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VERSITA

ANALYSIS OF STORMWATER RETENTION ON GREEN ROOFS

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Abstract: This study presents the results of tests conducted in 2009 and 2010 on experimental sites installed on the roof of the Science and Education Building of the Wroclaw University of Environmental and Life Sciences. The aim of the analysis was to determine the retention capacity of green roofs and the runoff delays and peak runoff reduction during rainfall recorded in Wroclaw conditions.

The research shows that green roofs allow to reduce the volume of runoff stormwater in comparison to conventional roofs, that they delay the runoff in time and influence the reduction of the maximum runoff intensity, and thus may limit the impact of stormwater on the stormwater drainage and combined sewage systems.

INTRODUCTION

In urban areas, stormwater is in most cases discharged through conventional sewage systems which, having received the runoff, transport it to the receiver, which results in a sudden, single discharge of a large volume of water. The reduction of the load imposed on the receiver is enabled by using modern stormwater management facilities called Sustainable Urban Drainage Systems (SUDS). Green roofs are one of the types of such systems. Their functioning is often compared to that of detention reservoirs. During rainfall, some of the water is discharged to the atmosphere in the process of transpiration from the part of the roof covered by plants. Excess rainfall is discharged from the multi-layered structure of green roofs later than it happens in the case of conventional roofs, and at a lower runoff volume. The retention capacity and the influence of rainfall runoff from the roof on the hydrograph depends on the meteorological conditions, the arrangement and type of construction layers in green roofs and on the type of plants growing on the top, organic layer of the green roof.

Studies on the retention capabilities of green roofs have been conducted throughout the world, i.e. in the United States [11−13], Germany [4−5], Sweden [1−2, 15], as well as in Italy [3, 9]. Various objects are being tested, starting from the use of specially constructed experimental sites, to existing structures constructed at a technological scale. The obtained results differ due to the differences in meteorological conditions specific for various countries and regions. Studies conducted by Lisecke [7] and Köhler and Schmidt [5] have shown that in Hamburg, where the total annual precipitation reaches 820 mm, an installed extensive green roof can retain approximately 60% of stormwater, whereas in Berlin, with a total annual precipitation reaching 500 mm an object identical to that installed in Hamburg was capable of retaining 75% of stormwater. Data presented in the literature shows that in Italy these values are much higher, due to different climate conditions [9, 10]. Although numerous experiments have been conducted abroad, there are still not enough systematic studies on the application of green roofs in Polish conditions. Only a few reports on this subject can be found, among others, in the publications of Mrowiec, Szajda *et al.* [8, 14].

CHARACTERISTIC OF THE RESEARCH AREA AND METHODOLOGY

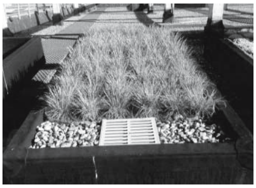
The studies on the retention capability of green roofs started in 2009 at the Wroclaw University of Environmental and Life Sciences. Experimental sites in the form of 5 dishes of the external dimensions 2.40/1.20/0.35 (length/width/height) inclined at an angleof 7.7% and of an internal volume capacity of 0.6 m^3 were installed on the roof of the Science and Education Centre of the Wroclaw University of Environmental and Life Sciences, located in the city centre, near to a high traffic road. Four of the dishes were equipped with models of extensive green roofs (marked in this study as DZ-2 − DZ-4), and one of the dishes was used as a reference object, hereinafter referred to as a conventional, impermeable roof (DR-1). The arrangement of individual structural layers embedded in the models of green roofs is presented in Table 1.In order to provide free discharge, each of the test plots containing extensive green roofs was equipped with drainage, consisting of a DALLBIT 62H inlet of a diameter of 75 mm, a drain hole and a gravel layer band of the following dimensions: width 0.25 m × length 0.7 m, measured along the narrow edge. The rainfall and runoff from test plots is being continuously, automatically recorded in time intervals of 30 seconds. Runoff is captured by Naja 0404 meters that measure the weight of the runoff. The meters are connected to a Memory Hilogger 8430-20 data logger, manufactured by HIOKI. Rain depth and intensity is monitored using a Parsivel laser precipitation sensor manufactured by the German company OTT MESSTECHNIK GmbH&Co.KG [6].

