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Runoff and Water Quality in the Aspect of Environmental Impact Assessment of Experimental Area of Green Roofs in Lower Silesia

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Abstract: Green architecture, including green roofs, can limit the effects of urbanization. Green roofs soften the thermal effect in urban conditions, especially considering the significant increase in the European and global population and that a significant share of the age group, mainly the elderly is exposed to diseases caused by high temperatures. We studied runoff and the quality of water from green roof systems in Lower Silesia, within the area of the Agro and Hydrometeorology Station Wrocław-Swojec, in the years 2012–2016. In the study, two systems with a vegetation layer based on light expanded clay aggregate and perlite were analyzed. The studies were based on the assessment of peak flow reduction, rainwater volume preservation and peak wave reduction. The calculated maximum retention performance indicator, relative to rainfall, for perlite surfaces was up to 65%, and in relation to the control surface up to 49%. In addition, the quality of water from runoff was estimated in the conditions of annual atmospheric deposition, taking into account such indicators as electrolytic conductivity; the content of N, NO_3, NO_2, NH_4, P, PO_4; and the content of metals, Cu, Zn, Pb and Cd. The load of total nitrogen exceeded the values of concentration in rainwater and amounted to 7.17 and 13.01 mg·L^{-1} for leca and perlite, respectively. In the case of the metal content, significantly higher concentrations of copper and zinc from green surfaces were observed in relation to precipitation. For surfaces with perlite, these were 320 mg·L^{-1} and 241 mg·L^{-1}, respectively, with rainwater concentrations of 50 and 31 mg·L^{-1}.

Keywords: green roofs; integrated environmental assessment; quality of runoff water; performance system

1. Introduction

The increasing population and overall consumption, urban development, and the simultaneous change in the climate and extreme weather events due to the intensive planning of city development comprise the integrated society and environment rating. The growing amount of people aged 65 and over in Europe and especially in Poland represent a significant part of society that is vulnerable to high temperature diseases [1]. The urban heat island effect is the main reason behind a change in the quality of life for people living in cities areas [2–4]. This effect causes urban areas temperatures to be much higher than surrounding rural areas [5]. Another important aspect is the changing natural hydrologic systems and the impact on water quality, which is drained into the environment [6–9]. By 2050, almost 70% of the global population will live in cities [10]. Since the population is continuously growing, any problems currently facing cities will affect a staggeringly larger proportion of people over time.

Thus, finding solutions to problems like heat waves will be an integral part of future city living. One of the desired methods of reducing the effects of urbanization is green architecture, including green roofs.

Green roofs mitigate the effects that traditional building materials have on urban environments by decreasing air temperatures [11,12] and costly energy consumption [13,14]. Green roofs produce a cooling effect on roof surfaces and air temperatures through the process of evapotranspiration, the transfer of water from the soil and vegetation to the air. This endothermic process consumes heat energy, so the warmer the air is, the more evapotranspiration takes place [12].

Compact buildings will cause changes in water circulation compared to undeveloped areas. There are a variety of practices used in the management of rainwaters, but it appears that the unique properties of green roofs in terms of the reduction of runoff volume [15–19] and its quality [20–22] are of special importance in the approach to the growing urbanization. Similarly important is the reduction of noise and air pollution [23,24], the reduction of oxygen dioxide levels [25], the aesthetics of landscape, biodiversity [26,27], and improvements to the technical conditions and service life of structures [28].

At both the design and operation stages, such systems may require optimization in the aspect of hydrological features and water properties of the substrates used. For that purpose, one can use existing software allowing the analysis of the flow of water and dissolved substances in the partially unsaturated and saturated biological layer of the soil substrate [29]. The present authors analyzed the performance of the experimental roof systems during storm events in 2016. The analyses were carried out for two variants of models of green roof systems.

There are two main goals of our work. The first is the study of the hydrological performance of experimental models of green roofs based on the expanded clay and perlite of the extensive type. Inn Characteristic studies were based on the assessment of peak flow reduction, rainwater volume preservation and peak wave reduction. Hydrological conditions were simulated for the discussed model solutions. The prepared model was calibrated on the basis of experimental data, which allowed for the estimation of hydrological efficiency for the analyzed substrates. A literature review indicated promising results, with the assumption that the flow through the substrate has a unidimensional character [30–34]. The second goal was to study the impact of the areas in question on the quality of rainwater from runoff. The characteristics of nitrogen, phosphorus and some metals subject to runoff were assessed. The results were analyzed for rainfall and control area.

2. Research Methodology

2.1. Models of Green Roofs

The scope of the experiment comprised two models of extensive type green roofs with differing composition of the vegetation layer, including components improving the retention properties of the substrates. The functionality of the systems was estimated in the local climate conditions of the city of Warsaw (Wrocław; 51st 11′ N, 17st 14′ E), Poland, with a particular focus on the retention performance, which is reflected in the reliability of the system and in the runoff water quality. Based on the designed steel support structure, experimental models were built with dimensions of 1000 × 2000 mm at a height of 1 m above the surface. That height is also the reference level for meteorological station and disdrometer.

