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Rainwater runoff quantity and quality performance from a greenroof: The effects of short-term events

*Alar Teemusk, Ülo Mander**

Institute of Geography, University of Tartu, 46 Vanemuise Street, 51014 Tartu, Estonia

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ABSTRACT

This paper describes the stormwater retention potential and runoff water quality of a lightweight aggregates (LWA)-based greenroof in Estonia. Three rainfall events and snow cover melting were measured. The investigated extensive greenroof was also compared with the modified bituminous membrane roof. The studied greenroof effectively retained light rain—the retention for 2.1 mm rainfall was 85.7%. In the case of a heavy rainstorm (12.1 mm), the greenroof can delay the runoff for up to half an hour, but cannot fully retain it—the runoff volume was the same as that of the reference roof. The observation of snow cover melting showed that there are two meltings of a greenroof: the melting of the snow cover and the melting of the frozen water in the substrate layer. Snow cover melted fast, but the greenroof nevertheless prolonged the runoff to a longer timescale than that of the reference roof. The quality of the runoff water varies depending on the character of the runoff and the pollutants accumulated on the roof. When rain and runoff were moderate, values of COD, BOD_7, and concentrations of total N and total P were higher on the bituminous roof. In samples taken during a heavy rainstorm, the components were less concentrated, as the rain washed more phosphates and nitrates off the greenroof. In snow melting water, the concentrations of all components were greater on the greenroof. In addition, the greenroof runoff always contained more sulphates and Ca–Mg salt because of their presence in the LWA-material.

1. Introduction

Greenroofs are investigated more and more often to determine how they can improve the quality of the urban environment. In addition to their ability to reduce problems of urban stormwater runoff quantity (Mentens et al., 2006) and quality (Berndtsson et al., 2006), greenroofs also have the following benefits: helping to keep buildings cool in summer and also to reduce a building's energy consumption (Del Barrio, 1998; Eumorfopoulou and Aravantinos, 1998; Theodosiou, 2003; Wong et al., 2003a; Liu and Baskaran, 2005) reducing the temperature fluctuation in the roof membrane (Liu, 2003) improving air quality by catching a number of polluting air particles and gases, and smog as well. The evaporation and oxygen-producing effect of vegetated roofs can contribute to the improvement of the microclimate. Considering the above-mentioned benefits, it may be concluded that greenroofs can thereby mitigate the urban heat island effect (Wong et al., 2003b). Planted roofs also provide food, habitat and a safe place for many kinds of plants, animals and invertebrates (Brenneisen, 2003). In city centres, where access to green space is negligible, greenroofs create space where people can rest and interact with friends or business colleagues. Greenroofs provide a psychological benefit because of their appearance, which differs greatly from the ordinary. Therefore, aesthetic value is the most apparent benefit of greenroofs (Green Roofs, 2006).

* *Corresponding author.*
E-mail address: mander@ut.ee (Ü. Mander).

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Rainfall in urban areas is typically more problematic than in rural areas, because of impervious surfaces such as roofs, parking lots and roads. These collect the flow and direct it into the urban drainage system, causing rapid runoff and higher peak flows. Greenroofs reduce rainwater runoff and thereby mitigate this problem. The reduction consists in delaying the initial time of runoff due to the absorption of water in the greenroof, reducing the total runoff by retaining part of the rainfall and distributing the runoff over a long time period through a relatively slow release of the excess water that is stored in the substrate layer (Mentens et al., 2006). The amount retained depends on many factors, such as the volume and intensity of the rainfall, the amount of time since the previous rainfall event, the depth and wetting scale of the substrate layer and the slope of the roof. Liptan (2003) and Mentens et al. (2006) showed that a greenroof can retain more rainwater in warm weather than during cold weather. A great deal of research (Moran et al., 2003; Liu, 2003; Connelly and Liu, 2005) has shown that the substrate layer of a greenroof will be fully saturated with rainwater if rain events occur too soon after one another, and thereby a greenroof cannot delay a heavy rain runoff. Villarreal and Bengtsson (2005) in Lund, Sweden, found that greenroof slope does influence retention volumes for dry initial conditions: the lower the rainfall intensity and slope, the greater the retention.

