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Hydrological Performance of LECA-Based Roofs in Cold Climates

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Abstract: Rooftops represent a considerable part of the impervious fractions of urban environments. Detaining and retaining runoff from vegetated rooftops can be a significant contribution to reducing the effects of urbanization, with respect to increased runoff peaks and volumes from precipitation events. However, in climates with limited evapotranspiration, a non-vegetated system is a convenient option for stormwater management. A LECA (lightweight expanded clay aggregate)-based roof system was established in the coastal area of Trondheim, Norway in 2016. The roof structure consists of a 200 mm-thick layer of LECA® lightweight aggregate, covered by a concrete pavement. The retention in the LECA-based roof was estimated at 9%, which would be equivalent to 0.27 mm/day for the entire period. The LECA-based configuration provided a detention performance for a peak runoff reduction of 95% (median) and for a peak delay of 1 h and 15 min (median), respectively. The relatively high moisture levels in the LECA-based roof did not affect the detention performance. Rooftop retrofitting as a form of source control may contribute to a change in runoff characteristics from conventional roofs. This study of the LECA-based roof configuration presents data and performance indicators for stormwater urban planners with regard to water detention capability.

Keywords: detention; cold climate; hydrological performance; LECA-based roof; lightweight aggregate; sustainable drainage systems (SuDS); water-detaining non-green roof

1. Introduction

Stormwater management is experiencing raised awareness due to an increased frequency of damaging rain-induced flood events across the world. The existing infrastructure is not typically fit to handle the combined effects of ever-increasing urbanization (including the proliferation of impervious surfaces) and climate change [1]. Densely-urbanized areas have limited space for retrofitting with green solutions, or for the reduction of imperviousness. This encourages communities to seek out new, emerging solutions. One possible way to rethink stormwater management is to focus on building rooftops. In developed cities, rooftops account for almost half of impervious surfaces [2].

New constructions and retrofitting existing buildings with sustainable drainage systems (SuDSs) seem to be efficient measures to counteract the effect of impervious covers in the cityscape [1,3,4]. Additionally, they contribute to the reduction of both sewer overflows and flood risks. Rooftop retrofitting differs from many other SuDS approaches, as it does not require additional land acquisition. Rooftop solutions such as green roofs belong to the first of the so-called three-step stormwater treatment train as a form of source control [5,6]. In 2008, the Norwegian Water Association adopted a national guideline for surface stormwater management that uses a three-step approach, where a source control should be able to collect and infiltrate runoff following small events (the rainfall intensity classification of small is location-specific) [7].

The main drivers behind rooftop source control are detention and retention of runoff. Retention occurs through the combined process of evapotranspiration for vegetated solutions, and its annual runoff reduction has been extensively investigated [8–13]. On the other hand, detention performance indicators are increasingly required by stormwater designers to alleviate urban flooding due to capacity exceedance in sewer systems [14,15]. Green roof performance depends largely on the local climate. Most studies scrutinized within the context of this research have reported limited hydrological performance in cold and wet climates, when evaporation and transpiration is limited due to climatic factors [14–20]. Johannessen et al. [20] investigated potential evapotranspiration in cold and wet regions across 14 locations in northern Europe, and concluded that retention on green roofs varied between 0% and 1% for Nordic countries in the winter period. In order to address the challenges outlined in the literature, it was decided to test the performance of a non-vegetated lightweight filter. For the sake of reference, this paper benchmarks the hydrological performance of the new non-vegetated solution against that of green roofs.

A LECA-based roof system was constructed at Høvringen (Trondheim, Norway), where the testing of roofs for water detention and retention are piloted. The Trondheim region registers an average of 150 days of precipitation a year [21]. Based on research studying the evapotranspiration and evaporation from vegetated and non-vegetated roofs, the water loss was comparable for both roofs for a period of approximately 50 h [22]. The following two weeks of dry period demonstrated that the additional ability of plants to transpire water outperformed the evaporation by more than 60%.

Hydrological performance indicators relevant to this study are peak flow reduction, peak flow delay with an event-based perspective, and retention within a long-term rainfall/runoff water balance perspective.

In order to address the hydrological performance of the LECA (lightweight expanded clay aggregate)-based roof, the following research questions were proposed:

(1) What is the seasonal and annual retention capacity of the LECA-based roof in cold climates?
(2) What is the event-based detention capacity of the LECA-based roof in cold climates?
(3) How do antecedent stormwater events affect the hydrological performance of the examined roof?

Limitations to the Study

Given that this is an in-situ field setup, the study is limited to the actual weather phenomena that occurred during this period. As such, there was only one event with a return period greater than 2 years. Thus, a limited amount of data was collected to investigate the extreme performance of the roof.

2. A Brief Literature Review

A brief literature review was performed to address challenges within stormwater management, more specifically stormwater retention and detention on rooftops. Most of the relevant studies focused on rooftops with vegetation. Thus, water losses due to plant uptake show a clear difference when comparing results between vegetated and non-vegetated solutions. In this study, no transpiration was expected because of the non-vegetated setup. Furthermore, seasonally low evaporation rates were expected due to the cold and wet weather conditions [20,23]. The review identified the requirements of stormwater designers and planners regarding sustainable solutions that enable the reduction of annual runoff, as well as the management of short and large design vents. A dataset based on 18 studies was analyzed. Emphasis was given to studies which focused on non-vegetated roofs (including reference black roofs), as well as cold and wet climates. The majority of the studies were focused on retention performance, rather than detention.

