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Retention of snowmelt and rain from extensive green roofs during snow-covered periods

Bent C. Braskerud[a,*] and Kim H. Paus[b]
[a] City of Oslo, Agency for Water and Wastewater Services, Norway
[b] The Norwegian University of Life Sciences, Ås, Norway
*Corresponding author. E-mail: bent.braskerud@vav.oslo.kommune.no

ABSTRACT

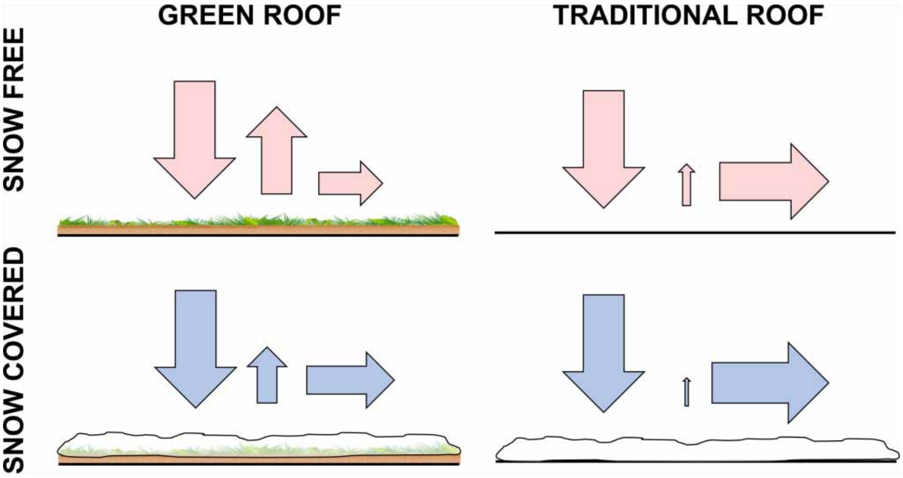
Green roofs are a popular way to include nature in an urban environment. A reduction in stormwater runoff peaks and volumes are among the benefits one can expect. How is runoff from green roofs in the cold and snow-covered part of the year, when growth media freeze, plants are dormant and covered with melting snow? This paper investigates 11 years of runoff from three green extensive roofs in Oslo, Norway. Precipitation through the snow-covered period (SCP) was approximately one-third of the annual precipitation (970 mm). When runoff from green roofs is compared to runoff from a non-vegetated bitumen roof, retention of 16–31% is seen through the SCP, depending on the drainage system, fabric, soil quality, and depth. The difference in buildup did not influence the detention of the largest runoff intensities. Dampening the runoff happened even though the substrate was saturated. According to the soil moisture sensors, the capacity of the roof with the highest water retention could be increased even more if drainage could be restricted. The runoff from the bitumen roof always exceeded the runoff from green roofs. As a result, harmful inundation may be reduced in a part of the year when infiltration is restricted due to frost.

Key words: cold climate, detention, runoff intensity, sedum, snowmelt intensity, stormwater

HIGHLIGHTS

- The combination of snowmelt and precipitation can cause harmful flooding in a cold temperate climate.
- Green extensive roofs reduce runoff even in colder months of the year with minor evaporation.
- Soil depth and green roof buildup influence the runoff retention, but not so much detention.
- This paper is probably one of the first to test green roofs in the snow-covered period of the year.

GRAPHICAL ABSTRACT



INTRODUCTION

While green roofs have been used in Norway for more than 1,000 years, extensive green roofs with low-weight mineral soil and a minimum of organic matter have become popular during the last decade. Despite the modest soil depth of extensive green roofs (i.e., 30–90 mm), studies such as Johannessen *et al.* (2018) have documented retention of rainwater in these stormwater best management practices (BMPs). Research typically reports that green roofs can both retain much of the annual precipitation via the sponge effect of the soil substrate, plant uptake, and evapotranspiration (ET) (Berndtsson 2010; Carson *et al.* 2013; Kuoppamäki 2021). Additionally, green roofs dampen the runoff peaks during heavy rainfall (e.g., Bengtsson 2005; Li & Babcock 2014). The water management properties of a green roof typically depend on the thickness of the porous media, type of vegetation, slope, configurations of outlets, and the local climate (e.g., Mentens *et al.* 2006; Losken 2008; Junker 2013; Kemp *et al.* 2018; Squier-Babcock & Davidson 2020).