This study presents the results of measurements recorded during the period from July to October, 2009 and 2010 on three of the four green roof models and on the reference impermeable roof. Basing on the measured rainfall and runoff on the test plots, the retention, stormwater runoff delay and the peak runoff reduction were determined in relation to the maximum intensity of the given rain event.

RESULTS AND DISCUSSION

During the analysed test period from July to October 2009 and 2010,117 days were dry, whereas rainfall occurred on 129 remaining days, of which 112 were the subject of analysis. The daily rain depth ranged from 0.01 to 51.19 mm. The most rainy days occurred in October 2009 (77.4% of all), whereas the same month in the subsequent year, i.e. October 2010 was characterised by the lowest number of rainy days recorded (16.1%). In the remaining months (July–September 2009 and 2010) rainfall occurred on

Table 1. Comparison of structural layers of specific green roof models

			
Marking	DZ-2	DZ-3	DZ-4
Plants	Sheep Fescue var. *Sina/Festuca ovina ‘Glauca’*	*Sedum acre ‘Golden Queen’*	*Sempervivum x hybridum ‘Othello’*
Growing medium	Substrate: Optigrün type E -0.15 m^3/m^2	Substrate type PERL KÖRNUNG 2/10 mm, drainage characteristics – 0.15 m^3/m^2	Substrate: Optigrün type M – 0.15 m^3/m^2
Filter fabric	Filtration geotextile type 105		Filtration geotextile type 105
Drainage elements	Plastic profiled drainage elements type FKD 12		Layer of gravel of a granulation of 2–5 cm – 0.05 m^3/m^2 of roof
Protective layer	Absorptive/protective geotextile RMS 500		

nearly half of the days. In both years the largest group of rain events consisted of rainfall of a total daily depth below 2 mm, whereas heavier precipitation (>6 mm) accounted for 20% of all recorded rain events in 2009 and for 38% in 2010 (Figs 1 and 2).

Average daily air temperature during the test period in 2009 fell within the range from 22.0°C (August 2009) to -1.0°C (October 2009), and in 2010 – from 24.5°C (July

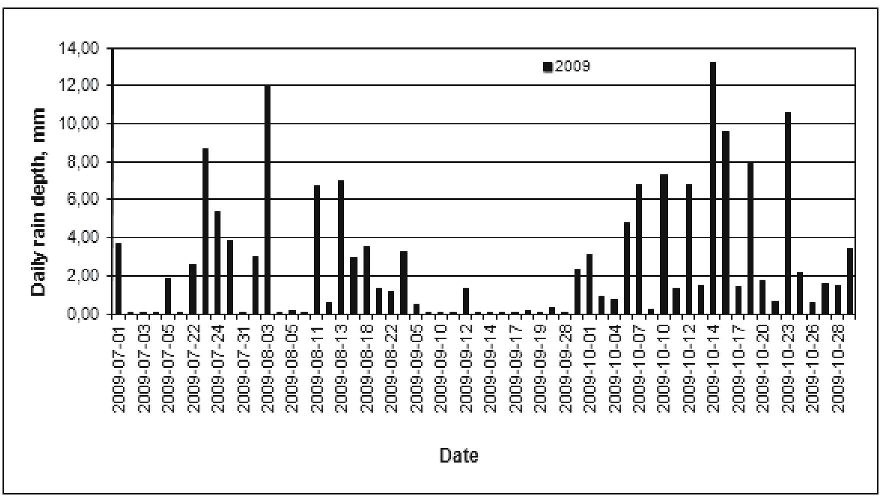


Fig. 1. Daily rain depth analysed during the period July − October 2009

2010) to 7.7°C (October 2010) (Fig. 3). Temperature was measured at the level of the roof of a 5-storey building.