The experimental green roofs (Figure 1) with thickness of 8 cm, was composed of a geotextile layer and a gravel drainage layer with a particle size fraction of 1–2 cm and water proofing membrane for the hydroinsulation of the roof. In this case, RMS 300 Optigrün International AG production geotextile was used, allowing the retention of up to 2 L·m^{-2} of water, and additionally a water proofing membrane. To provide thermal insulation for the models, extruded polystyrene (XPS) was applied in the horizontal and vertical part of the construction, with a 5 cm layer thickness. In both cases, the vegetation layer was prepared on the base of horticultural soil, the share of which was 60% v/v. The substrate was based on an expanded clay aggregate contained sand with fine and medium fraction (20% v/v) and an expanded clay aggregate with small and medium fraction of 4–8 mm (20% v/v). In the case of the substrate based on perlite, it contained 20% v/v of sand, as in the previous case; 5% v/v of expanded clay aggregate; and 15% v/v of perlite. It was characterized by suitable properties, in particular a stable structure preventing settlement, and a proper hydraulic capacity.

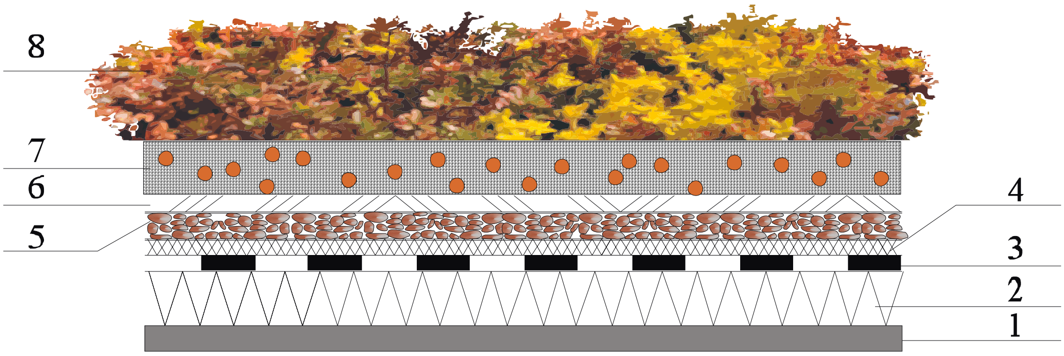

Figure 1. The construction details of green roof extensive models: substrate with expanded clay aggregate and substrate with perlite. 1—model support construction; 2—thermal insulation, extruded polystyrene (XPS); 3—insulation water proofing membrane; 4—geotextile, type RMS 300; 5—gravel layer with granulation from 1 to 2 cm; 6—filtration geotextile; 7—substrate of light expanded clay aggregate or perlite (depth substrate together with filtration geotextile and gravel layer, 80mm); 8—plants of the sedum species *(Sedum spurium, Sedum sexangulare, Sedum telephium, Sedum floriferum,* and *Sedum album).*

The substrate used as the vegetation layer was prepared using horticultural soil with a pH close to neutral (pH 6.7), sand fraction, and the specified admixtures improving the retention properties. The performed particle size analysis revealed that the substrate was a sandy loam, the properties are presented in Table 1.

Table 1. Properties of the substrates composed of leca and perlite.

Parameter	Unit	GR1 (Leca)	GR2 (Perlite)
Bulk density	g·cm^{-3}	0.40	0.27
Specific density	g·cm^{-3}	1.81	1.85
Water capacity *			
pF 0	mm	37.0	39.0
pF 2.0		16.5	19.8
pF 2.9		13.5	17.0
pF 4.2		3.0	4.4

* Water content was calculated for 50 mm substrate thickness.

The calculated water leachability for the vegetation layer was 22.5 mm in the case of expanded clay aggregate and 32.6 mm in the case of perlite, and the values of the leachability coefficient amounted to 40.9% and 38.4%, respectively. Air permeability, calculated as the ratio of leachability and absolute porosity, was 55.3 and 49.2%.

In the design of the vegetation layer, species of stonecrops (*Sedum*) from the family *Crassulaceae* were used: *spurium, telephium, floriferum* and *sexangulare*. The choice of *Sedum* species was dependent on extensive models, and by the plant care method, especially for the maintenance-free roof without any possibility of irrigation [35].

The measurement period began on 1 April and ended on 31 October 2016. During that time, all events with atmospheric precipitation were recorded. During the entire cycle, measurements of moisture and runoff from the analyzed surfaces were made in real time. In the case of moisture, measurements were taken using a multi-channel sensor TDR (Time Domain Reflectometry, E-TEST, Poland, Lublin) with data recorded at 1 min intervals. The range of accuracy of the sensors was ±0.02 $cm^3 \cdot cm^{-3}$ (water). The measurements of runoff was implemented with the use of a system based on a set of tilt troughs and recoding of impulses using data loggers Hobo UX120 (model: Hobo UX120–006M, Onset Computer Corporation, Bourne, USA). One measurement impulse was equal to a runoff of 0.01 $mm \cdot min^{-1}$. The laser disdrometer (Precipitation Monitor: 5.4110.10 and LNM View software) allowed the continuous measurement of rainfall (0.005 $mm \cdot h^{-1}$ minimum intensity and 0.16 mm minimum droplet size).

The retention properties of the model surfaces were designated by the retention indicator calculated in relation to rainfall or to the control surface (RPI_{ratio}):

$$RPI_{ratio} = 1 - \frac{\sum runoff\ GR}{\sum P} 100\% \tag{1}$$

where: runoff GR is runoff green roof area, and P is precipitation. Using Equation (1) the runoff from the green surfaces and the precipitation were determined.