While several studies have been conducted to evaluate the performance of green roofs in warm climates, or during frost-free periods, there is an obvious gap in knowledge on green roof performance during the winter season in cold temperate regions. During winter in cold climates, the growth media typically freeze, and snow is accumulated up to several months. Today, little is known about the performance of green roofs during such conditions as most studies in cold climates have excluded episodes with snow precipitation and melting from the investigation (e.g., Carson *et al.* 2013; Squier-Babcock & Davidson 2020). However, studies that include snow-free winter seasons often report that retention is decreased in the cold part of the year (e.g., Mentens *et al.* 2006; Squier-Babcock & Davidson 2020), even though no difference has been observed for low precipitation intensities (Carson *et al.* 2013). There are several reasons for less retention in the winter, but the absence of ET and a different rainfall distribution are often regarded as major factors (Mentens *et al.* 2006; Johannessen *et al.* 2017; Kuoppamäki 2021). In a review of green roof papers in cold temperate climates, Sysoeva & Gelmanova (2020) highlights the gap in knowledge on green roof ability to retain water under winter conditions.

Net radiation, air temperature, humidity, and wind speed are the main factors influencing snowmelt. While rain precipitation and heat from underground affect snowmelt rates, they are regarded as less important (Otnes & Ræstad 1978): For example, condensation of 1 mm of water vapor releases 7.5 mm of melting water, whereas 10 mm of rain at 8 °C only releases 1 mm. In addition, solid water can be lost through sublimation. A simpler approach than applying a full energy balance for quantifying snowmelt is the use of temperature index methods (e.g., degree-day methods). Here, snowmelt is related solely to temperature, reducing the need for the measurement of many variables such as radiation, humidity, and wind speed.

In the eastern region of Norway, the winter season has less precipitation than the other seasons. Nevertheless, winter is of special concern in the context of stormwater management due to frosty ground and ice-covered drains. Hence, a relatively small amount of snowmelt and/or precipitation on impermeable surfaces and frozen soils have the potential to generate relatively large amounts of surface runoff. In case the runoff is conveyed to the sewage system, the low temperatures of the runoff can, in turn, challenge operation at biological treatment plants.

Objectives

In this paper, we present hydraulic data from three pilot-sized green roofs in Oslo, Norway, monitored over 11 years. The main objective of this study is to obtain further knowledge on the functionality of green roofs during cold parts of the year in cold temperate climates with snow in the winter; Dfb according to the Köppen–Geiger climate classification (Peel *et al.* 2007). Given the frozen conditions and dormant vegetation, our hypothesis is that green extensive roofs have minor effects on retention (permanent holding water for ET) and detention or temporary holding runoff when compared to traditional non-vegetated roofs.

MATERIALS AND METHODS

Site description

The experimental site is located in Oslo, Norway, approximately 210 MASL (59°58′02″N, 10°44′81″E), and is a roof of a separate garage with a roof size of 24 m^2 and slope of 5.5% (‘flat roof’). The roof type is a black bitumen membrane. The garage roof is split into three 8 m^2 plots with separate green roof configurations (Figure 1). All green roofs were constructed with 30-mm pre-grown reinforced vegetation mats with a variety of sedum species supplied by two different manufacturers:

- *Roof 1*: Vegetation mat over a 25 mm of high-density polyethylene (HDPE) drainage layer from 2009 to 2011. Due to drought stress, a 10-mm retention textile fabric (RTF) was placed between the vegetation mat and the

Figure 1 | The green roof experimental site in summer (July 2017). Roof 1 to the left is drained. Roof 2 used to be a reference without vegetation for 5 years. Roof 3 has no drainage layer.

drainage layer in summer of 2011. Total height 65 mm + vegetation. Theoretical water storage based on Johannessen *et al.* (2018): 19 mm.

- *Roof 2*: Non-vegetated from 2009 to 2014 and acted as a reference for the first 5 years. During summer of 2014, roof 2 was vegetated with a vegetation mat, covering a substrate of 40 mm, a permeable fabric (0.4 mm) over an egg carton like HDPE drainage (20 mm). A 5-mm RTF was placed between the drainage layer and the bitumen roof. The main reason for changing the reference was that the discharge gauge registered very similar values to the precipitation gauge. Furthermore, at high precipitation intensities, the reference roof resulted in some water splash over to the green roofs which, in turn, complicated the water balance calculations. The total depth of the green roof is 125 mm + vegetation. Theoretical water storage is 24 mm.
- *Roof 3*: Vegetation mat over a 10-mm RTF. Total height is 40 mm + vegetation. Theoretical water storage is 13 mm.