Greenroofs may reduce the pollution of urban rainwater runoff by absorbing and filtering pollutants, but they can also potentially contribute to pollutants released into water from the soil, plants and fertilizers. The quality of runoff from a greenroof depends on the type of the roof (the thickness of the substrate layer, its composition, vegetation and the type of drainage), the age of the roof, its maintenance; and also on the type of the surrounding area and the local pollution sources (Berndtsson et al., 2006). For the majority of roof runoff water components, the results differ depending on the different greenroof systems and the composition of the substrate layer. Moran et al. (2003) in North Carolina, USA, showed that compost in the substrate layer may cause high concentrations of nitrogen and phosphorus in greenroof runoff. Berndtsson et al. (2006) in Malmö and Lund, Sweden, studied different greenroofs that behave as a sink for nitrate nitrogen and reduced ammonium nitrogen and total nitrogen. They are sources of potassium, phosphate phosphorus and total phosphorus.

The objective of this paper is to analyse how a lightweight aggregates (LWA)-based greenroof functions in the local weather conditions, as the result of observing an existing greenroof in Tartu, Estonia. The task was to assess the stormwater retention potential and runoff water quality of a greenroof, and to compare those with the modified bituminous membrane roof. Three different rain events and also snow cover melting were observed, and runoff water samples were taken for three different water runoff conditions.

2. Materials and methods

2.1. Site description

The studied greenroof was established in May 2003 and is situated near the city centre of Tartu, Estonia. It consists of the following layers: a modified bituminous base roof, a plastic wave drainage layer (8 mm), rock wool for rainwater retention (80 mm) and a substrate layer (100 mm) with LWA (66%), humus (30%) and clay (4%). The reference roof is a modified bituminous membrane roof; the distance between roofs is approximately 350 m. Both the non-fertilized greenroof and the reference roof have no slope and the same area (120 m^2). The length of the greenroof is 18 m, and its width 6.60 m; its height from the ground is 4.5 m. The building covered by the greenroof is a one-storey printing-plant annex to a three-storey office building (with a conventional flat roof). During the measurement period the amount of plant cover was 45% of the whole roof area. The most common plant species were *Sedum acre* (planted and seeded; cover percent 55%), *Thymus serpyllum* (20%), *Dianthus carthusianorum* (5%) and *Cerastium tomentosum* (all seeded; 3%); also *Veronica filiformis* (occasional species; 7%).

2.2. Sampling and analysis

The measuring period was from June 2004 to April 2005. Stormwater runoff was measured for two similar light rain events and for one heavy rain event with the following rain events. Two weekly snow cover melting events were measured in the spring. Runoff volume was measured until runoff finished. Therefore, when the runoff of the first rain event had not finished before the next rain event occurred, it was also measured. Stormwater runoff was manually measured on an hourly basis with 20-l canisters. If the canister filled with water in less than 1 h, then water volumes were added. The greenroof had two outflows (gr1 and gr2), and there was one outflow for the reference roof (rr). Roof runoff samples were taken during light rain runoff (21 September 2004), during heavy rain runoff (31 August 2004) and after the melting of the snow cover (26 March 2005, 27 March 2005, and 30 March 2006). Rainwater samples were taken during heavy rain from the standard gauge, and collected in a bowl. In the melting period, snow was collected near the building with the greenroof and melted in a bowl. All water samples were analysed for pH, BOD_7, COD, total P, PO_4^{3-}, total N, NO_3^-, NH_4^+, SO_4^{2-}, Ca^{2+} and Mg^{2+} by the laboratory of Tartu Veevärk Ltd. (Water Works of Tartu). These water quality parameters were chosen because they are the core indicators of runoff water quality from catchments, and also, they indicate groundwater quality. Five replicate samples of LWA from five different places were taken for the chemical analysis of this material. In the Plant Biochemistry Laboratory of the Estonian University of Life Sciences, the concentration of phosphorus, potassium, calcium, magnesium and organic matter in four fractions of LWA (<2, 2–4, 4–10, 10–20 mm) was analysed. The temperature was measured every 15 min using sensors (Pt1000TG8/E), and recorded with a data logger produced by Comet System Ltd. The temperature was measured both on the surface of the roof and at 1 m above the roof, and also at a depth of 50 and 100 mm in the substrate layer.