2.2. Runoff Water Quality Monitoring

The quality analysis was carried out on the basis of water samples coming from runoff from model surfaces, control surfaces and precipitation. Out of all recorded events, eight enabled us to obtain a quantity allowing for determination. Rainwater for analysis was collected using adapted apparatus for measuring real-time runoff from the surface. So, the times of the beginning of the event and the times of starting the runoff and their end were known. The time between obtaining samples for analysis and their direct determination was short and met the criteria for their preparation for determination. The analyses of all indicators were carried out at the Faculty Laboratory for Environmental Research of Wrocław University of Environmental and Life Sciences. In the determination of the pollution indicators, the methods used followed the standards PN-EN 26777:1999, PN-82C-04576/08, PN-ISO 7150:2002; for phosphates, the method followed the PN-EN 1189-2000; for concentrations of metals, with the method of atomic absorption spectrometry AAS.

For the independent samples, statistical tests were conducted with the use of the t-test, and comparison was made of the quality indicators in runoff water and in rainwater. Two hypotheses were proposed: the zero hypothesis H_0: the quality indicators from the green surfaces were the same as in the precipitation and control area; and the second hypothesis H_1: the mean values of water quality indicators for the green surfaces differ from those in rainwater and in water from the control surface. The adopted level of significance was 5%. Conclusions concerning the equality of the mean values were preceded with Levene tests.

2.3. Runoff Modelling

The simulation for the experimental models was conducted with the use of the program, based on Richards' Equation (2), assuming one-dimensional flow direction, for the variant single porosity model. The standard van Genuchten hydraulic model was adopted in the solution. The hysteresis effect was not included, the variant without hysteresis gives the expected results [30].

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta) \cdot \left(\frac{\partial h}{\partial z} - 1\right)\right] - S \tag{2}$$

where θ is the volumetric content of water [$L^3 \cdot L^{-3}$], z is the spatial coordinate [L], t is the time [T], K is the unsaturated hydraulic conductivity [$L \cdot T^{-1}$], and S is the unit uptake of water by the plants [$L^3 \cdot L^{-3} \cdot T^{-1}$]. The effect of temperature gradients on the flow in a porous medium was neglected. For the description of the hydraulic properties of the soil the van Genuchten–Mualem Equation (3) was used, in the form [36–38]:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{3}$$

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

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

where θ_r is the residual moisture $[L^3 \cdot L^{-3}]$; θ_s is the saturated moisture $[L^3 \cdot L^{-3}]$; S_e is the effective saturation *(5)*; α is the constant $[L^{-1}]$; n, $m = 1 - 1 \cdot n^{-1}$ is the form parameter; K_s is hydraulic conductivity $[L \cdot T^{-1}]$.

The modeled vertical profiles with a drainage and vegetation layer were discretized with the use of 77 elements.

Solving Equations (3) and (4) requires the estimation of parameters θ_r, θ_s, α, n and K_s [36], the values of which on the depend type of substrate. The parameters are shown in Table 2. The values of the parameters were determined in laboratory conditions (K_s, θ_s), or adopted and calculated (θ_r, α, n) [39]. K_s was measured in several replicates in laboratory conditions. The boundary conditions at the boundary of the soil and the atmosphere can change from an unsaturated value to full soil saturation, and depend on hydrological processes (infiltration and evapotranspiration, and atmospheric precipitation), and, consequently, on the moisture and the soil substrate [30]. The initial water content before the occurrence of subsequent events was determined by means of the time domain reflectometry technique (TDR). The measurement interval was 30 seconds. The vegetation cover factor of the experimental models was included. The model's performance was evaluated statistically based on the Nash–Sutcliffe (NSE) Equation (6), and the performance and mean square error RMSE (7). The range of this statistic can be within ($-\infty$, ∞). The calculated Nash–Sutcliffe performance could be from $-\infty$ to 1. NSE = 1 corresponds to a perfect match, when NSE = 0 model the predictions were as accurate as the average observed.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{t=te}\left[q_{mea}(t) - q_{sim}(t)\right]^2}{\sum_{t=1}^{t=te} 1}} \tag{6}$$

$$NSE = 1 - \frac{\sum_{t=1}^{t=te}\left(q_{mea}(t) - q_{sim}(t)\right)^2}{\sum_{t=1}^{t=te}\left(q_{mea}(t) - q_{amea}\right)^2} \tag{7}$$

where q_{mea} is the measured flowrate, q_{sim} is the simulated flowrate, q_{amea} is the average measured flowrate, and t_e is the end of the run off measure.

Table 2. Parameters for the green roof model.

Model	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (m m^{-1})	n (–)	K_s (mm min^{-1})
Substrate with leca GR1	0.015	0.731	0.1627	1.1298	15.95
Substrate with perliteGR2	0.001	0.787	0.0092	1.0137	0.610

Using the described and validated model, runoff simulations were conducted. The model was calibrated for measured and theoretical runoffs were analyzed for 13 June 2016.

3. Results and Discussion

The model study in the conditions of the differentiated vegetation layer in relation to the control surface was conducted in the years 2012–2016. Detailed studies conducted in 2016 showed that 27 out of 37 events caused runoff. Twelve events generated runoff with intensity below 0.1mm·min^{-1}, and two above 1mm·min^{-1}. Eight selected events from the entire observation period generated runoff, the size of which enabled the determination of indicators. In each case, runoff was initiated by rainfall larger than 10 mm. The stoppage of the runoff and its delay varied and depended not only on the type of surface, but also on the substrate moisture content and rainfall intensity. For all events (Table 3) the runoff was initiated each time, but the runoff delay and hold varied. This depended mainly on the initial humidity of the ground and the intensity of the rain. Each green roof model reduced the mean peak discharge indicator. For example, on day 5.10, rainfall with a total of 26.4 mm and an intensity of 0.11 mm·min^{-1} was retained for models based on expanded clay and perlite in the amounts of 63 and 70.1%, respectively. In another case (5.09) at a significant intensity of 1.31 mm·min^{-1}, but with a smaller sum precipitation of 13.9 mm, the holding amounts was 28.9 and 50.7%, respectively.