The roofs are herein named GR1 (green roof 1), GR2 (green roof 2 during 2014–2021), GR3 (green roof 3), and REF (traditional non-vegetated roof during 2009–2014).

The substrate was an engineered soil and had a rather coarse texture. The typical particle size is 2–16 mm (only 7% had particle size less than 0.06 mm). The substrate for GR1 and GR3 was from the same manufacturer and was made of crushed lava rock, rock, and limestone; organic matter was 7–9%. GR2 had 17–19% organic matter in the vegetation mat, but only 4–6% in the substrate below (measured as a loss of ignition). Mineral matter was dominated by crushed bricks and Leca® (expanded clay).

Vegetation cover was 100% or close to fully covered most of the years. Dominating species are *Phedimus kamtschaticus*, *Sedum album*, *Sedum acre*, *Hylotelephium ewersii* and includes several other succulents.

Data collection

Runoff (i.e., the sum of runoff and drain) from the roofs was collected in a gutter from each plot and sent via a pipe to a 220 L of insulated collection tank (diameter: 575 mm). At low temperatures, a heating device kept the system frost-free. A Sutron 9210-B logger unit with pressure transducers (4techUC2) in each tank measured water depth every 5 min. When the water level in the tank reached 0.8 m, a pump automatically emptied the tank until the water level reached 0.2 m. 1 mm of runoff from the roof equaled a 33 mm rise in the tank. Each plot was calibrated separately prior to establishing vegetation. The whole system, except the heating, was driven by a 12-V battery to minimize the loss of data under thunderstorms with possible loss of external energy supply. Data were exported to the Norwegian Water Resources and Energy Directorate (NVE.no) for storage multiple times a day. Only 1% of the data have been lost during the 11 years of investigation.

Precipitation was measured with a Lambrecht 1518 H3, which has a snowmelt function. The rain gauge was situated 5 m west of the site, 1.7 m above ground. Precipitation was measured every minute and with a precision of 0.1 mm.

The air temperature was measured with a PT-100 and placed in a Young sunscreen 0.65 m from the north side of the site at the same level as GR1. Temperature sensors under the separate roofs were insulated from the garage room and pressed to the wooden roof under the bitumen cover. The temperature was measured every 15 min.

Soil moisture was measured via two systems, both situated approximately 1 m from the gutter. From the summer of 2010–2014, Vegetronix VH400 was used to measure the volumetric water contents of the soils in GR1 and GR3. The sensor was calibrated. The maximum water content was 45%. From the summer of 2014, Decagon 5TM sensors were used on all roofs. The sensors were not calibrated but gave 48% water content as a maximum.

Snow depth on the three roofs was measured manually using a ruler. Measurements were usually carried out after a snowfall and through melting periods. Four to seven measurements were done approximately 50 cm from the top side of each of the roofs and averaged. In situations where only parts of the roof were covered with snow (Figure 2), measured snow depth was average, as if the snow-cover was covering the whole plot.

Snow water content was measured several times through the winter season of 2017/18 using tubes (diameter: 10 cm and height: 50 cm).

Data analyses

Statistical analyses were carried out to identify the governing variables that best explain maximum roof runoff during SCPs. The complete dataset was employed to create a number of separate runoff episodes defined using the following criteria: (1) at least 6 h of runoff less than 0.1 mm/h before and after the episode, (2) runoff intensity exceeds 0.1 mm/h for at least 2 h during the episode, and (3) at least 1 cm of snow depth on the roof during the episode.

For each episode, the following variables were calculated for each episode using hourly resolution on observations: Maximum runoff intensity (mm/h), total precipitation (mm), precipitation fallen as snow and rain (mm), maximum precipitation intensity (mm/h), average precipitation intensity (mm/h), total duration of precipitation (h), mean, minimum and maximum air temperatures (°C), mean air temperature 24 and 48 h prior to the episode (°C), mean, minimum and maximum snow depth on the roof (mm) and change in snow depth between the start and end of an episode (mm). Additionally, roof type was included as dichotomous variables coded as 1 for the green roof and as 0 for the reference roof.