3. Results and discussion

3.1. Rainwater runoff retention

Two light rain events and one heavy rain event were measured. The key parameters of the measured rain events and

Table 1 – The key parameters of measured rain events and roof runoff results (gr1 and gr2—greenroof outflows; rr—reference roof)

Runoff measurement time	Rain (mm)	Rain duration (min)	Runoff volume (mm)			
			gr1	gr2	gr (gr1 + gr2)	rr
2 August, 16.30 h to 3 August,	0.8	100				
23.00 h	1.3	80	0.1	0.2	0.3	1.9
14 September, 18.00 h to 16	1.4	35	0.04	0.04	0.08	1.3
September, 15.00 h	1.0	20	0.03	0.04	0.07	1.0
			0.07	0.08	0.15	2.3
31 August, 21.00 h to 06	6.8	60				
September, 11.00 h	5.3	85	5.3	5.9	11.2	11.9
	3.7	130				
	0.8	75	1.9	3.0	4.9	4.4
	1.0	170				
	0.5	60	0.6	1.1	1.7	1.1
	0.1	195	nr	nr	nr	0.1
			7.8	10.0	17.8	17.5

nr—no runoff.

roof runoff results are collected in Table 1. The first light rain event runoff was measured from 2 August 2004, 16.30 h to 3 August 2004, 23.00 h. It consisted of the two following rain events—with 0.8 and 1.3 mm rainfall. The greenroof was able to retain this rainfall efficiently because of the previous days on which no rain fell. The runoff began when the sockets on the reference roof were filled. Runoff from the greenroof began 1 h later than from the reference roof, but it was only dripping. The runoff of the reference roof ceased 9 h before the runoff of the greenroof. The total runoff from the reference roof was 1.9 mm, while the runoff of the greenroof was only 0.3 mm. Retention was 85.7%.

The second light rain event runoff was measured from 18.00 h on 14 September 2004 to 15.00 h on 16 September 2004. It consisted of the two following rain events—with 1.4 and 1.0 mm rainfall. The greenroof was once again able to retain this rainfall efficiently, in spite of the previous runoff that ended the day before. Thus the sockets on the reference roof were filled with previously fallen rainwater, and runoff began very rapidly. The runoff from the reference roof had almost ended when the next rainfall began. The runoff from the greenroof was once again only dripping (0.15 mm), whereas runoff from the reference roof was intensive (2.3 mm).

For almost every rainfall runoff from the first outflow (gr1) of the greenroof, less water was emitted, and runoff time was longer than from the second outflow (gr2), when more water was emitted and runoff time became shorter (Table 1). The reason for this is probably that on one side of the roof (gr1 outflow side) the plant cover was thicker than on the other side (gr2 outflow side), where plant cover was thinner. The roots of plants in the substrate layer held water and slowed water release from the substrate layer. The estimated water holding capacity of the 100 mm substrate layer of the greenroof was 30–40 mm. Some investigations show that in summer, depending on the plants and depth of substrate layer, greenroofs retain 70–90% of the precipitation that falls on them; in winter they retain between 25 and 40% (Green Roofs, 2006). For example, a grass roof with a 4–20 cm layer of growing medium can hold and evapotranspirate 10–15 cm of water.

Exceptionally, in the course of 6 days a total of 18.2 mm of rainfall took place (31 August 2004 to 6 September 2004). 12.1 mm of this fell during the first 5 h. In the case of a heavy rainstorm the greenroof can delay the runoff for up to half an hour, but not fully retain it. The runoff began 20 min after rainfall from the reference roof; the greenroof was able to retain water up to 15 min longer. The runoff intensity from the two studied roofs was different. Initially the intensity from the reference roof (15 l min^{-1}) was noticeable higher than from the greenroof (10 l min^{-1}), while in the third rainfall hour the intensity was similar for both roofs (12–15 l min^{-1} from the greenroof and 10–17 l min^{-1} from the reference roof). Since the fourth rainfall hour the intensity was higher from the reference roof.