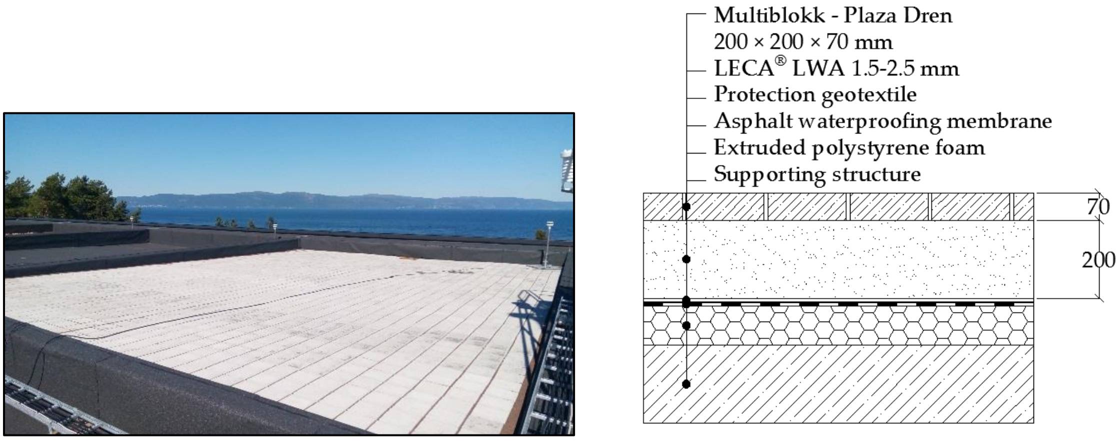
Retention occurs during dry periods, when water is evaporated into the atmosphere. In terms of retention performance, VanWoert et al. [3] studied the total rainfall retention from different media. The retention ranged from 27.2% for gravel ballast to 50.4% for a bare growing media, and 60.6% for a green treatment. Similarly, Mentens et al. [1] compared the annual runoffs from green and gravel-covered roofs. They presented a 25% reduction for the gravel roof, and a 50% reduction for the green roof. Berghage et al. [22] reported the annual rainfall retention from three different setups. The retention ranged from 14.1% for an asphalt roof to 29.7% for a media roof, and 52.6% for a vegetated roof. Comparing LECA-based (non-vegetated) and vegetated setups, higher levels of retention were observed using vegetated beds [10], with an annual volumetric retention of 54.5% for a LECA-based setup and 75.1% for a green roof. Johannessen and Muthanna [24] presented an annual runoff reduction of 17–30% for three coastal cities in Norway. In a study focused on a long dry period, major differences were found in retention through evapotranspiration by vegetated and non-vegetated configurations [25]. Berretta et al. [9] studied moisture loss from a growing medium during a dry period of cold and warm months. They presented a mean moisture loss ranging from 0.34 mm/day to 1.65 mm/day in the period of March through July. Special attention should be given to the regeneration of roof storage capacity, which depends on physical configuration, precipitation patterns, and evaporation during dry periods [17]. Overall, the average retention performance is useful in a context where stormwater discharge to the sewer system is billable.

The detention effect occurs when temporally detained stormwater is subsequently released [14,15,18]. The evapotranspiration effect, which restores storage capacity during dry periods, may be neglected at this time in the interest of detention. Comparing detention performance, Liu et al. [26] and Villarreal et al. [14] presented peak flow reductions and peak delays of an intensive green roof on an event basis. The peak reductions varied between 25% and 65%, and peak delays varied between 20 min and 40 min. Stovin et al. [10] concluded that peak reduction for rainfall larger than 10 mm varied from 29% for a LECA-based bed to 68% for a sedum roof. They also noted that vegetated beds with brick-based substrates offer consistently greater attenuation compared with the LECA-based substrate. Stovin et al. [2] investigated the performance of an extensive green roof subjected to events with a return period of over one year. They presented a per-event peak reduction of 59.22% (mean) and 58.67% (median), and a per-event peak-to-peak delay of 54.16 min (mean) and 18 min (median). Li et al. [27] reviewed the typical hydrological performance of green roofs. It was shown that they attenuate a peak flow of 22% to 93%, and delay a peak flow of 0 to 30 min.

3. Materials and Methods

3.1. Geometrical Description and Structure Composition of the LECA-Based Roof

A full-scale LECA-based setup (Figure 1) was built to monitor the hydrological balance between rainfall and runoff on the roof of a wastewater treatment plant at Høvringen in Trondheim, Norway, approximately 50 m a.s.l. (63°26′47.5″ N; 10°20′11.0″ E). According to the Köppen-Geiger climate classification map (http://koeppen-geiger.vu-wien.ac.at), Trondheim is situated at the interface of oceanic (Cfb) and subarctic (Dfc) climates [23]. Main characteristics are strong seasonality, short summers, and no predominant dry seasons. The Norwegian Meteorological Institute recorded an annual precipitation of 950 mm and an annual average temperature of 3.8 °C in 2016. Cold climate is defined as a climate where the mean temperature of at least one month per year is below +1 °C [28]; in Trondheim, this occurs in January, February, November, and December [21].



(**a**) (**b**)

Figure 1. The LECA-based roof with concrete paving stones and its cross-section. LWA: lightweight aggregate. (**a**) The full-scale LECA-based roof at Høvringen (Trondheim, Norway); (**b**) The LECA-based roof components in a cross-section

The dimensions of the LECA-based roof-cells are 8 × 11 m, with a longitudinal slope of 2%. The full-scale configuration prevents impact associated with the scaling factor, which is important when accounting for the lateral flow across the roof-to-roof drain. The structure composition is made up of an underlying protection layer, a 200 mm thick layer of LECA® lightweight aggregates (LWA), and covering concrete pavers (200 × 200 × 70 mm). A geotextile is used as a separation layer, and to prevent fine particles from being washed out. LECA® LWA is an expanded lightweight crushed clay aggregate with a bulk density of 500 kg/m^3, a particle density of 1050 kg/m^3, and a particle size range of 1.5–2.5 mm [29]. Laboratory tests were also performed. The specific fraction was found to be ~60% of the proportion of voids in a sample, with a maximum water holding capacity (MWHC) of 26.2%, which is defined as the water content of a substance after two hours draining post-saturation. The tests were performed according to the Guidelines for the Planning, Construction and Maintenance of Green Roofing of the German Landscape Development and Landscaping Research Society [30]. The saturated hydraulic conductivity was measured to be 143.2 cm/h. The weight of the LECA-based roof was calculated at 251 kg/m^2 based on completely dry materials, and 310 kg/m^2 for wet conditions (MWHC). This includes LECA and pavers.

3.2. Data Collection and Event Analysis

Hydrological data were collected for all four seasons, from January 2017 to November 2017. Precipitation was monitored by a heated tipping bucket rain gauge (Lambrecht meteo GmbH 1518 H3, Lambrecht meteo GmbH, Göttingen, Germany) with a resolution of 0.1 mm at 1-min intervals. The runoff collection was measured using a weight-based system with two tanks downstream of the drainage outlets. The collection tanks had two conditions for emptying: they were automatically emptied either every 30 min, or when the weight of the water approached the capacity of the tank (30 kg).