Table 3. Rainfall and runoff characteristics of the studied events in experimental object.

Rainfall Event	Rain Depth (mm)	Peak of Rain Intensity (mm·min^{-1})	Rain Duration (min)	Retained Volume (%)		Flow Peak (mm·min^{-1})		Peak Reduction (%)		Moisture (Initial) (% v/v)	
				Leca	Perlite	Leca	Perlite	Leca	Perlite	Leca	Perlite
13.06	22.6	1.47	367	31.4	64.9	1.41	1.22	26.1	38.9	15.7	16.6
17.06	12.2	1.1	381	311	55.1	0.92	0.87	33.6	39	20.3	23.1
31.07	10.1	0.8	1249	55.8	63.4	0.57	0.53	40.5	47.7	19.1	21.3
21.08	21.2	0.4	466	43.2	68.3	0.29	0.26	44	62.7	17	19.1
5.09	13.9	1.31	458	28.9	50.7	1.19	1.12	29.1	38.9	19.9	22.8
17.09	20.7	0.22	686	54.3	62.2	0.18	0.16	42.4	49.8	22.3	23.6
3.1	29.8	0.26	1433	62.1	74	0.21	0.19	52.2	60	23.6	24.9
5.1	26.4	0.11	1640	63	70.1	0.09	0.08	51	59.1	25.3	27.1

The analyzed surfaces delayed the start of the runoff. The calculated retention performance indicator amounted to 9 and 11 min, respectively (Figure 2).

For the event of the 13.06 used to calibrate the model, the mean square error (RMSE), (6) was 0.16 mm·min^{-1} (GR1, leca) and 0.12 (GR2, perlite), while the calculated statistics describing the relative value of residual variance, the Nash–Sutcliffe efficiency (NSE) (7)), and the assumed values at the level 0.74 (GR1) and 0.84 (GR2). A simulation can be accepted as satisfactory when NSE >0.5 (a higher model accuracy for NSE values close to 1). The calculated NSE and RMSE values for validation are presented in the Table 4. During validation, the models designed as leca- and perlite-based displayed a good representation of flow volume intensity, accurately simulating events observed in other periods. It can, therefore, be concluded that in both cases the level of matching achieved was close to good.

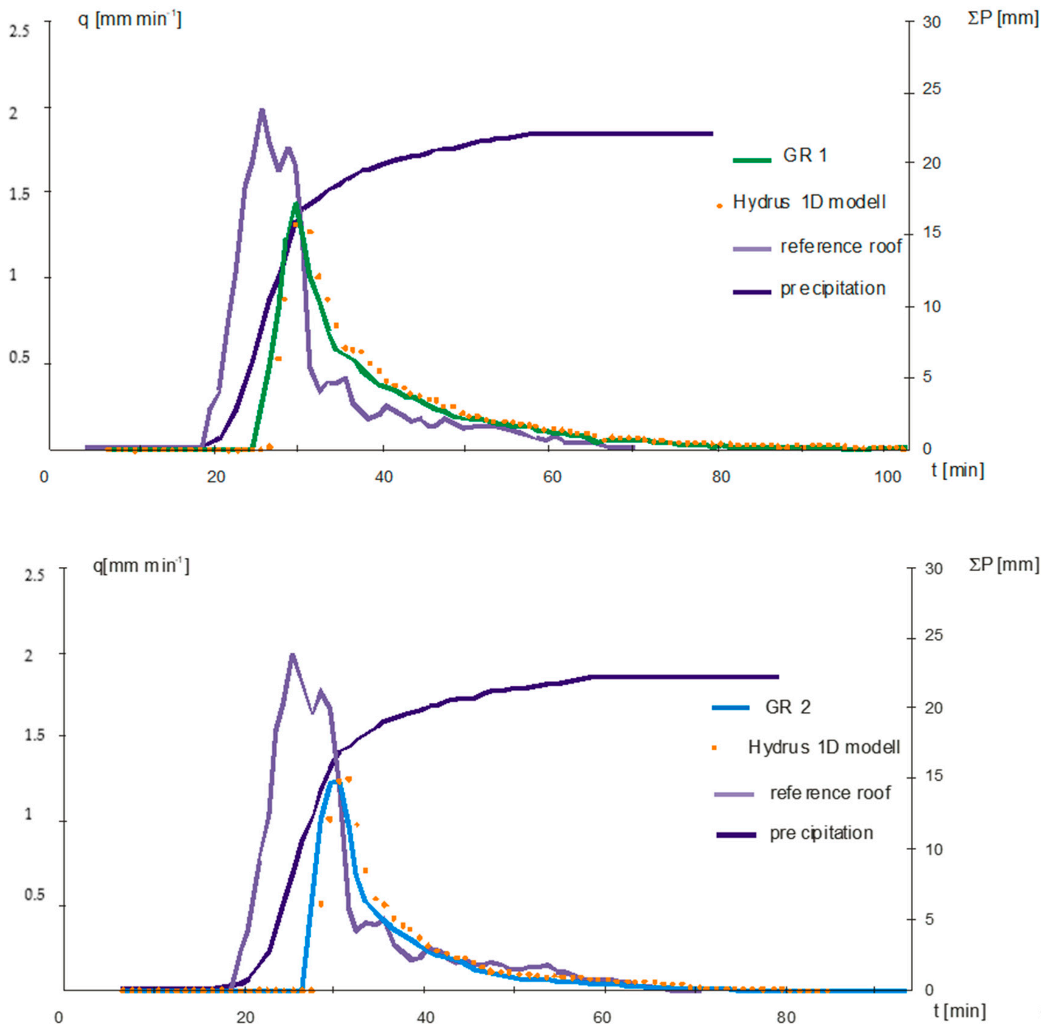

Figure 2. The intensity of runoff and accumulated precipitation for the surface GR1 and GR2 and the control surface in June 2016.