The retention of single (daily) rainfall, determined as the percentage of volume of water retained in the test plots in relation to the volume of stormwater falling on the model surface of roofs during the analysed period ranged from 3.6% to 100% for the conventional impermeable roof and from 29.5% to 100% for green roofs. 100% retention rate was noted during rainfall that usually did not exceed 0.5 mm for impermeable roof and 1 mm for green roofs. The rainfall volume falling on the surface of green roofs was completely infiltrated only on single days with rainfall exceeding 1 mm, i.e. on the

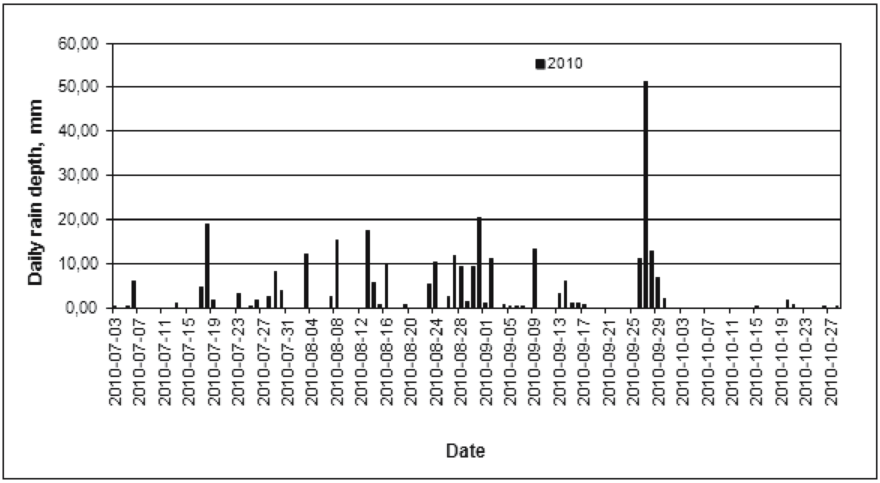


Fig. 2. Daily rain depth analysed during the period July − October 2010 r.

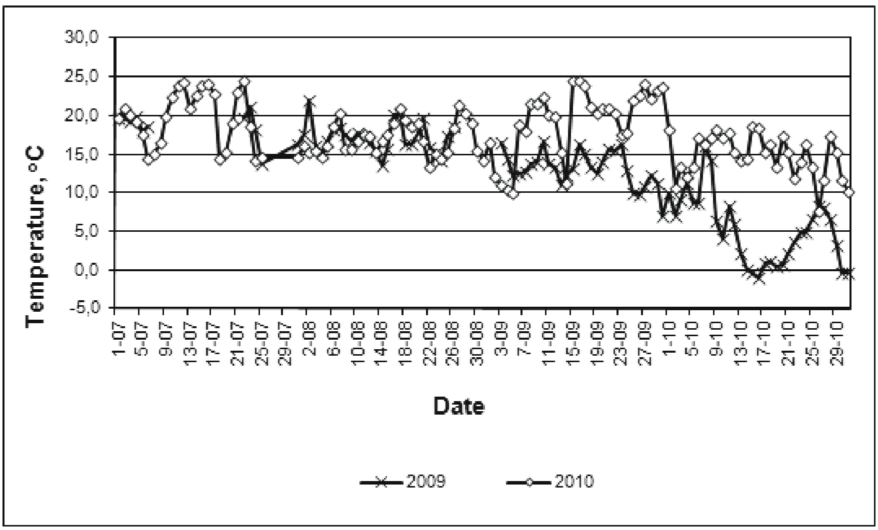


Fig. 3. Average daily air temperature during the periods: July – October 2009 and 2010

12.09.2009, 7.08.2010, 30.09.2010 and 20.10.2010. The highest rain depth, for which no runoff from the green roof was recorded, was 2.44 mm on the 26.08.2010 and 3.28 mm on the 3.09.2009. In the first instance, 100% retention was noted on roofs DZ-2 and DZ-4, in the second – on roofs DZ-3 and DZ-4. This was probably due to low substrate media moisture content, as these events were preceded by dry periods lasting, respectively, for 3 and 11 days. The lowest retention rate for green roofs was recorded on the 31.08.2010, when it amounted to 29.5% for DZ-2, 32.82% for DZ-4 and 49.5% for DZ-3. During that day the daily depth of rain layer reached 20.32 mm, and the rainfall lasted for nearly 12 hours.

During the tests it was noted that the retention capacity of green roofs was decreasing along with the occurrence of subsequent rainy days. Such situation occurred on all plots containing green roofs.

