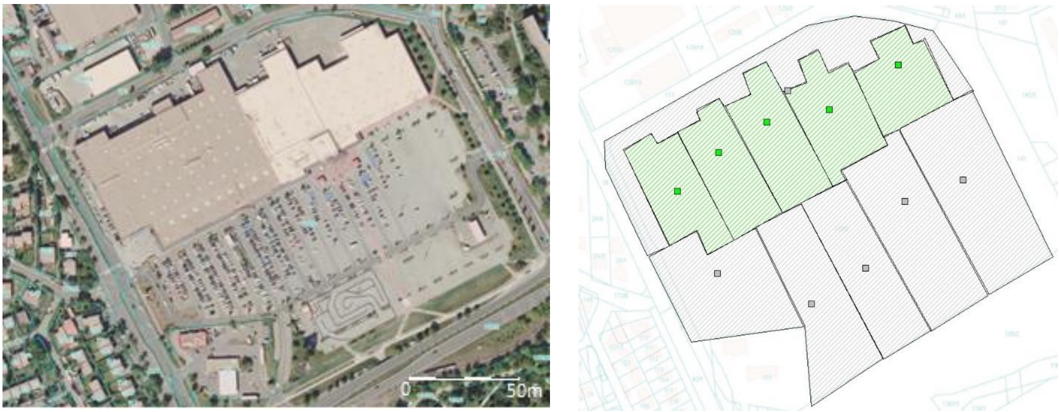

Fig. 3. Scheme of the modeled catchment catchment (commercial building with parking spaces): a) orthophotomap, b) model of the catchment in SWMM

A model of green roof was made using Low Impact Development (LID) module in SWMM, considering its specificity and limitations presented by Burszta-Adamiak and Mrowiec [16]. In recent years, many authors have conducted research on the accuracy of the SWMM in the field of green roof simulation. The comparison of the results between the experimental green roof monitoring and the hydrodynamic simulations proved that the model has accepted capabilities in simulating the shape of runoff hydrographs from green roofs, as demonstrated by the high values of the Nash–Sutcliffe model efficiency coefficient [17]. According to the results published by Peng and Stovin [18], continuous simulations using the uncalibrated parameter values generally achieved good agreement between the measured and simulated runoff from the green roofs. The lower modelled runoff during summer period is interpreted as an over-prediction of evapotranspiration, because the model does not account for the reduction in actual evapotranspiration that is known to occur when moisture is restricted. For single event simulations results show poor agreement between the simulated and measured runoff from the green roofs. The predicted maximum runoffs are lower than the measured and the duration of modelled runoff is shorter than observed. Additionally, the time to the start of runoff was predicted to be later than observed as well as the time of maximum runoff [18]. Another source of error is the assumption of constant evapotranspiration rate during day, while it is varying according to diurnal cycle. SWMM is capable of producing correct runoff hydrographs from green roofs, but the evapotranspiration rate is critical for the accuracy of long-term simulations.

Green roof in LID is represented by three layers: surface layer, substrate layer and drainage mat. The parameters of a substrate: thickness, porosity and conductivity are recognized as a main influence in the system's capacity to store rainfall [19]. Extensive green roofs available on the market are characterized by the values of retention capacity (h_R) usually expressed in as liters per m^2 or in millimeters. In order to obtain the required values of h_R, two parameters were adjusted: thickness of substrate and thickness of drainage mat. On the basis of the literature information and results of research conducted on test beds [11], four variants of layers were applied:

h_R = 15mm (soil layer thickness 50mm without storage layer),
h_R = 25mm (soil layer thickness 50mm + storage layer thickness 10mm),
h_R = 35mm (soil layer thickness 70mm + storage layer thickness 15mm),
h_R = 50mm (soil layer thickness 70mm + storage layer thickness 30mm).