Table 4. Standard measures of model evaluation.

Date of the Event	**Rain Intensity mm min^{-1}**	**Substrate of Leca NSE (–)**	**RMSE (%)**	**Substrate of Perlite NSE (–)**	**RMSE (%)**
		Calibration data			
13.06	1.47	0.74	0.16	0.84	0.12
		Validation data			
17.06	1.1	0.75	0.15	0.83	0.12
20.06	0.2	0.65	0.028	0.69	0.023
31.07	0.8	0.79	0.07	0.82	0.05
9.08	0.05	0.57	0.009	0.63	0.008
		Other events			
21.08	0.4	0.75	0.085	0.8	0.061
5.09	1.31	0.78	0.069	0.85	0.063
17.09	0.22	0.64	0.058	0.7	0.055
3.1	0.26	0.66	0.061	0.71	0.059
5.1	0.11	0.58	0.048	0.61	0.043

The water content and time and depth illustrate the conditions of infiltration in the green roof systems (Figure 3). In the conditions of high saturation of the designed profiles, one can note that in the model based on expanded clay extrudate (GR1) the state of moisture close to porosity was attained in minute 45. In the case of surface GR2 a significant level of saturation was observed already in minute 20. In this case, this may indicate an improvement of the retention capacity of the profile and of the hydrological properties of the systems as a result of the application of the admixture of perlite in the substrate.

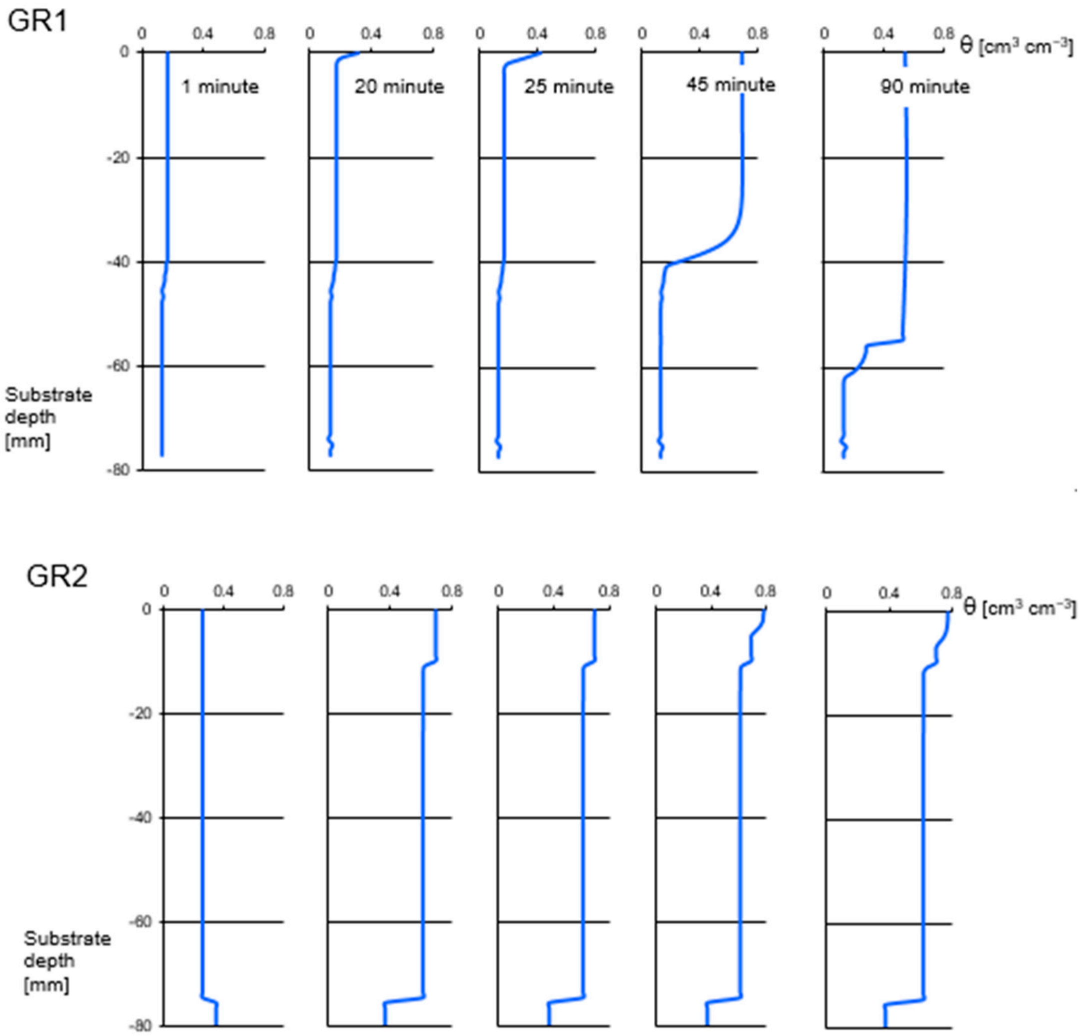

Figure 3. Water content profiles in models with leca (GR1) and perlite (GR2) at different time steps for 13 June 2016.