A CR1000 data logger (Campbell Scientific, Inc., Logan, UT, USA) recorded all the parameters at 1-min intervals. Single precipitation events were defined according to a minimum period of 6 h of antecedent dry weather (ADWP), as commonly used by several previous studies, among others [2,3]. A threshold precipitation depth of 0.5 mm was used to exclude insignificant precipitation events. Similarly, a threshold discharge of 0.1 L/min was set to specify the start and end of runoff events. The moisture content in LECA® LWA was recorded using Decagon 5TM soil moisture and temperature sensors, which were delivered at the end of June. The moisture sensors were pre-calibrated in the laboratory for minimum and maximum degrees of saturation (0% and 100% saturation). Events were identified and sorted into five groups based on the type of precipitation: *rain*, *rain on snow*,

snow, *snowmelt,* and *mixed*. A total of 127 events were registered in the period between January 2017 and November 2017: 94 *rain* events, 12 *rain on snow* events, 9 *snow* events, 4 *snowmelt* events, and 8 *mixed* events. The events which were designated as *mixed* typically had a long duration (several days) and experienced several changes of precipitation type.

3.3. Retention Capacity

Retention was considered as long-term permanent water removal on a monthly basis, and a mean value for the entire studied period. Retention capacity was determined as follows:

$$Ret = P - R, \tag{1}$$

where P is precipitation, R is runoff and Ret is retention.

The retention at any given time will be the sum of the evapotranspiration and the water currently stored in the LECA medium.

3.4. Detention Capacity

The detention capacity of the LECA-based roof was assessed as the ability to attenuate and delay peak flows compared to the response of the black roof. This analysis was carried out on an event basis. In some cases, several peaks were observed in a single event due to the long duration (several days). In these cases, only the highest peak per event was analyzed. Peak flow reduction (PR) was determined as follows:

$$\mathrm{PR} = 1 - \frac{Q_{\mathrm{LR,max}}}{Q_{\mathrm{BR,max}}}, \tag{2}$$

where $Q_{\mathrm{LR,max}}$ is the maximum flow recorded per event from the LECA-based roof (LR), and $Q_{\mathrm{BR,max}}$ is the maximum flow recorded per event from the black roof (BR). Peak delay (PD) was determined as follows:

$$\mathrm{PD} = T_{\mathrm{LR,max}} - T_{\mathrm{BR,max}}, \tag{3}$$

where $T_{\mathrm{LR,max}}$ is the time of maximum flow recorded per event from the LECA-based roof (LR) and $T_{\mathrm{BR,max}}$ is the time of maximum flow recorded per event from the black roof (BR). Additionally, any delays were analyzed as delays of centroid of individual events.

4. Results

4.1. Precipitation Events and Time for Regeneration of the LECA-Based Roof Storage Capacity

The event durations and precipitation depths varied considerably. Of the selected highest-intensity events, the shortest lasted 8 min in July, and the longest lasted 122 h in October. This presents a widespread range; therefore, the median value of 8.2 h might be more representative. In terms of total precipitation depths, the events ranged from 0.5 mm to 85.4 mm. The total duration of precipitation events and dry periods were determined. Assuming the 6 h ADWP, precipitation occurred 22% of the time during these eleven months. This leaves 78% of the time (dry period) for the regeneration of the roof storage capacity, considered as time between events.

The precipitation at Høvringen (11-months dataset) was compared to the Risvollan stations, located 82 m a.s.l, at an areal distance of 7 km, due to the unavailability of Intensity–Duration–Frequency (IDF) curves at Høvringen. For the observation period, there was 8% more precipitation recorded at Høvring than at Risvollan. The higher elevation of Risvollan makes this difference expected. Comparing the observed events at Høvringen with the IDF curves from the Risvollan station, one can see that the all the events fall below a 2-year return period, with the exception of one from August 19, which lasted more than 1 day (Figure 2). The figure also shows a zoom to a 30 min resolution, where eventual rapid storms can be found. However, they registered low precipitation depths.

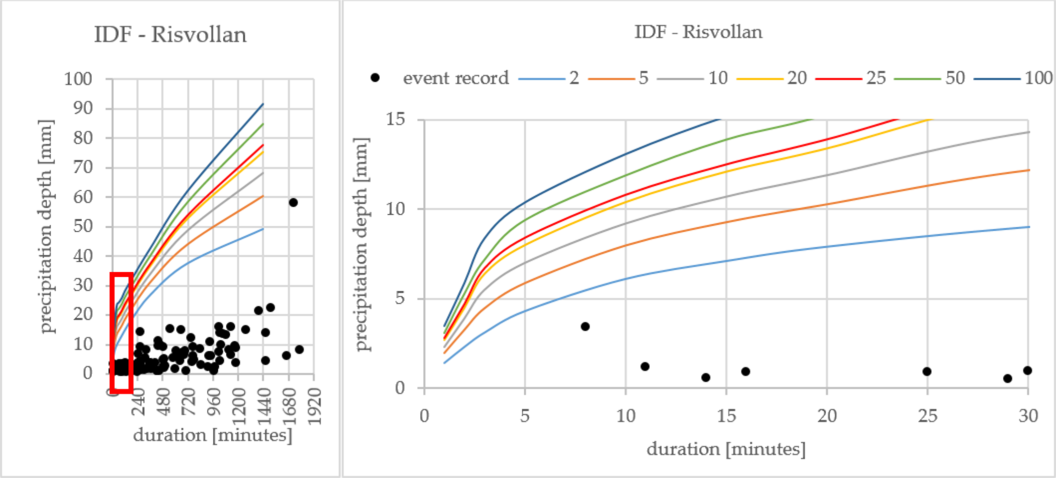


Figure 2. (**left**) The event record comparison with Risvollan Intensity–Duration–Frequency (IDF) curves for different return periods; (**right**) 30-min resolution.

The mean event intensities ranged from 0.1 mm/h to 25.6 mm/h. Particularly, the maximum mean intensity from July 26 that lasted 8 min exceeded the rest of the values; however, it is still below a 2-year return period event.

4.2. Retention Performance

The total rainfall-runoff rate can be observed between 23 January 2017 and 30 November 2017. During this period, the precipitation gauge measured 937.6 mm precipitation. The runoff depths during the examined period were 912.1 mm and 852.4 mm for the black and LECA-based roofs, respectively (Figure 3, Table 1). This indicated a discrepancy of 59.7 mm (black vs. LECA-based roof) and 85.2 mm (precipitation gauge vs. LECA-based roof), which is the evaporated volume. Overall, the difference between the precipitation and runoffs was a 3% volume reduction by the black roof, and 9% for the LECA-based roof.