In the scenarios including a storage tank at the outlet from the catchment, the following unit outflow-rates were defined: q_0= 15L/s ha, 30L/s ha and 50L/s ha. For the defined outflow-rate q_0, the required storage volume was calculated using the Intensity-Duration-Frequency

(IDF) relationship, used by Bogdanowicz and Stachy to design the drainage systems in Poland. The required volume is calculated for varying duration of rainfall and intensity, for return period C = 2 years. The obtained storage volumes for defined release rate q_0: $V_R = 294m^3$ ($q_0 =$ 15L/s ha), $V_R = 210m^3$ ($q_0 = 30$L/s ha) and $V_R = 155m^3$ ($q_0 = 50$L/s ha). Storage tank is equipped with (Fig. 4): flow regulator (to fix q_0), side weir (to fill storage chamber) and orifice with flap gate (to release storage chamber).

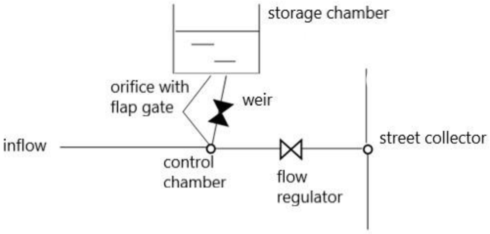

Fig. 4. Representation of the storage tank in the hydrodynamic model

Continuous simulations required preparation of the precipitation data for the period of 2008÷2017 (10 years) with time resolution $\Delta t = 10$ minutes. Because intensive rainfalls, critical for the drainage infrastructure, occur during summer months, the simulations covered the months April to September. The rainfall data was acquired from a local rain gauge (SEBA RG50). The characteristics of rainfalls for given period are summarized in table 1.

Table 1. Characteristics of rainfalls recorded in Czestochowa (Poland) in 2008÷2017 (months April to September)

		April	**May**	**June**	**July**	**August**	**September**
Monthly rainfall depth (mm)	min.	2.6	27.6	33.6	34.3	30.1	12.1
	mean	46.8	80.4	77.2	90.2	65.4	63.9
	max.	93.9	184.4	147.1	135.2	128.7	145.8
Days with precipitation (h>1mm)	min.	1	3	7	4	4	3
	mean	8	10	10	11	8	10
	max.	15	19	20	16	13	16
Daily precipitation depth (mm)	mean	5.8	8.2	7.6	8.4	8.3	6.5
	max.	37.9	54.1	37.6	42,5	70.7	29.7
Number of rainfall events	h>30mm	2	2	2	6	2	0
	h>20mm	2	7	7	10	5	5
	h>10mm	11	26	27	26	15	21

In order to assess the impact of the green roof on the urban drainage system relieving, 36 rainfall events were selected using criterion of rainfall depth h>20mm. Minor rainfalls (under 20mm) are not critical for drainage system. Short intensive rainfalls used in design calculation (in example rainfall depth h = 12mm during t = 10min) under real conditions does not occur as an isolated event but are the phase of rainfall event of longer duration.

Evapotranspiration (ET) of green roofs was measured (mainly with a lysimeter) in a variety of studies in order to quantify the rooftop behavior [14, 20]. The results from these studies show the evaporation rates are in the range 1-4mm per day. Since the evapotranspiration rate measurements were not available for Czestochowa in 2008÷2017, it was necessary to apply a model to simulate ET. Numerous models have been developed to predict the evapotranspiration based on available meteorological data [21]. The models developed to estimate ET such as Hargreaves model, Priestley–Taylor model and Penman–Monteith model estimate the “potential evapotranspiration” or “reference evapotranspiration”. The Priestley–Taylor and Hargreaves models are based on a composite of the energy and temperature data, while the Penman–Monteith model also include the wind speed and humidity measurements. On the basis of literature review, the Penman–Monteith model was finally selected:

$$\mathrm{ET} = \frac{0{,}408\Delta(\mathrm{R_n}-\mathrm{G})+\gamma\frac{900}{\mathrm{T}+273}\mathrm{u_2}(\mathrm{e_s}-\mathrm{e_a})}{\Delta+\gamma\,(1+0{,}34\mathrm{u_2})} \quad [\mathrm{mm}]$$

where: R_n – net radiation at the green roof surface [MJ/m^2/day],
G – soil heat flux density [MJ/m^2/day],
T – average mean daily air temperature [°C],
u_2 – wind speed (at 2 m height) [m/s],
e_s – saturation vapor pressure [kPa],
e_a – actual vapor pressure [kPa],
Δ – slope vapor pressure curve [kPa/°C],
γ – psychrometric constant [kPa/°C].