Studies of green roofs, reflected in their reliability in the context of retention capacity, have been conducted by other authors. Pala et al. [32] monitored the green roof of the University of Genova. They confirmed that it can significantly mitigate the generation of runoff, with the median values of retained volume and peak reduction equal to 94 and 98.7%, respectively. The authors applied a conceptual linear reservoir and a Hydrus-1D models to simulate the hydrologic behavior of the system. The simulations with both models reproduce acceptable matching capabilities the experimental measurements, as confirmed by the Nash–Sutcliffe efficiency index that was generally greater than 0.60 [32]. Wong [40] conducted a study in the region of Hong Kong, a humid and tropical climate. Thin layer (40 mm) solutions of green roofs ensured a reduction of runoff intensity at the expected level. Despite the small thickness of the layers, controlled runoff was achieved, and the retention capacity and thus good performance were obtained in a relatively short time. The methods of modelling with the use of the program Hydrus applied by Feitosa and Wilkinson [41] showed that the effectiveness of the analyzed systems, reflected in their reliability, decreased with increasing intensity and duration of rainfall. Locatelli et al., on the basis of the analyses of statistical data from three locations, concluded that in the case of a single event the peak discharge and the reduction of runoff volume decreased with the extension of the period of event recurrence [42]. Data concerning the quality of runoff water in the Swojec object were based on eight rainfall episodes. The increase in total nitrogen concentration was recorded in the samples. The data were compared with the use of t-tests, assuming a 5% level of significance. Two hypotheses were adopted: the zero hypothesis H_0: the quality indicators from the green surfaces were the same as in precipitation and control area; and the second hypothesis H_1: the mean values of the water quality indicators were different in relation to rainwater and water from the control surface.

For each of events, samples were collected from the model green roofs, from the control surface, and from atmospheric precipitation. The Analyzed indicators were total nitrogen (TN), NO_2, NO_3, NH_4,T-P, PO_4, Cu, Zn, Pb, Cd and electrolytic conductivity. Contrary to the adopted hypothesis, there was no distinct improvement of water quality in the runoff from the experimental surfaces. An increase in the level of concentration of nutrients was noted in runoff from the same surfaces. Table 5 presents the results of the water quality and mean values of the determined indicators. The load of total nitrogen in the runoff from the green roofs exceeded the concentration in rainwater and amounted to 7.17 and 13.01 mg·L^{-1}. Distinctly higher levels of concentration of total nitrogen for the substrate with perlite could have been a result of the composition of the substrate. It should be emphasized that a variation of the loads of that indicator was observed among all of the analyzed rainfall events, in particular for surface GR2, as seen Figure 4. In order to illustrate the observed variability of the pollutant load in relation to rainfall and control surface, frame charts were prepared. The lower and upper boundary of each box indicate respectively the 25th and 75th percentiles. Whiskers above and below each box indicate the 90th and 10th percentiles. For the NO_3 and NO_2 indicators, no significant differences were observed compared to rainwater. The recorded values of NO_2 were at trace.

Table 5. Summary of average indicators for green roof runoff, control site runoff and precipitation from the green roof experimental models in Wroclaw-Swojec.

Pollution Indicators	Green Roof Substrate in Leca	Green Roof Substrate in Perlite	Control Site	Precipitation
N mg·L^{-1}	7.17	13.01	5.52	5.23
NO_3–N mg·L^{-1}	1.96	3.93	1.72	1.68
NO_2–N mg·L^{-1}	0.01	0.01	0.059	0.065
NH_4–N mg·L^{-1}	0.15	0.10	0.128	0.187
P (total) mg·L^{-1}	0.25	0.26	0.207	0.246
PO_4–P mg·L^{-1}	0.15	0.12	0.106	0.121
Pb (total) mg·L^{-1}	113.8	61.5	110.2	103.6
Zn (total) mg·L^{-1}	237.6	241.4	32.1	31.1
Cd (total) mg·L^{-1}	2.3	1.2	1.3	1.3
Cu (total) mg·L^{-1}	220.8	320.2	54.1	50.2

The content of ammonium nitrogen NH_4 was relatively stable, both in relation to the experimental surfaces and to the rainwater (maximum 0.53 mg·L^{-1}). For the analyzed cases, the type of media did not affect the value of the indicator.