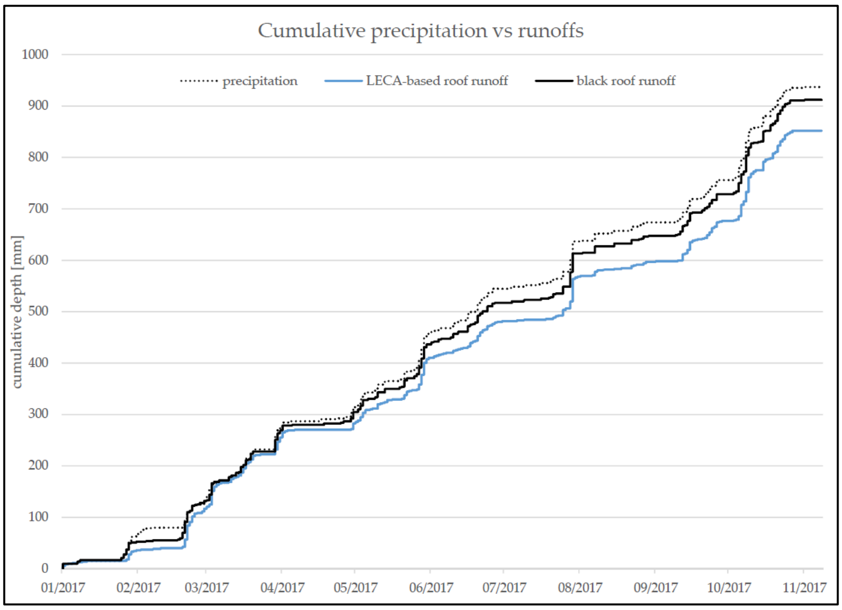


Figure 3. Cumulative hydrograph from the rain gauge and runoffs of the black and the LECA-based roofs.

The seasonal variations are shown in Table 1. The 11 months were divided into four groups: November, January, February, and March represent the winter period; April, May, and June represent the spring period; July and August represent the summer period; and September and October represent the fall period. The winter period confirmed zero evaporation during the cold climate condition. The minor negative difference between the black roof and the precipitation gauge can be attributed to signal noise and measuring uncertainties. The snowfall measurements are most likely the most significant here. Evaporation in the spring season exceeded values from the summer season (Table 1). This could be explained by an alteration of rainfall patterns in the summer season, when higher intensity rainfalls occur, resulting in decreased retention.

Table 1. Seasonal variation in retention performance.

Season	Number of Days	Total Precipitation (mm)	Total Runoff (mm)		Runoff Reduction (%)		Retention (mm)		Normalized Daily Retention (mm/day)	
2017		Rain Gauge	LECA	Black	LECA	Black	LECA	Black	LECA	Black
Winter	97	349.4	343.6	355.3	2%	−2%	5.7	−5.9	0.06	−0.06
Spring	91	301.3	251.9	276.7	16%	8%	49.4	24.7	0.54	0.27
Summer	62	182.7	160.9	179.1	12%	2%	21.8	3.7	0.35	0.06
Fall	61	104.2	96.0	101.1	8%	3%	8.3	3.2	0.14	0.05
Total	311	937.6	852.4	912.1	9%	3%	85.2	25.5	0.27	0.08

The runoff coefficients calculated from total precipitation and runoff records were 0.97 for the black roof and 0.91 for the LECA-based roof. The normalized daily retention estimated from total precipitation and runoff measurements was 0.27 mm per day. This reflects the fact that the climate in the Trondheim region is relatively cold and wet. The detention in the expanded clay aggregate (LECA), followed by a subsequent slow drainage of the system, was much greater than the evaporation loss rate.

4.3. Detention Performance

The detention capacity of the system was evaluated using peak flow delay and peak flow reduction. Evaluating the LECA-based roof using a wide range of performance indicators for all events indicated that the performance was mainly influenced by duration, intensity, moisture content, and ADWP of the individual events. At the same time, the detention indicators were highly sensitive to the chosen subsets of the rainfall dataset which was used in the calculations. Therefore, the eight events with the highest 5-min peak intensity were selected for detailed examination. Figure 4 illustrates the eight largest events, ranging in duration from 8 min to almost 3 days, with depths of 3.2 mm to 59.6 mm (Table 2). Additionally, the largest snowmelt (event 24) and rain-on-snow event (event 27) were included to show the different types of events observed on the roofs. For event 24 (the pure snowmelt event), there was a negative lag time delay between the black and the LECA-based roof. This can be explained by the observed temperatures in the LECA-based roof, which were more stable compared to the black roof. The black roof was typically colder than the LECA-based roof, meaning that higher net radiation was needed to initiate snowmelt. Though this was the largest snowmelt event, it was a relatively small compared to the other events in Tables 2 and 3, making the peak flow reduction less relevant. Event 27 (the rain-on-snow event) is very difficult to evaluate without knowing the mass of snow on the roofs at the onset of rain. It is not possible to compare peak lag times, as it is possible that the snowmelt initiated prior to the precipitation runoff. A complete mass balance would be needed of the initial snowfall until it was completely melted again. Due to these constraints, these two events were excluded from the comparisons in Tables 2 and 3.