Studies have shown the evapotranspiration predictions to be unstable under high-advection, high vapor pressure deficit conditions various wind functions have been employed with the Penman-Monteith equations in the past to improve estimates. *El Khoury* [22] found the Pennman-Montieth equation of evapotranspiration to be an order of magnitude more sensitive to wind than any other climatic parameter; in contrast, *Martin* [23] reported greater sensitivity to relative humidity for simulated green roof runoff. On the basis of meteorological parameters (summarized in table 2) required for the Pennman-Montieth equation, the evapotranspiration for each day was calculated and the input file to SWMM model has been prepared to run continuous simulations. The percent of initial saturation was set to be zero.

Table 2. Statistics of temperature, wind, vapor pressure, insolation and evapotranspiration in Czestochowa in 2008-2017

Parameter		April	May	June	July	August	September
temperature - daily average, °C	min	7.5	12.8	16.1	18.0	18.0	12.5
	average	9.7	14.1	17.7	19.9	19.6	14.7
	max	12.2	15.3	19.0	21.1	22.9	16.7
wind. m/s	min	2.4	2.2	1.9	1.9	1.8	1.8
	average	2.8	2.5	2.4	2.2	2.0	2.2
	max	3.2	3.1	2.7	2.5	2.1	2.5
vapor pressure, hPa	min	6.80	10.00	12.30	14.10	13.90	10.90
	average	7.65	10.86	13.45	15.52	14.97	12.36
	max	8.90	12.10	14.90	16.70	16.40	13.90
insolation, h	min	136.3	96.8	172.7	158.9	201.9	109.6
	average	183.9	223.2	238.7	257.6	246.7	159.3
	max	289.6	304.8	293.0	337.0	296.4	222.7
monthly evapotranspiration, mm	min	73.1	78.5	96.6	104.2	93.4	58.6
	average	82.4	87.5	103.1	113.1	98.5	66,5
	max	92.2	100.9	108.7	120.1	105.2	78.0

The results of simulations were analyzed in two stages:

Stage I. Efficiency of green roof (long-term simulation, all rainfalls included): calculation of runoff coefficient C_R (defined as ratio volume of runoff to volume of rainfall) for varying retention capacity of green roof (h_R), estimation of period (days) with full retention capacity, reduction of runoffs to the drainage system in comparison to a traditional roof.

Stage II. For the selected 36 rainfall events, the influence of green roof on the performance of drainage system included two variants:

- direct discharge to the drainage system – reduction of volume and peak flows discharged street collector from the catchment (including both roof and parking),
- outflow from the catchment regulated by a storage tank (for fixed outflow-rate q_0): reduction of flooding events. reduction of stormwater stored in the tank, possible reduction of storage volume as a result of the green roof operating.

Results and discussion

The results of the hydrodynamic simulation for a period of 10 years enabled to compute the runoff coefficient C_R: average for whole years, minimum and maximum for particular year

(Table 3). General relationship between the average runoff coefficient and retention capacity h_R is quasi-linear and starts from $C_R = 0.111$ (h_R = 50mm) to $C_R = 0.331$ (h_R = 15mm). The analysis of the C_R value for particular years shows significant variability depending on h_R. Standard deviation (SD) of runoff coefficient for h_R = 50mm is SD = 0.051, while for h_R = 15mm is SD = 0.089, so the runoff coefficient for green roofs with low retention capacity is more uncertain. In the years characterized by high temperatures and lower precipitation, C_R drops below 0.10 (h_R = 35mm and 50mm) which means over 90% reduction of stormwater runoff during 6 months in comparison to a conventional roof.