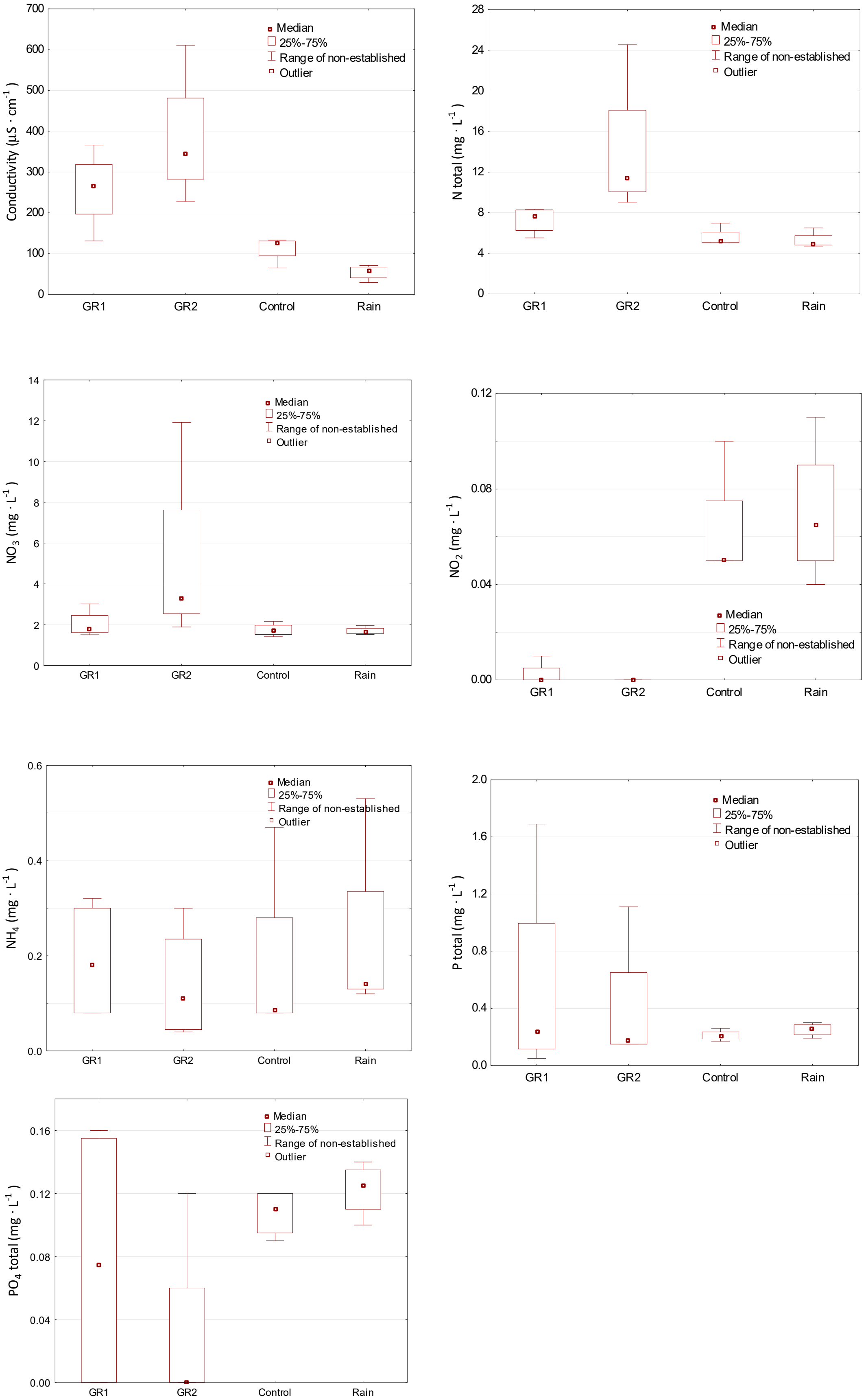

Figure 4. The range and average values for nutrients and conductivity in extensive roof experimental models in Swojec object.

The concentrations of PO_4 in the runoff from the analyzed surfaces, and in rainwater, were relatively uniform, but in the case of runoff from surface GR2 the concentrations were the lowest. Phosphorus compounds in the alkaline soil environment can be bound by calcium and manganese. This may indicate considerable concentrations discharged in the course of the vegetation season and during the winter period. The maximum concentrations of biogens can be observed after at least a dozen days from fertilization [43].

In a study concerned with the chemical composition of rainwaters, MacAvoy et al. [21] determined for 9 rainfall events higher concentrations of NO_3 and NH_4 in runoff from green roofs relative to that from a control surface. In that study it was also found that over the entire cycle of a 16-month experiment the load of nitrates was reduced by up to 32%. An experimental study conducted by Harper [44] showed that a considerable load of phosphates and nitrates was carried away in runoff in the initial period of operation of a green roof system. As a result of a nine-month operation, the load of phosphates was reduced by 5 mg·L^{-1} and that of nitrates by 10 mg·L^{-1}. In studies on organic carbon by Yang and Lusk, Mitchell et al. [45], Carpenter, Kuoppamaiki, and Beecham [6,46,47] a decrease of concentrations was observed in the range from 500 to 50 mg·L^{-1}.

In the analyzed runoff waters from the experimental surfaces, electrolytic conductivity assumed higher values in relation to runoff from the control surface and rainwater (Figure 4). Studies by other authors supported the results obtained in the experiment at Swojec. For example, Vijayaraghavan and Joshi studied the outflows from four different green roof systems and found that a better quality of runoff water was generated at a lower conductivity, relative to atmospheric precipitations [48].

The analysis of the content of metals in runoff from the green surfaces revealed several times higher concentrations of copper and zinc in comparison to those determined in rainwater. It can be assumed that in this case, the structural materials of the model (galvanized steel, zinc) or components of the substrate were a source of contamination with those elements (Table 4, Figure 5).