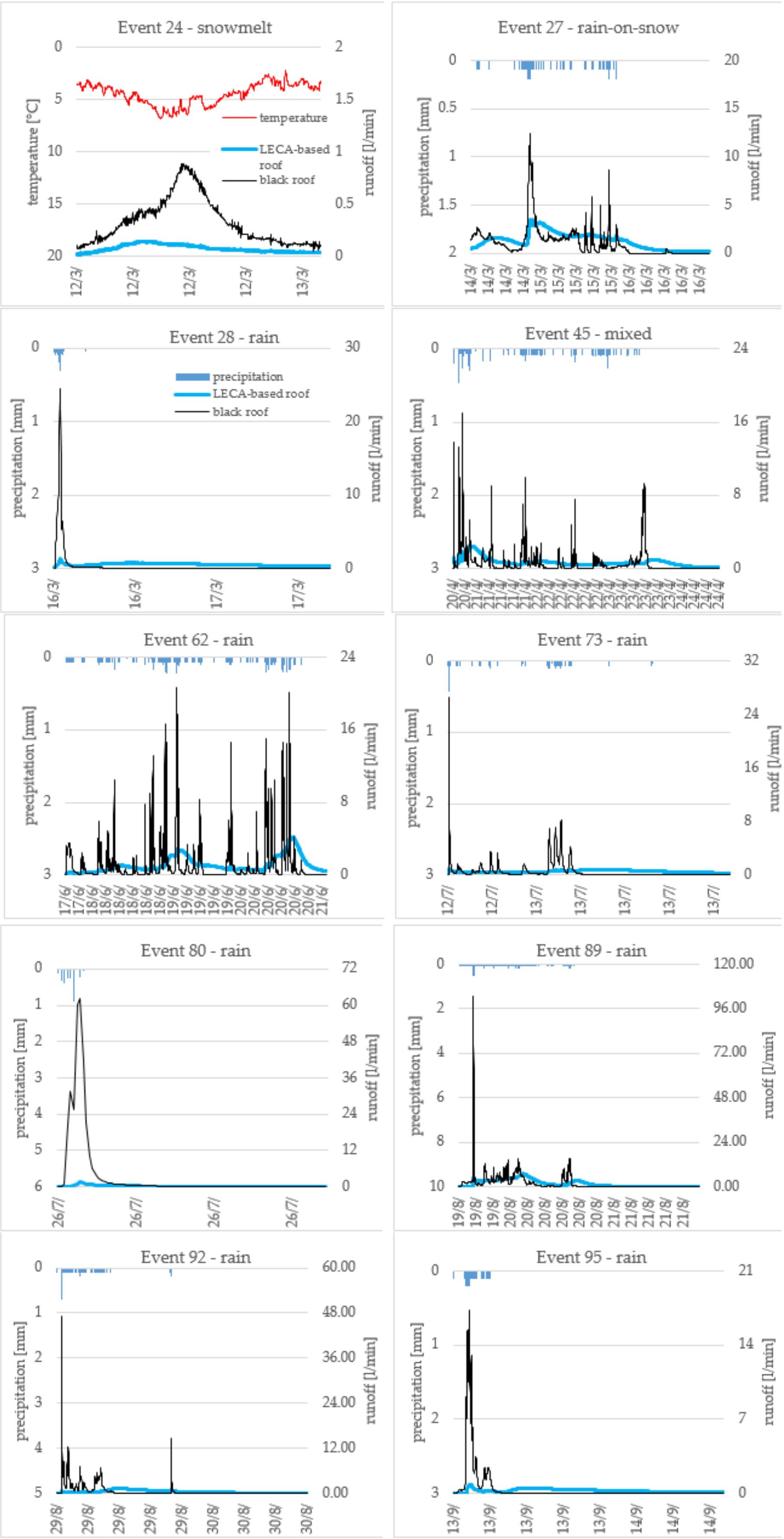


Figure 4. The events with the highest peak 5-min intensity.

Two alternative precipitation intensities were presented. The mean intensity indicates the ratio between the depth and duration, whereas the peak 5-min intensity is the peak intensity measured over 5 min. Event 45 turned to snow at a later stage, followed by a snowmelt in the end, and therefore the event type was classified as mixed. However, this event was used in the final evaluation, since the peak 5-min intensity and corresponding runoff occurred during "rainy" conditions. Event 80 was quite untypical in terms of mean intensity, which was more than ten times higher than the remaining events. With respect to the return period, event 89 was the only one that fell between the 2-year and 5-year return period (Figure 2).

Table 2. Rainfall characteristics for the significant events.

Event	Type	Start	Duration (hh:mm)	Precipitation Depth (mm)	Mean Intensity (mm/h)	Peak 5-min Intensity (mm/h)
28	rain	16.03.2017 19:43	1:38	3.3	2.13	14.40
45	mixed	20.04.2017 19:04	69:34	35.6	0.57	17.64
62	rain	17.06.2017 16:47	74:38	59.6	0.81	11.64
73	rain	12.07.2017 16:53	19:35	8.8	0.46	16.32
80	rain	26.07.2017 16:20	0:08	3.2	25.58	21.60
89	rain	19.08.2017 13:41	28:47	57.7	2.02	40.80
92	rain	29.08.2017 02:52	7:15	11.2	1.57	21.60
95	rain	13.09.2017 03:05	5:25	7.9	1.51	12.00

Table 3 summarizes responses of both black and LECA-based roofs for the eight events. Here, individual events were characterized by comparing the maximum (peak) values registered from the roofs. Overall, the peak delay totaled 1 h and 15 min in median and 7 h and 23 min in mean. A long dry period before the events naturally led to the freeing of the storage capacity. However, this does not necessarily mean ideal conditions for delaying peak runoffs, as can be seen for event 95. On the contrary, the short dry period led to a sufficient delay for event 45. A focus on maximum values was not always the best solution when evaluating the runoff delays. One can see very long delays for the long-duration events 62 and 89. Event 62 even experienced two heavier rainfalls, which obviously led to two responses. Because of this, two alternative solutions of peak delays were suggested (Figures 5 and 6).

In terms of peak reduction (Table 3), the roof demonstrated a high efficiency, with a reduction rate of 80% to 97%, irrespective of the length of the antecedent dry period or the degree of previous saturation. The latter indicates the extent to which the voids in the expanded clay aggregates are filled with water. The saturation measurements ranged between 31% and 61% for the period after which the sensors were installed. In addition to the degree of saturation, the initial runoff may also be used as a performance corrector or predictor. Higher initial runoffs correlate to higher degrees of saturation in the media from previous events.

Table 3. Comparison of runoff characteristics of black and LECA-based roofs for the significant events. ADWP: antecedent dry weather period.

Event	ADWP	Peak Delay	Peak Reduction	Initial Degree of Saturation	Initial Runoff	Runoff Duration	Runoff Duration
		Peak-to-Peak	Peak-to-Peak		LECA	Black	LECA
	(hh:mm)	(hh:mm)	(%)	(%)	(L/min)	(hh:mm)	(hh:mm)
28	23:41	0:00	95%	-	0.27	2:43	14:26
45	7:37	2:30	85%	-	0.7	69:42	93:40
62	17:14	36:42	80%	-	0.08	74:57	81:41
73	8:44	0:01	97%	35.7	0.42	13:00	27:02
80	23:56	0:00	97%	32.1	0	0:51	1:22
89	62:42	12:17	93%	32.5	0.02	29:25	58:04
92	66:36	7:35	97%	32.2	0.01	15:46	33:28
95	165:12	0:00	95%	32.1	0.01	4:56	29:51

There were large differences in the runoff duration between the examined roofs. The median runoff duration of the LECA-based roof (31.5 h) lasted 2.2 times longer than of the black roof (14.5 h). Considering average values, the mean runoff duration of the LECA-based roof (42.5 h) lasted 1.6 times longer than of the black roof (26.5 h).