The next morning there was 3.7 mm rainfall. The greenroof did not retain it well, but runoff was significantly less intensive than runoff from the reference roof. The heavy rain event lasted longer for the greenroof than for the reference roof, where runoff finished rapidly (Table 1). A small amount of rain (1 mm), however, caused rapid runoff from the reference roof. A drizzling rain (0.1 mm) caused the reference roof to drop, and therefore the gr2 runoff finished before that of the reference roof. The gr1 runoff finished later than the others, 40 h after the other outflows. Throughout the duration of the study, a total of 17.5 mm of water ran off the reference roof, and 17.8 mm of water ran off the greenroof. 7.8 mm ran off the first outflow of the greenroof (gr1), which collected water from the more plant-covered side, and 10 mm ran off the second (gr2), less plant-covered side. The results presented here show that the greenroof can effectively retain light rain events, but in the case of a heavy rainstorm, rainwater runs off relatively rapidly. These results are similar to the results of other studies (Moran et al., 2003; Liu, 2003; Connelly and Liu, 2005).

3.2. *The melting of the snow cover of the greenroof*

The melting of snow cover with an average thickness of 220 mm on the greenroof was observed over a period of 17 days (22 March 2005 to 7 April 2005), during which there was

Table 2 – Melting of the snow cover (gr1 and gr2—greenroof outflows, rr—reference roof), median temperature of air and substrate (at a depth of 100 mm in the substrate layer), and sunshine conditions of studied roofs

Day	Runoff volume (mm)				Median temperature (°C)		Sunshine description
	gr1	gr2	gr (gr1 + gr2)	rr	Air	Substrate	
22.03	0.7	1.0	1.7		−1.0	−1.6	Sunny
23.03	0.03	0.05	0.08		−0.3	−1.2	Cloudy
24.03	1.6	2.7	4.3	0.4	3.5	−0.3	Sunny/cloudy
25.03	3.5	5.5	9.0	14.6	5.8	0.3	Sunny
26.03	0.7	1.9	2.6	9.9	3.4	0.4	Sunny/cloudy
27.03	0.2	0.3	0.5	1.6	0.2	0.1	Sunny/cloudy
28.03	0.07	0.1	0.17	0.2	−0.5	0.1	Sunny/cloudy
29.03	0.05	0.03	0.08	0.02	−2.5	−0.1	Cloudy
30.03	0.02	0.04	0.06	0.06	0.1	0.1	Sunny
31.03	0.2	0.6	0.8	2.0	2.8	0.3	Sunny
01.04	0.1	0.4	0.5	1.8	1.2	0.2	Sunny/cloudy
02.04	0.4	1.1	1.5	1.4	3.4	0.5	Sunny
03.04	0.8	2.1	2.9	0.8	8.9	1.5	Sunny
04.04	0.4	1.2	1.6		7.6	1.5	Sunny
05.04	0.1	0.5	0.6		11.5	2.4	Sunny
06.04	0.07	0.05	0.12		6.0	1.8	Cloudy
07.04	0.02	0.02	0.04		5.8	3.0	Cloudy
Sum	9.0	17.6	26.6	32.8			

no precipitation. Melting was observed in two periods: snow cover melting and substrate layer melting on the greenroof. Measured runoff volumes and description of days are collected in Table 2. Due to slight differences in sunshine and the amount of initial snow cover of the two roofs, the comparison is not 100% correct: the reference roof was shadowed before 14.00 h by the wall of the building's second storey. However, this review shows how snow cover on the greenroof melted.

The melting of the snow cover of the greenroof began on the sunny 22nd of March, when 1.7 mm of water ran off. On the 24th of March melting also began on the reference roof. The sunny 25th of March was a very intensive melting day, when the snow cover on the greenroof melted all at once, and runoff was 9 mm. The melting of the snow cover of the reference roof was more intensive—runoff was 14.6 mm, but there was also thicker snow cover (an average of 290 mm). From 26 March, all of the greenroof's runoff water came from the substrate layer. The runoff volume of the greenroof decreased day by day. The snow cover of the reference roof continued to melt.