Table 3. Runoff coefficient for green roofs (average, minimum, maximum) for the period of 2008÷2017

Runoff coefficient C_R	Retention capacity of a green roof h_R=15 mm	h_R=25 mm	h_R=35 mm	h_R=50 mm
minimum	0.152	0.110	0.070	0.023
average	**0.331**	**0.242**	**0.166**	**0.111**
maximum	0.460	0.345	0.275	0.234

Simulations allow analyzing the frequency of discharges from green roofs in comparison to a conventional roof (564 runoff events during 1830 days of simulations). A significant reduction of the runoff events was found, as presented in figure 5. Even for a minimum retention capacity (h_R = 15mm), the runoff events were reduced by 76% (133 runoff events), while for h_R = 50mm the reduction reached 90% (only 53 runoff events recorded).

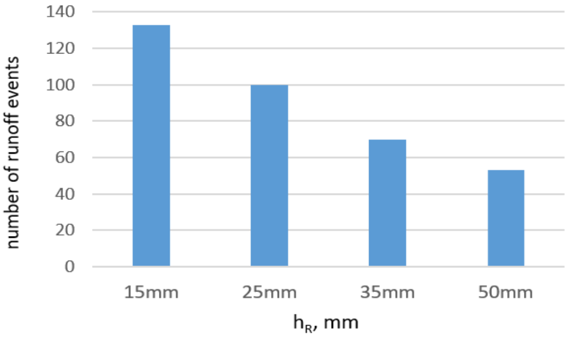

Fig. 5. Number of runoff events from green roofs depending on h_R – reference value for a conventional roof equal to 564 runoff events over 10 years

The calculation of the mean runoff coefficient for a green roof is not sufficiently precise information for the design purposes. The high variability of the C_R value over time requires determining what conditions should be assumed for sizing conduits and storage devices (drainage infrastructure). The performed simulations showed (fig. 6) that the maximum retention capacity h_R was available only for a short time of analyzed period (total 1830 days). It is characteristic that the greater retention capacity h_R, the number of days with maximum retention capacity is lower. For h_R=15mm, the maximum retention capacity lasted 412 days (22% of the modeled period), while for h_R=50mm it was only 240 days (13% of the modeled period). On the other hand, the water availability in substrate enhances the survival of the vegetative cover during the dry periods. No statistical significance has been shown between ADP and retention capacity. This is due to the imprecise and inconsistent definition of the ADP definition. For example if preceding rain event was not exceeded 1.0 mm this result in a small value of ADP, suggesting low availability of storage capacity, but in fact the substrate and drainage layer could still retain a significant volume of the following rainfall [24].

The second stage of the analysis was focused on the selected 36 rainfall events (depth higher than 20mm) and whole catchment (roof, parking lot, roads and sidewalks).

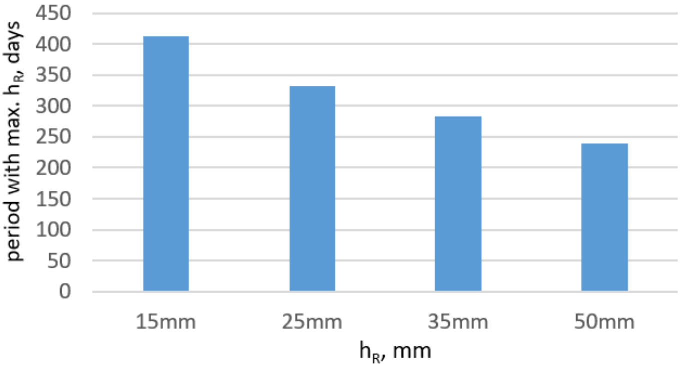

Fig. 6. Days with maximum retention capacity of green roof (hR) – simulations covered the period of 1830 days

In the scenario of direct discharge to drainage systems, the following reductions of runoff volume were achieved for green roofs in comparison to a conventional roof:

11.3% for $h_R = 15$mm (unit reduction: 52.6m^3 per 1mm h_R),
20.9% for $h_R = 25$mm (unit reduction: 58.2m^3 per 1mm h_R),
28.4% for $h_R = 35$mm (unit reduction: 56.4m^3 per 1mm h_R),
35.9% for $h_R = 50$mm (unit reduction: 50.0m^3 per 1mm h_R).