The test results show that green roof DZ-2 (drained with use of plastic profiled drainage elements) is characterised by a higher volume retention in comparison with green roof DZ-4 (gravel layer) in the event of rainfall with daily rain depth exceeding 6.0 mm. The average volume retention for this group of rain events is, respectively, 82.3% on roof DZ-2 and 77.6% on roof DZ-4. However, the green roof DZ-4 is characterised by higher retention (97.0%) than DZ-2 (96.7%) in the cases when the daily rain depth is lower than 6.0 mm, although in this case there is only a slight difference in retention capability. Green roof DZ-3 (drainage within the substrate) is characterised by medium retention capacity, falling between the two applied drainage layer solutions.

The capability of roofs to retain stormwater varies depending on the volume and intensity of rainfall. Mean monthly retention during the analysed period, taking into account all recorded rainfall and runoff values, fell within the range from 34.8% to 84.7% for the reference roof and from 82.6% to 99.9% for green roofs (Fig. 4). For both types of roofs the highest retention values were noted in September 2009. During that month, 86% of the occurring rain events did not exceed 2 mm. On the other hand, the lowest values for conventional impermeable roof were recorded in August 2010 and for green roofs in October 2009. These months were characterised by the highest number of rain events exceeding 5 mm (71% of all rain events) – August 2010 and by the highest total number of rainy days (77.4%) – October 2009. The average monthly values of rainfall volume retained in the test plots are slightly lower when one considers only rainfall exceeding 1 mm that occurred from July to October in 2009 and in 2010 (Fig. 5). For this group of rain events the lowest retention, 28.9%, for the reference roof was noted in July 2009, whereas the highest retention was noted in September 2010 when it reached 43.7%. For green roofs, in spite of the decrease in the retention values for rainfall exceeding 1 mm, the periods with recorded lowest and highest monthly retention, reaching respectively, 77.8% and 99.6%, remained the same, i.e. October and September 2009. During that period rainfall exceeding 1 mm accounted for, respectively, 77.3% and 26.7% of all recorded rain events. The differences in the retention values noted for specific groups of rainfall classified according to daily rain depth (all recorded rain events and rainfall exceeding 1 mm) are significantly higher (reaching even up to 47%) in the case of conventional impermeable roof in comparison to the differences in retention values noted for green roofs. This proves that the rain depth has a stronger influence on the runoff volume for the reference roof than for the green roofs, which, due to their structure, are capable of retaining higher volumes of rainfall as well.

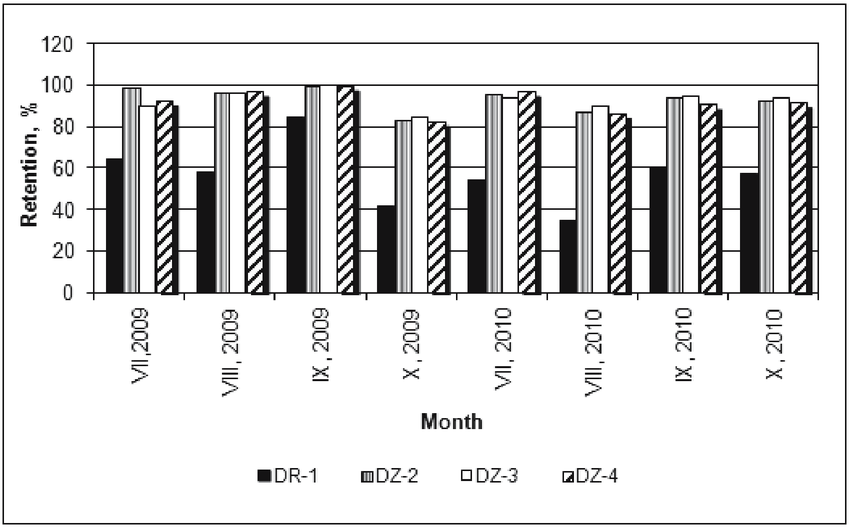


Fig. 4. Average monthly retention value for all recorded rain events during the period July–October 2009 and 2010