From the 31st of March the runoff of the greenroof began to increase, since the lower part of the substrate layer then began to melt. On those days 8 mm of water ran off. Thus we may distinguish two melting times of the greenroof: the melting of the snow cover and the melting of the frozen water in the substrate layer. The runoff of the reference roof ended on 3 April. On cloudy days, the 6th and 7th of April, it was clear that the runoff of the greenroof was coming to an end. At 17.00 h on 7 April, rainfall began, and then the measurement of melting ended. The last hourly runoff from the greenroof outflows was 0.08 l. The total runoff from the greenroof was 26.6 mm, and 32.8 mm from the reference roof. Due to the difference in the amount of sunshine that fell on the roofs, the runoff of the reference roof began later than that of the greenroof. The snow cover of the greenroof, however, melted too quickly (during 1 day), and the substrate layer of the greenroof was unable to retain it effectively.

Comparing the two outflows of the greenroof, it is clear that the thickness of plantcover influences the rate and volume of runoff. Less water seeped from the more plant-covered side of the greenroof (outflow gr1), and the rate of flow was slower, whereas flow from the less plant-covered side (gr2) was greater (by 8.6 mm) and more rapid. For example, considering the melting of the frozen water in the substrate layer, there was a clear difference between the two outflows. In addition, considerably more water was released from the less plant-covered side on the 25th of March.

3.3. *Quality of roof runoff water*

The results of all water quality indicators are presented in Table 3. The values of pH in the greenroof outflow rose by several units compared with the rainwater, i.e. from 5.2–5.6 to 7.2–8.3. The same high level of the values of the pH of the outflow water from both roofs occurred in the case of moderate runoff. In the case of melting water, the greenroof had higher values, probably due to the carbonate contents of the LWA component.

The BOD_7 pattern of both roofs' runoff water was similar to the results for COD. The organic compounds released (e.g. from the decomposition of plants remnants) from the substrate layer of the greenroof caused higher concentrations of BOD_7 in the melting water sample, and also in the moderate runoff sample. During the second sampling, the event was rapid, and organic compounds were not added to the runoff water. The COD value of the greenroof runoff water was higher in the first and third samples. One possible reason for this was the dust accumulated in the substrate layer, and the chemical components of the precipitation. Some of dust components can be the carcinogenic polyaromatic hydrocarbons (PAHs), so the greenroofs may function as a potential filter or phytoremediation unit of these dangerous organic compounds (Green Roofs, 2006). In the moderate runoff from

Table 3 – Water quality indicators of rainfall (r) and different outflow samples from studied roofs

Indicator	Runoff case	Samples			
		r/s	gr1	gr2	rr
pH	Moderate		8.26	8.14	8.43
	Heavy	5.62	7.94	7.85	6.73
	Snowmelt’05	5.24	7.21	7.23	6.08
	Snowmelt’06		7.71	7.60	
BOD_7 ($mg\,O\,l^{-1}$)	Moderate		5.3	4.1	7.0
	Heavy	2.9	2.6	2.0	2.9
	Snowmelt’05	1.4	8.3	8.9	2.5
	Snowmelt’06		12	7.8	
COD ($mg\,O\,l^{-1}$)	Moderate		37	26	43
	Heavy	4	22	21	23
	Snowmelt’05	8	39	40	4
	Snowmelt’06		61	38	
Total P ($mg\,l^{-1}$)	Moderate		0.036	0.026	0.104
	Heavy	0.012	0.090	0.074	0.102
	Snowmelt’05	0.019	0.054	0.056	0.029
	Snowmelt’06		0.044	0.034	
PO_4-P ($mg\,l^{-1}$)	Moderate		0.012	0.006	0.032
	Heavy	0.004	0.036	0.066	0.054
	Snowmelt’05	0.003	0.011	0.012	0.005
	Snowmelt’06		0.028	0.014	
Total N ($mg\,l^{-1}$)	Moderate		2.1	1.9	2.6
	Heavy	1.3	1.2	1.3	1.4
	Snowmelt’05	0.6	1.1	1.0	0.9
	Snowmelt’06		0.25	0.20	
NH_4-N ($mg\,l^{-1}$)	Moderate		0.33	0.28	0.43
	Heavy	<0.015	0.12	0.16	0.09
	Snowmelt’05	0.22	0.29	0.35	0.18
	Snowmelt’06		0.20	0.17	
NO_3-N ($mg\,l^{-1}$)	Moderate		0.7	0.8	0.4
	Heavy	0.18	0.46	0.42	0.19
	Snowmelt’05	0.09	0.28	0.33	0.26
	Snowmelt’06		<0.03	<0.03	
SO_4 ($mg\,l^{-1}$)	Moderate		38	34	3
	Heavy	<1	23	20	2
	Snowmelt’05	1	21	30	1
	Snowmelt’06		16	18	
Ca–Mg salt ($mg\,equiv.\,l^{-1}$)	Moderate		2.80	2.83	0.45
	Heavy	0.08	2.15	2.14	0.12
	Snowmelt’05	0.07	1.84	2.16	0.18
	Snowmelt’06		2.23	2.10	