Considering the unit reduction defined as a reduced runoff volume to retention height h_R, the best results were obtained for h_R = 25mm. Even for the highest retention capacity (h_R=50mm), the results are far from a 50% reduction, since the green roof constitutes half of the catchment. Two factors are decisive: a) initial conditions – green roofs have maximum retention capacity only for part of analyzed events due to the condition during the antecedent period, b) two rainfall events have exceeded 50mm (54.1mm and 70.7mm). The statistics of initial retention capacity (h_{RI}) for the green roofs is summarized in table 4.

Table 4. Initial retention capacity for green roofs for 36 selected rainfall events

Retention capacity	$h_{RI}=h_R$	$h_R > h_{RI} > 0.5h_R$	$0.5h_R > h_{RI} > 0$	$h_{RI}=0$
h_R = 15 mm	14	8	6	8
h_R = 25 mm	13	10	9	4
h_R = 35 mm	12	11	11	2
h_R = 50 mm	9	17	9	1

Only for 60÷70%, intensive rainfall events green roof have the retention capacity higher than 50% of its maximum value.

The green roof peak rainfall rate reduction performance has historically received limited attention, especially compared to the volume retention performance. Thus, the next of the analyzed parameters was the reduction of the peak outflows (R_Q) from the catchment in comparison to a scenario with conventional roof, defined as:

$$R_Q = \frac{Q_T - Q_{GR}}{Q_T} \cdot 100\%$$

where: Q_T – max outflow rate in variant with conventional roof (l/s),
Q_{GR} – max outflow rate in variant with green roof (l/s)

Three ranges of R_Q were distinguished:

R_Q= 0% (no reduction of peak-flow)
$0 < R_Q < 50\%$ (partial reduction of peak-flow).
R_Q=50% (maximum peak flow reduction).

The results presented in table 5 show a significant influence of the retention capacity on the reduction of the maximum outflow-rates. The green roofs with $h_R \geq 35$mm effectively reduce peak flows in 80÷90% of the considered rainfall events, while for h_R = 15mm it was only 25%. The performance variations between the thin systems (h_R = 15mm) and deeper systems

(h_R = 35mm, 50mm) match the findings by *Fassman-Beck et al.* [25] that the demonstrated deeper substrates attenuated the peak runoff flow more effectively.

Table 5. Distribution of R_Q for 36 rainfall events, depending on the green roof retention capacity

Retention capacity	R_Q=50%	0 < R_Q < 50	R_Q =0%
h_R = 15 mm	9	11	16
h_R = 25 mm	11	21	4
h_R = 35 mm	29	5	2
h_R = 50 mm	32	3	1

The next stage of simulations included the operation of a storage tank as a regulator from the catchment for fixed unit outflow-rate q_0. Because the storage tank controls the peak flows, the application of a green roof does not affect peak flow attenuation. In this scenario, the analysis concerned the reduction of stormwater stored in a detention tank during 36 events for different roof types and possible reduction of the storage volume. The simulation results are summarized in table 6. Considering the relative values, the best efficiency was achieved for h_R = 50mm (55.8% to even 78.4%), but also for h_R = 25mm the reduction is meaningful (32.9% to 47.1%) in comparison to the scenario with a conventional roof.

Table 6. Volume of stormwater stored in a detention tank during 36 rainfall events for different values of reduced outflow (q_0 = 15, 30 and 50L/sha) and types of roofs

Roof type	V_{q15} (m^3)	Reduction (%)	V_{q30} (m^3)	Reduction (%)	V_{q50} (m^3)	Reduction (%)
Conventional roof	9201	-	5152	-	2605	-
GR h_R=15 mm	7422	19.3	3892	24.5	1789	31.3
GR h_R=25 mm	6178	32.9	3070	40.4	1378	47.1
GR h_R=35 mm	5295	42.5	2298	55.4	811	68.9
GR h_R=50 mm	4074	55.8	1750	66.1	563	78.4

Table 7. Estimated reduction (%) of the detention tank volume for different values of reduced outflow (q_0 = 15, 30 and 50L/sha) and types of roofs.