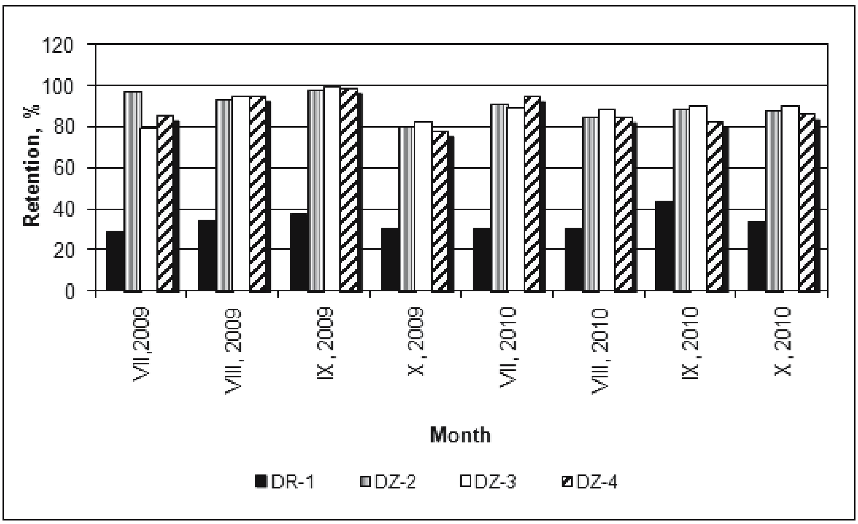


Fig. 5. Average monthly retention value for rainfall exceeding 1 mm during the period July–October 2009 and 2010

Another fact noted during the analysed period was the delay in runoff of stormwater from the test plots in relation to the moment of the beginning of rainfall. Such slowdown in runoff is enabled through the absorption and evaporation of water from the surface of the reference roof and through the absorption of water by the substrate and specific construction layers of green roofs. Some of the water falling on the part of the rooftop covered with plants during rainfall is also transmitted back to the atmosphere in the process of evapotranspiration from roof surface and transpiration from plant surface.

The longest delay occurring during the analysed measurement days was noted during the rainfall on the 7th/8th of August, 2010. On these rainy days the runoff delay on green roof DZ-3 exceeded 26 hours. For the other analysed green roof (DZ-2) the runoff delay for the same rain event reached 24 hours, and for DZ-4 – over 20 hours, whereas for the conventional impermeable roof the runoff delay was only 9 minutes. The rainfall lasted for over 8 hours, and the depth of daily rain layer reached 17.51 mm. In spite of the fact that the rain depth was relatively high for the analysed region, significant runoff delays were noted. The most likely cause influencing such long attenuation of stormwater and runoff reduction could have been the antecedent dry period that had lasted for 3 days and the rainfall hyetograph showing that the analysed rainfall reached its peak intensity as late as in the second day of rain (maximum intensity 73.4 mm/h). The influence of the rainfall hyetograph on the runoff delay is also confirmed by the results noted during other rainfall events, which took place, among others, on the 11.08.2009 and on the 17/18.08.2009. These rain events were characterised by similar rain depth (respectively 6.67 and 6.36 mm), but different times of occurrence of peak intensity during rainfall. In the first case, maximum intensity was noted in the 3rd hour of rainfall, thus runoff from green roofs could be observed only after that time. In the case of rainfall that took place on the 17th/18th of August, 2009, the rain reached its peak intensity already in the second minute, so the delay periods both for the reference roof and for the green roofs were relatively short (Figs 6 and 7).

The occurrence of relatively quick runoff from green roofs after the beginning of rainfall in some cases might also be a result of the discharge of water from an already saturated green roof profile, as a result of the accumulation of runoff from the previous rain event and the analysed rainfall. Such situation was observed, among others, during the rainfall that occurred on the 14.08.2010, when runoff from green roofs appeared a few