Figure 5 serves to recognize centroid delays of individual runoffs. The steep rises in cumulative runoffs associated with the black roof response after intense rainfalls may be considered a potential cause of rapid floods. One can see that the LECA-based roof transformed these rises to either flat (effective detention performance) or—in extreme cases—gradual runoffs. The extreme cases may be seen in events 45, 62, and 89. Additionally, Figure 5 shows the largest snowmelt and rain-on-snow events; however, these were different types of events, shown only for comparison. Further calculations include only the eight largest events, as outlined in the methods.

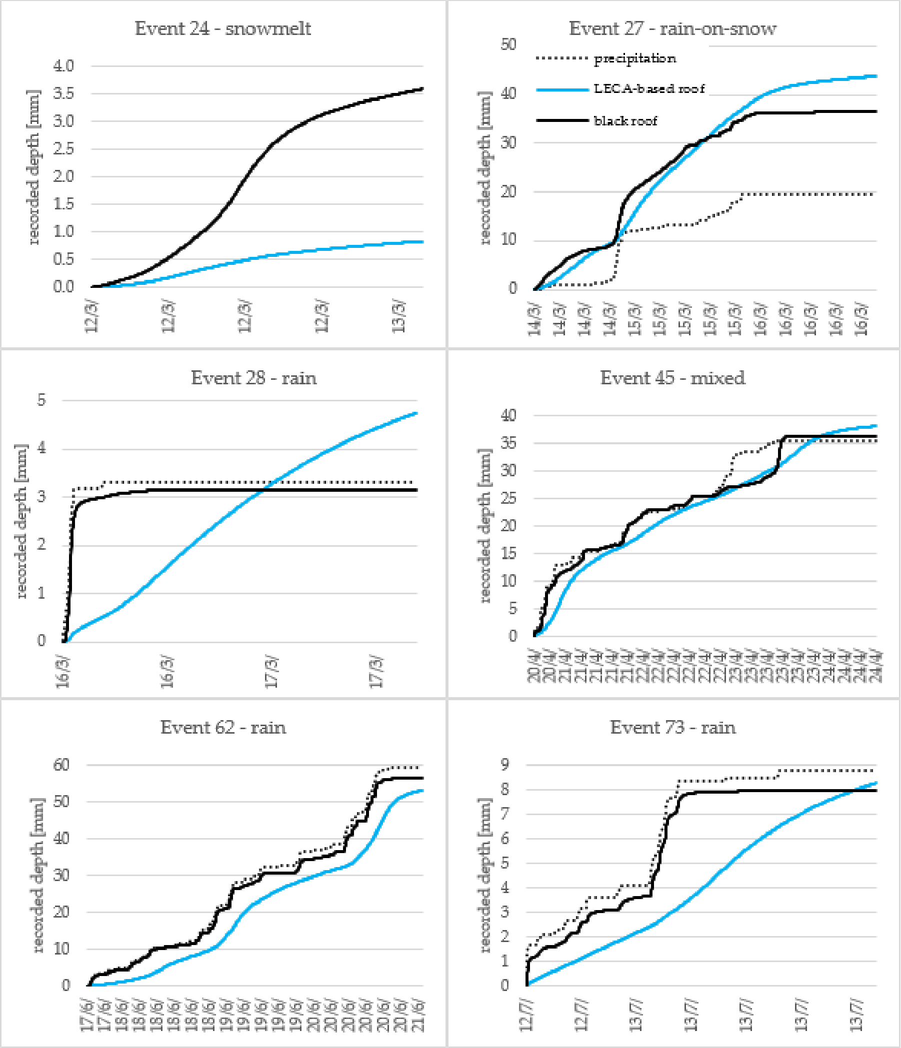

Event 24 - snowmelt
Event 27 - rain-on-snow
Event 28 - rain
Event 45 - mixed
Event 62 - rain
Event 73 - rain

Figure 5. *Cont.*

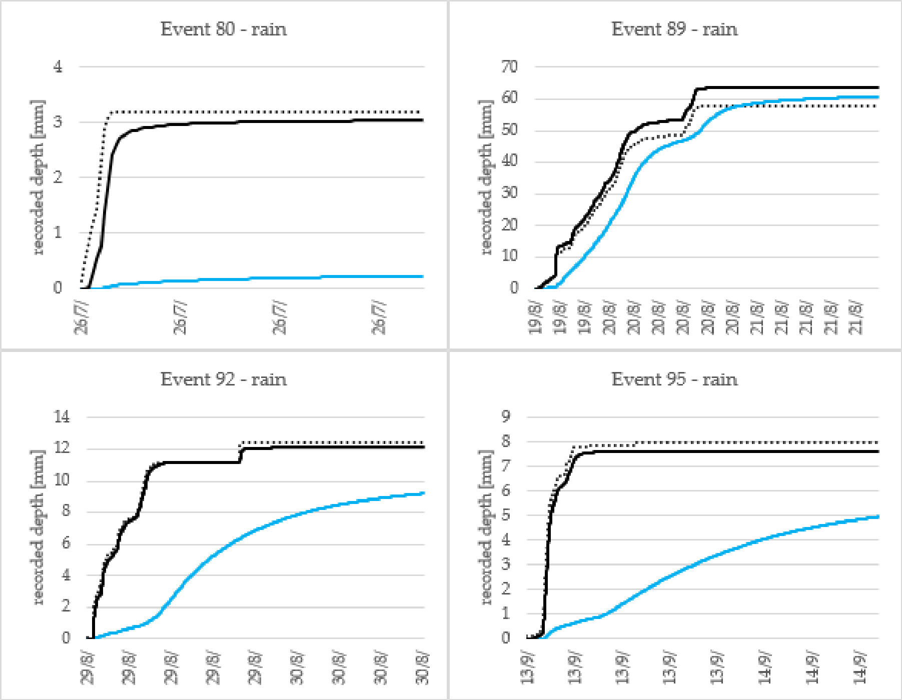


Figure 5. Cumulative runoff responses to the events with the highest peak 5-min intensity.