s—melted snow-water; gr1 and gr2—runoff water from two different greenroof outflows; rr—runoff water from bituminous reference roof, and corresponding different runoff cases (moderate, heavy and snowmelt).

the gr1 outflow, the COD value was higher, because runoff was emitted more slowly than from the gr2. The COD value of the bituminous reference roof was higher than that of the greenroof. The COD value of the greenroof melting water was higher than that of the reference roof, because the greenroof contained more wintertime pollutants. This effect is also evident for other components. In the bituminous reference roof their concentration in melting water was much lower than on the greenroof, which is probably due to the time the samples were taken—almost all of the snow had melted, and it appeared that pollutants had been washed out. In the second runoff samples the results were equal due to the rapid runoff and shorter retention time, combined with the shorter contact between the water and the substrate. One year later, in March 2006, the water quality of the snowmelt was worse for gr1, which indicated that more organic matter accumulated on the greenroof than in March 2005.

Total phosphorus concentrations were higher in the bituminous roof runoff due to dust and other contaminants, causing an increase in total P concentration. For the greenroof it is clear that in the case of moderate runoff, the substrate layer of the greenroof retained phosphorus well, but in the case of the heavy rainstorm, phosphorus was washed out. The results of the melting water of the greenroof were

Table 4 – Elements partitioning of different fractions of the LWA-material

	P ($mg\,kg^{-1}$)	K ($mg\,kg^{-1}$)	Ca ($mg\,kg^{-1}$)	Mg ($mg\,kg^{-1}$)	Organic material (%)
<2 mm	124.1	223.11	3547.4	230.1	9.8
2–4 mm	23.1	55.4	842.8	101.2	0.8
4–10 mm	20.1	70.0	745.6	153.7	0.5
10–20 mm	17.7	63.3	616.2	129.4	0.3

intermediate. The principle of the results for phosphates (PO_4-P) was similar to the results for total P. In the case of moderate rainfall runoff the greenroof retained phosphates well, but in a heavy rainstorm phosphates were washed out, more from the gr2 outflow side. In melting water we found a relatively low concentration of phosphates. However, the washing out of phosphorus from LWA is surprising, taking into account the fact that LWA is often used as filtrate material to bind phosphorus in constructed wetlands (Johansson, 1997; Jenssen et al., 2005). Significantly less P was washed out in melting water in March 2006 than in March 2005. Again, the reason is the lower pollution load of the snow cover in 2006.

The content of total nitrogen was relatively equal for both roofs. Nitrogen came to a roof either from the air or from bacterial activity. In the case of moderate runoff there was more total N than in other cases. During the heavy rainstorm the rainwater contained 1.3 $mg\,l^{-1}$ total N, and neither of the two roofs increased this. The principle of the results of ammonium nitrogen (NH_4-N) concentration is similar for moderate runoff. In cases of heavy rainstorm and snow melting, there was more ammonium nitrogen in the runoff water of the greenroof. The reason for this is probably the influence of plants and the substrate layer. In all cases the nitrate nitrogen (NO_3-N) content is higher in the runoff water of the greenroof, depending on the character of the runoff. Once again, this is influenced by plants and the substrate layer. In March 2006, the concentration of all forms of nitrogen in melting water was lower than in March 2005. This may be related to stabilized conditions in the greenroof over a year of functioning, but also to the lower pollution load of the snow cover in 2006.