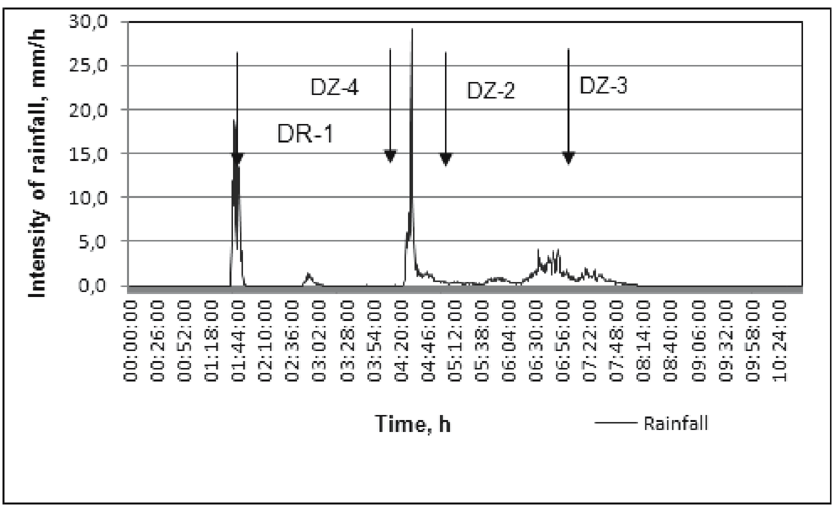


Fig. 6. Rainfall hyetograph with marked time of beginning of runoff from individual roofs on the 11.08.2009 (rain depth − 6.67 mm)

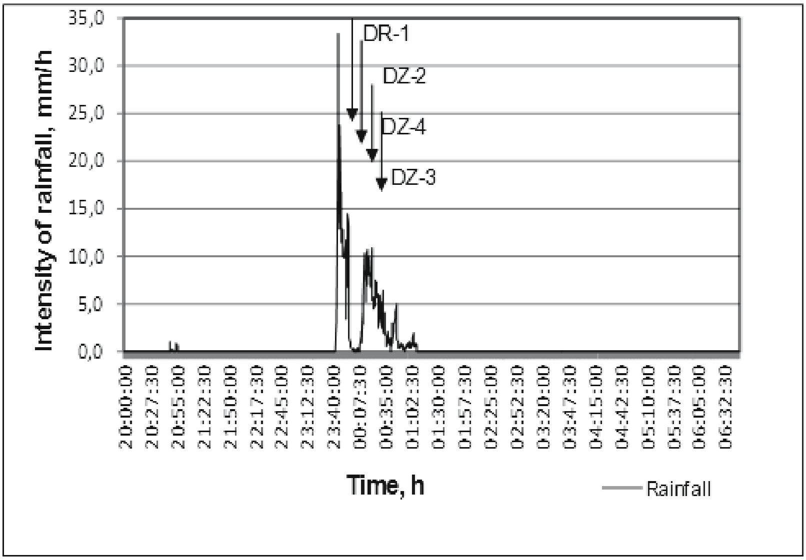


Fig. 7. Rainfall hyetograph with marked time of beginning of runoff from individual roofs on the 17/18.08.2009 (rain depth − 6.36 mm)

minutes before the rainfall started, as a result of water discharge from the multi-layered roof structure after the rainfall of a total depth of 17.38 mm that had taken place on the preceding day.

On most measurement days, the first recorded runoff from green roofs occurred after 3−5 hours from the moment of the rainfall start. The longest runoff delays were recorded on green roof test plots DZ-3 and DZ-4, whereas runoff from the reference roof usually occurred after a few or more than ten minutes from the beginning of the same rainfall (Table 2).

The slowdown in runoff and the attenuation of part of the rainfall within the structure of green roofs causes a noticeable peak runoff reduction, as compared to the maximum recorded intensity of rainfall. During all the analysed rain events the peak runoff reduction on the reference roof was lower than the reduction recorded on green roofs (Table 2). However, neither on the reference roof, nor on green roofs no clear correlation was recorded between the intensity, depth and duration of the rainfall and the value of peak runoff reduction. This phenomenon requires further analysis in order to formulate more precise conclusions.

CONCLUSIONS

The conducted analysis of rainfall and runoff on the reference roof and green roofs in the period July–October 2009 and 2010 allowsfor the following final conclusions:

1. In local conditions, the application of extensive green roofs results in a significantly higher retention of stormwater on the surface covered with plants than on conventional, impermeable roof. Daily retention of stormwater ranged from 3.6% to 100% for conventional roof and from 29.5% to 100% for green roofs. Complete infiltration of

Table 2. Presentation of data on selected rainfall and runoff events during the analysed period