Retention capacity	q_0 = 15L/sha		q_0 = 30L/sha		q_0 = 50L/sha	
	V_T (m^3)	reduction %	V_T (m^3)	reduction %	V_T (m^3)	reduction %
h_R = 15mm	48	16.3	34	16.2	22	14.2
h_R = 25mm	82	27.9	56	26.7	33	21.3
h_R = 35mm	106	36.1	77	36.7	49	31.6
h_R = 50mm	140	47.6	92	43.8	55	35.5

Because the storage capacity of the tank is dependent on the q_0, the obtained volumes (V_q) were divided by number of rainfall events (36) and referred to the storage volume. The achieved values (V_T) can be treated as estimation of possible reduction of the storage volume if the green roof is applied. The obtained results confirm that a possible reduction of the storage volume may reach over 40%, but it requires a green roof of high retention capacity (h_R = 50mm). In the case of the green roofs with smaller retention capacity – h_R = 35mm, the reduction is below 30% while for h_R = 15mm, the reduction is not exceeded 17%. Bearing in mind that in the case the green roof area covers up to 10 000m^2, the cost of expanding the storage reservoir even by 70m^3 is definitely more beneficial from an economic point of view. However, it should be emphasized that the hydrological effects are not the only reasons behind the decision to implement a green roof and should be treated rather as extra benefits.

Conclusions

Urbanized areas are dominated by impervious surfaces, such as building' roofs, concrete sidewalks, paved parking lots and roads. Urban runoff is quickly transported via drainage systems to natural receiving waters bringing loads of dissolved pollutants, heavy metals, suspended solids, chlorides, oils and grease that arise from surfaces the water has passed over. Green roofs are one of the most effective measure in reduction of the runoff:

- between 40% and 80% of annual precipitation can be stored in substrate, drainage layer and absorbed by the plants,
- delay the time that runoff occurs, reducing the number and volume of overflows in combined sewer systems,
- reduce the velocity of direct runoff,
- reduce the pollution load contained in the stormwaters.

The paper presents presented the investigation on the green roof efficiency applied on a commercial area. A series of continuous simulations carried out for variable values of retention capacity of green roofs enabled to quantify the impact of green roofs on the drainage infrastructure. A general relationship between the average runoff coefficient and retention capacity of the green roof (h_R) is quasi-linear and starts from $C_R = 0.111$ ($h_R = 50$mm) to $C_R = 0.331$ ($h_R = 15$mm). The results of simulations showed a meaningful reduction of the runoff frequency by green roofs -– even for minimum retention capacity ($h_R = 15$mm) the runoff events were reduced by 76%, while for $h_R = 50$mm the reduction reached over 90%. During these intensive rainfalls, the green roof reduced the runoff volume by 11.3% for $h_R = 15$mm to 35.9% for $h_R = 50$mm. The shape of runoff hydrographs to specific rainfall events depend upon a complex set of processes and interactions involving the roof configuration (substrate type and depth, drainage layer vegetation), rainfall characteristics (intensity, duration, depth) and antecedent dry period duration, in particular the role of evapotranspiration in restoring the substrate's retention capacity.

In many countries buildings with green roofs are eligible for lower stormwater fees due to the fact that green roofs reduce the volume of stormwater discharged to the municipal drainage infrastructure. Properly selected vegetation cover and engineered substrate also act as a filter and help to neutralize acid rain, and trap dust and airborne particles.

The paper is focused on water management issues but green roofs can provide a variety of other benefits linked to: the reduction of urban heat island, energy efficiency of buildings, improving air quality, promotes biodiversity as well as aesthetic of an urban landscape.

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