The results concerning sulphates (SO_4) and Ca–Mg salt (total hardness) clearly indicates that the greenroof had a significant influence on these contaminants. Sulphates are present in the LWA-material, and therefore its concentration is higher in the case of moderate runoff, when water filters through the LWA. In other cases the concentrations of both sulphates and Ca–Mg-salt were also high. In March 2006 the results indicated that the influence of the LWA-material decreased, and the concentrations were lower than in March 2005.

The chemical analysis of the LWA-material shows that the finest fraction (<2 mm) had the largest proportion of organic matter, P, K, and Ca, whereas Mg was more equally distributed (Table 4). The possible outwash of the finest fraction explains why after heavy rainfall, the concentration of total P in the outflow from LWA greenroofs was significantly higher than after a moderate rainfall.

Köhler and Schmidt (2003) in Berlin, Germany, found that the tested greenroof substrates cause a rise in pH: in rainfall, median pH was 6.2, whereas in the runoff of the conventional roof it was 4.6, and in the runoff of substrates it was up to 7.5. This was probably due to the high pH value of the substrates used (e.g., Ulopor). In the Estonian study, median pH values were 5.6, 7.08 and 7.74, respectively, whereas the concentrations of total N and total P were much lower than that in Moran et al. (2003) or Liptan and Strecker (2003) studies, because the Estonian greenroof did not contain compost like the others. Total N and total P concentrations in the Moran et al. study were 2.1–5.4 and 1.2–1.5 $mg\,l^{-1}$, respectively. In the Liptan and Strecker study, total P concentrations varied between 0.24 and 1.11 $mg\,l^{-1}$. In the Estonian study, the total N concentration was 1–2.1 $mg\,l^{-1}$, and the total P concentration 0.03–0.09 $mg\,l^{-1}$. Thus the composition of the substrate layer should be taken into consideration in selecting the soil mix.

4. Conclusions

The results show that a greenroof can effectively retain light rain events that do not occur too soon after one another, if the substrate layer is not fully saturated. The greenroof can retain rainfall more efficiently if the preceding days are rainless and the substrate layer is dry. The greenroof can also retain a moderate rain even when the substrate layer is wet from previously fallen rain. In the case of a heavy rainstorm, the LWA greenroof cannot retain it, and rainwater runs off relatively rapidly. The greenroof can distribute the runoff over a longer period. Snow cover of the greenroof melted during 1 day, while melting of the substrate layer lasted 12 days.

The LWA greenroof has a considerable effect – both positive and negative – on the quality of runoff water. This clearly depends on the character of the runoff: the slower the runoff rate, the higher the concentrations of total N, NH_4-N and organic material (after BOD_7 and COD) in the runoff water. Total P concentration did not vary significantly in relation to water discharge. Heavy rain washed more phosphates and also nitrates out of the greenroof. In snow melting water, the concentrations of all components were greater on the greenroof due to the accumulation of atmospheric pollutants in snow. The LWA greenroof generally acts as a storage device: pollutants are accumulated in the substrate layer and released when intensive rainwater washes them out. It is also clear that the material used in the substrate layer has an important influence on runoff quality. As the measurements showed, the greenroof runoff always contained more sulphates and Ca–Mg-salt, because of their presence in the LWA-material. On the other hand, for example, the concentrations of P and N, and also COD and BOD_7, were higher in the runoff water of the reference roof in the case of moderate runoff. Although this study found that greenroofs have both negative and positive effects, in terms of water quality greenroofs definitely have more positive than negative effects, and they play an important role in improving the quality of the urbanizing environment. The further investigations should concentrate on the materials used to construct the greenroof, especially the substrate layer, and on the maintenance problems of extensive greenroofs (e.g., fertilizing of plants).

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