Event [dd/mm/yyyy]	Raindepth [mm]	Max, rain intensity [mm/h]	Antecedentdry period	Rain duration h:min:s	DR-1		DZ-2		DZ-3		DZ-4	
					RunoffDelay [min]	Peakreduction [%]	RunoffDelay [min]	Peakreduction [%]	RunoffDelay [min]	Peakreduction [%]	RunoffDelay [min]	Peakreduction [%]
11.08.2009	6,67	29,15	4 h 17 min	04:32:00	9,5	23	214	94	338	97	178	97
17/18.08.2009	6,36	33,25	3 d 17 h 38 min	01:38:00	3,5	76	8	99	35,5	98	33	95
7.10.2009	6,78	34	8 h 24 min	02:24:30	34	55	671	85	73	95	66,5	88
10/11.10.2009	8,61	11,66	2 d 6 h 32 min	09:10:00	6,5	68	216	83	239,5	93	160,5	92
14/15.10.2009	22,82	8,86	11 h 9 min	10:19:30	215	57	654,5	54	500	66	625,5	54
22/23.10.2009	11,24	15,55	1 d 7 h 32 min	06:46:30	28	48	151,5	96	106,5	94	126,5	83
28/29.10.2009	4,88	2,8	1 d 4 h 6 min	13:58:00	157,5	45	472,5	73	287,5	75	481,5	59
8/9.11.2009	13,42	6,87	1 d 4 h 40 min	09:35:30	13	71	48	88	44	88	74,5	84
17/18/19.07.2010	22,84	22,34	2 d 3 h 23 min	26:46:30	8	49	165	92	410	85	205,5	90
29/30.07.2010	11,92	9,98	4 h 25 min	13:01:00	11	67	21	94	32	96	153,5	96
7/8.08.2010	17,51	73,34	3 d 9 h 17 min	07:53:30	9	48	1442,5	83	1572,5	93	1212	89
13.08.2010	17,39	187,35	4 d 23 h 20 min	01:06:30	27,5	75	41	91	37	96	52	91
16.08.2010	10,03	47,89	1 d 2 h 14 min	02:48:30	3,5	60	47	94	54	99	46,5	98

the rainfall volume in the multi-layered structural arrangement of green roofs was recorded for over 40% of the rain events (46 out of 112). In comparison, in the case of conventional roofs the value reached only 25% (28 out of 112).

2. The average monthly retention during the analysed period, taking into account all recorded rain events, fell within the range from 34.8% to 84.7% for the reference roof and from 82.6% to 99.9% for green roofs. The highest retention values for both types of roofs were recorded in September 2009. During that month 86% of the occurring rain events did not exceed 2 mm.
3. During the tests, it was noted that the green roof with gravel layer (DZ-4) was characterised by a higher retention capability in the case of rainfall of the depth below 6.0 mm, than the green roof equipped with plastic profiled drainage elements (DZ-2). In the case of rainfall exceeding 6.0 mm an opposite effect was observed, i.e. green roof DZ-2 was characterised by higher retention capability than DZ-4.
4. The analysed systems of extensive green roofs contribute to the delay in the runoff of stormwater. On most of the measurement days the first recorded runoff from green roofs occurred after 3–5 hours from the moment of the beginning of rainfall. Highest runoff delays were observed for the green roof test plots DZ-3 and DZ-4. Runoff from the reference roof during the same rain events usually occurred after several or over ten minutes from the moment of the beginning of rainfall.
5. The attenuation and delay of stormwater runoff within the structure of green roofs has contributed to a peak runoff reduction in comparison to the maximum intensity recorded for a given rainfall. During each of the analysed rain events the peak runoff reduction was lower for the reference roof than the reduction noted on green roofs.

Further research is recommended, in order to provide data that will constitute the basis for a broader determination of the functioning of green roofs in local Wroclaw conditions.

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BADANIA RETENCJI WÓD OPADOWYCH NA DACHACH ZIELONYCH

W artykule przedstawiono wyniki badań wykonanych w 2009 r. oraz 2010 r. na stanowiskach badawczych zlokalizowanych na dachu budynku Centrum Naukowo-Dydaktycznego Uniwersytetu Przyrodniczego we Wrocławiu. Badania te miały na celu określenie możliwości retencyjnych dachów zielonych oraz opóźnienia spływów i redukcji szczytowej fali odpływu podczas opadów atmosferycznych zarejestrowanych w warunkach wrocławskich.

Badania wykazały, że dachy zielone pozwalają na zmniejszenie ilości odpływających wód opadowych w porównaniu z dachem tradycyjnym, opóźniają odpływ w czasie oraz wpływają na zmniejszenie maksymalnego natężenia odpływu, przez co mogą przyczynić się do odciążenia infrastruktury kanalizacji deszczowej i ogólnospławnej.