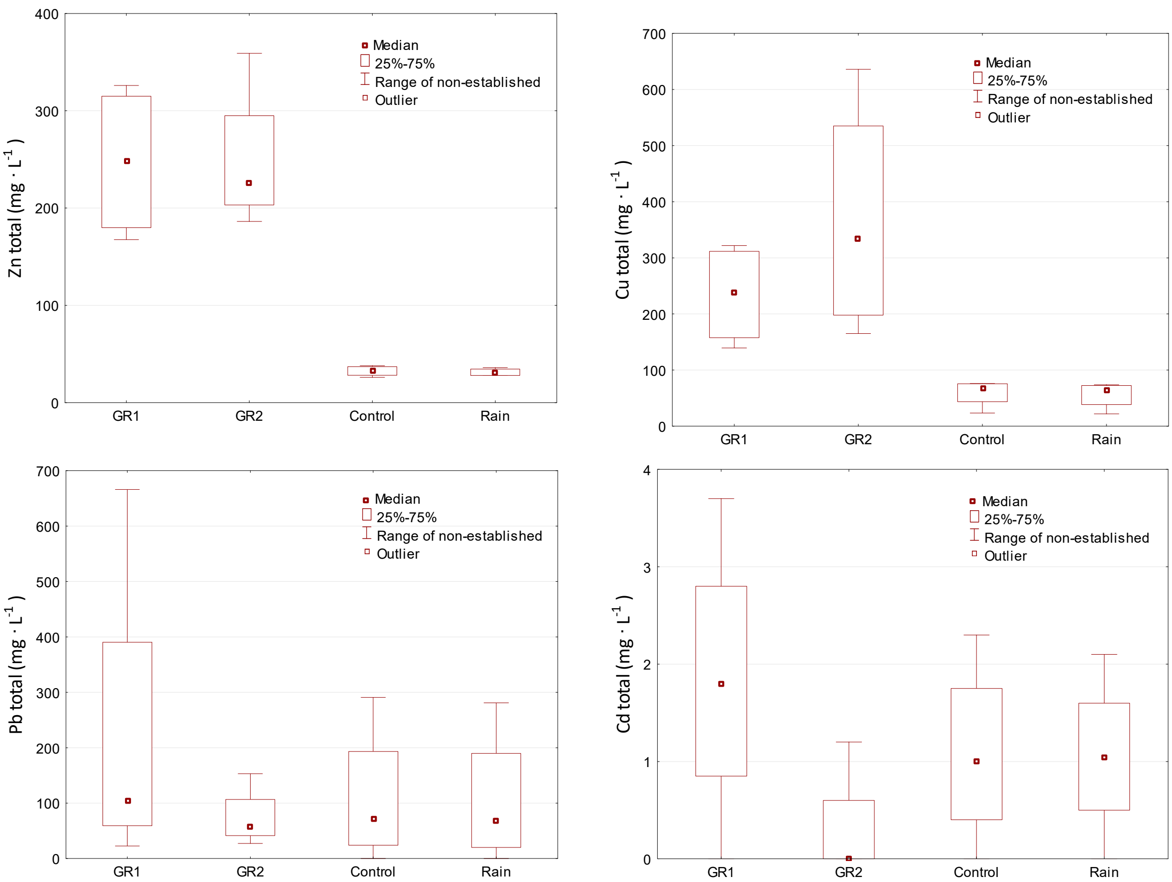

Figure 5. Range and average values for metals in extensive roof models in Swojec object.

On average, the outflow was about 30 mg·l^{-1}, Gnecco et al. [49]. A study conducted by Vijayaraghavan and Raja [50], based on artificial green roof profiles with the use of biomass demonstrated a high degree of reduction of the concentration of metals in relation to rainwater. The achieved efficiency of the removal of metals reached the level of 92%. The literature indicates that at the stage of design it is necessary to conduct an analysis of the materials used in the process of preparation of substrates. The main objective of such analysis is to identify their effects as a source of contaminants. A study conducted by Schwager et al. [51] on the leaching of certain metals and their sorption in selected substrates, and especially copper and zinc, indicated a high variation in their liberation, depending on the material. The time of equilibrium of those metals was high and amounted to 3 days

4. Conclusions

Green architecture, including green roofs, mitigate the effects of traditional building materials on urban environments. This property is directly relevant to the quality of life of society. Therefore, research into the properties of green architecture is important. A six-month study period in 2016 was analyzed. The analyses of the quality of runoff from those systems were conducted, taking into account certain pollution indicators and metals. In the study of the hydrological performance of the systems, a unidimensional model of infiltration was applied for the analysis of the hydraulic parameters. The model enabled the identification of parameters related with the infiltration that are usually determined with experimental methods. The calculated statistics for the measured and simulated values for the surfaces with expanded clay aggregates and with perlite indicated a good fit and enabled the accurate simulation of events observed in the remaining periods. The mean concentrations of nitrogen and phosphorus were higher than those determined in rainwater. The load of total nitrogen exceeded the values of concentration in rainwater and amounted to 7.17 and 13.01 mg·L^{-1} for leca and perlite, respectively. Therefore, at the level of 0.05, statistically significant differences were noted in relation to specific concentrations in rainwater and runoff from the control surface. Electrolytic conductivity assumed decidedly higher values, compared with runoff from the reference surface and atmospheric precipitation.

Excessive levels of concentration of metals, especially zinc and copper, were observed in the runoff from the green surfaces in relation both to the precipitation and to runoff from the control panel. The proper level of system performance with regard to runoff quality can be determined on the basis of longer observations. The calculated maximum retention performance indicator for the experimental green surfaces, relative to rainfall, was up to 65%, and in relation to the control surface was up to 49% (substrate with perlite). The peak discharge performance indicator was reduced by 26% in the case of leca and by 38% in the case of perlite.

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