Considering shorter ADWP between events would result in a larger number of individual events. For instance, event 62 needed a 3 h ADWP to separate the event into two parts. Events 89 and 92, sharing a similar pattern, needed shorter breaks within the rainfall dataset (e.g., approximately 5–10 min), as there was continuous rainfall during this whole event. Using shorter breaks in the rainfall dataset would underestimate the total performance. For instance, the peak delay would change dramatically to 1 min (median) and 28 min (mean). Considering the centroids as the representative values, the peak delay counted 6 h (median) and 5 h and 51 min (mean).

Figure 6 presents a comparison of the alternative methods for runoff delays. The centroid delays were influenced by the short event 80, with small rainfall depth lasting only 8 min; this obviously led to a shortening of the centroid delay as well. During events 28 and 95, the quick responses can be clearly seen by the LECA-based roof runoffs, compared to the black roof peak runoff at the very beginning. This was probably caused by water collecting directly in the outlet (0.25 m^2). Therefore, those peak runoffs should not be considered as real responses of the LECA-based roof. Overall, the peak reduction presents 95% in median and 92% in mean.

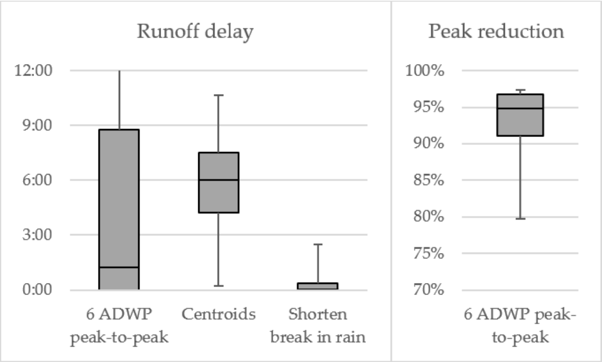


Figure 6. Comparison of the different methods of (**left**) the runoff delay and (**right**) the peak reduction.

5. Discussion

5.1. Retention Capacity

Retention is expected to be highest in the warm season. During the winter months, there was very limited measurable retention observed (2%). This is consistent with research [20] focused on potential evapotranspiration in cold and wet regions. Overall, the difference between the precipitation and runoff resulted in a 3% volume reduction for the black roof and 9% for the LECA-based roof. This is lower than the results presented by previous non-vegetated and green roof studies [1,3,10–13,22,24]. In terms of Norwegian conditions, Braskerud [31] presented a 25% runoff reduction in extensive green roofs in Oslo. This also agrees with the limited retention performance of the LECA-based roof. On the other hand, the result is most comparable with studies conducted in locations with wet and cool conditions [17,24]. The normalized daily retention during spring accounted for 0.54 mm per day, which is comparable with results from Beretta et al. [9]. As for the summer, 0.24 mm/day is about five times higher.

Nevertheless, it is a generally confirmed fact that water losses from vegetated roofs are higher due to evapotranspiration [25]. Berretta et al. [9] previously concluded lower daily moisture loss when using non-vegetated roofs compared to green roofs. Additionally, the reason for lower retention may be attributable to the concrete pavers, which cover and seal much of the surface area.

Average performance indicators may be useful for comparing different systems or even the same system exposed to different climatic conditions and/or for determining annual runoff, which does not have to be treated in a wastewater treatment plant. However, this data is very limited in terms of stormwater management design.

5.2. Detention Capacity

The performance indicators should reflect the performance in the non-daily events. Therefore, the eight largest events were examined. Evidence that the LECA-based roof can reduce peaks up to 95% (median) and 92% (mean) for significant events, as well as delay peaks by 1 h and 15 min (median) and 7 h 23 min (mean), provides support for its use in urban stormwater management strategies. The results of the peak reduction and delay, when neglecting the evapotranspiration effect, show a better performance than in the reviewed literature, for both the non-vegetated [10] and the green roofs [2,14,26,27,31].

The difficulties with defining events using the 6 h ADWP (resulting in some very long events) indicated that it might not be the best-suited time definition for the climate zone. These long duration events also cause decreasing mean intensity of individual events. Considering a maximum runoff as the representative value for an event may overestimate the overall performance in terms of the peak delay, even though it is more natural to compare events according to maximum registered values. The irregularity of natural rainfall patterns, combined with the variability within detention effect in specific events, complicates the identification of peak-to-peak delays. Centroid delays are perceived to be a more robust indicator of the delays in bulk runoff than peak delays [15]. Considering the centroids as the representative values, the peak delays total up to 6 h (median) and 5 h and 51 min (mean). Even though the vertical movement of stormwater (due to high saturated hydraulic conductivity; K_{sat} = 143.2 cm/hour) through the expanded clay aggregate is rather quick, the lateral movement through the media as well as the size of the roof (the distance between the sides to the outlet) and the slope of the roof are decisive and cause the high detention in the LECA-based roof.

5.3. Effect of Antecedent Events

Moisture levels in the expanded clay aggregate were higher than expected during dry periods. The expanded aggregate detains water for a long time, demonstrating why it is used for planting. However, very low saturation could be seen in November, when the moisture sensor registered low or negative temperatures. This can be explained by the inability of the sensor to accurately measure moisture in low temperatures, or a measurement error due to frozen media. Between July and November (Figure 7), every month experienced a long dry period: 156 h in July, 172 h in August, 278 h in September, 166 h in October, and 191 h in November.

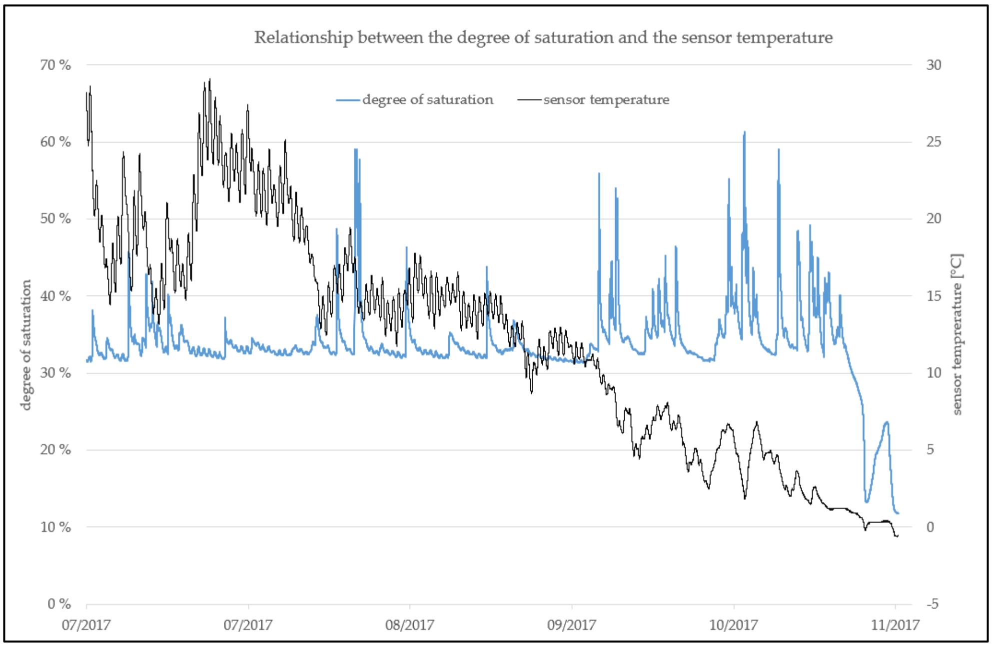


Figure 7. Variation of the degree of saturation within July and November.

Disregarding the long dry periods, the expanded clay aggregate kept a relatively high content of water within the medium. This clearly shows that the expanded clay aggregate was unable to fully regenerate its storage capacity to completely dry conditions, as in the laboratory. Despite the relatively high remaining saturation before an event, the LECA-based roof provided high performance in terms of peak reduction, as well as slowing down and transforming the runoff into a more natural flow for all seasons. Based on the moisture content measurements, a maximum storage capacity of 3.2 mm (0.28 m^3) was determined. This was also validated by a maximum observed precipitation of 2.7 mm, which did not generate runoff. The total available voids space (120 mm) is permanently taken by an inaccessible volume of 31%. This could indicate that there might be some capacity that could be gained by optimizing the size fractions. The void space is a function of this LECA type, making this yet another parameter which could be further investigated for optimal water detention. However, the water is adsorbed by the void spaces in the LECA, which additionally makes the water detention capacity dependent on the rainfall intensity.

5.4. Practical Implications

In light of the results and limitations, the LECA-based retrofitting shows promising results in terms of handling runoff from precipitation depths as a source control. This solution outperformed the conventional green roof solutions [14,18,26,27] in several aspects. The hydrological performance was evaluated for retention and detention, as well as for resistance to different forms of precipitation and durability. The practical implication of the LECA-based roof with respect to the detention performance includes runoff delays and peak flow reductions. Extending the durations of the runoff may significantly decrease the number of combined sewer overflows or the design volume of underground detention basins. The hydrological performance did not decline during the largest events recorded in this study, giving a strong indication of its performance, even during the more intense precipitation events. The LECA-based solution offers a detention capacity on the roof without allowing standing water on the roof membrane, as the water is held back and absorbed into the LECA material. An alternative solution would be an open or closed detention basin on the roof, or a cistern/closed tank system. A detention basin directly on the roof would exert water pressure on the roof membrane, increasing the risk of leaks. Standing water on the roof in a cold climate would freeze and contribute to blocked drains and ice formation on the roof. This would be a significant risk factor, as the ice expansion could also result in frost failure of the drains, which would lead to malfunctioning drains, and in the worst case, leaks into the underlying layers. A cistern-type solution would also experience freezing problems unless it was fully insulated or located indoors. The latter solution would be technically possible, as flat roofs always have internal roof drains in cold climates, again to minimize freezing of standing water. However, in urban areas where space is at a premium, it is more attractive to utilize the currently unused rooftop rather than sacrifice indoor space in buildings. The LECA-based solution is also an attractive solution to retrofit existing roofs, while the cistern solution would only be a feasible option for new buildings, due to the need for indoor space. Though it is not the only non-green alternative possible, the LECA-based system offers rooftop detention without introducing standing water pressure on the roof membrane, and with minimal ice formation risk due to the draining capacity, leaving no standing water on the roof.

In terms of estimated material costs per m^2, the LECA-based roof is approximately 40 €/m^2, whereas a green roof is 70 €/m^2 (following consultations with providers). Since the LECA-based roof performance does not rely on the evapotranspiration effect, it can used worldwide. The findings are specific to the LECA-based roof study and the specific actual rainfall that occurred during the study.

The weak points of the LECA-based roof in comparison to the green roof are in weight and in lower retention ability during warmer months. The LECA-based roof weighs 251 kg/m^2 in dry conditions and 310 kg/m^2 in wet conditions, whereas a green roof weighs 25 kg/m^2 in dry conditions and 50 kg/m^2 in wet conditions [32]. On the other hand, green roofs require irrigation during dry periods, periodical fertilization throughout the year, and have a deteriorated performance in extreme conditions [33].

6. Conclusions

The comparative study of precipitation and runoff data from two parallel rooftops (the LECA-based roof and the referenced “black” roof) was carried out at a coastal part of Trondheim, Norway. Eleven months of data were collected, analyzed, and divided into 127 events (94 rain events) according to a 6 h ADWP.

With respect to the previously reported findings, the retention performance of the LECA-based roof was lower than that of typical green roofs. This is because the water loss is only actuated by evaporation. For the entire studied period, the balance between precipitation and runoff of the LECA-based roof was estimated at 0.27 mm/day; this performance is 0.19 mm/day higher than the normalized daily retention of the black roof.

The runoff characteristics regarding to detention capacity of the LECA-based roof are particularly encouraging, even though the performance of source control systems typically struggle with intense rainfalls of short duration. Overall, the study demonstrated that the LECA-based configuration provided a large improvement compared with the black roof runoffs, with a peak reduction of 95% (median) and 92% (mean), and with a peak delay of 1 h 15 min (median) and 7 h 23 min (mean). This indicates that the LECA-based roof, with its improved detention performance, could be a good solution for the retrofitting of already-existing roof areas.

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and Jaran R. Wood interpreted the results with a general discussion with all authors. Jardar Lohne helped with structure of the manuscript and language correction. Vladimír Hamouz wrote the majority of the text, with feedback and input from Tone M. Muthanna, Jardar Lohne and Jaran R. Wood.

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