Stepwise multiple linear regression analyses were conducted using the MASS and caret packages in R (Venables & Ripley 2002; R Core Team 2013). Linear relationships between the dependent variable and independent variables were examined via scatterplots. Multicollinearity between independent variables was assessed by evaluating the Pearson pairwise correlation coefficients. When two or more variables showed a strong correlation (i.e., $|r| > 0.70$) only the variable that had the best correlation with the dependent variables was used in further analyses. Finally, the Shapiro–Wilk test was performed to test if the residuals were normally distributed. Statistical significance was declared with a threshold of a p-value < 0.05.

RESULTS AND DISCUSSION

A general overview

In 6 out of the 11 years, the annual precipitation passed 1,000 mm (827–1,066 mm). The precipitation and runoff amounts are divided into four seasons typical for the Nordic climate (Figure 3). For the winter

Figure 2 | Uneven snow melting from the three experimental roof plots (GR1 to the left). Photo: April 2, 2010.

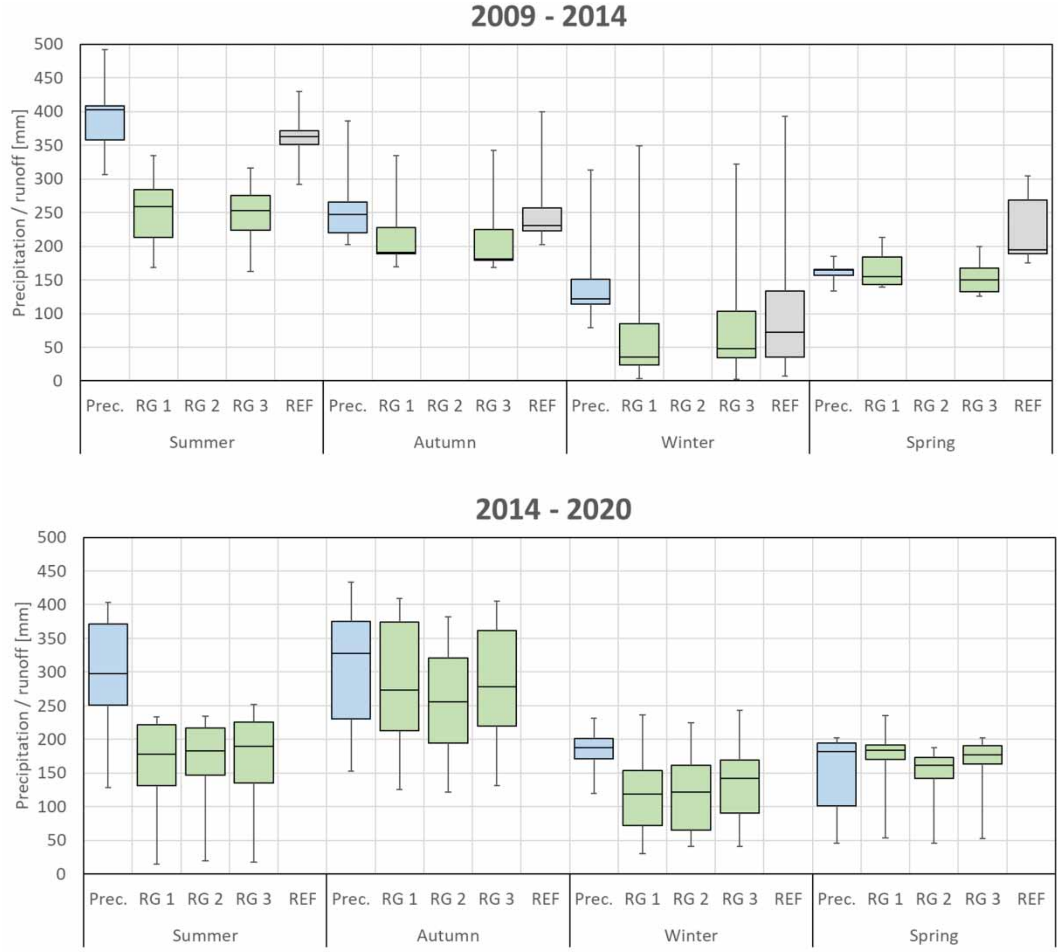


Figure 3 | Boxplots of precipitation and runoff on the three roofs through the two experimental periods (summer is June–August, winter is December–February). The first period (5 years) includes a black roof as a reference. The second period (6 years) all roofs were vegetated. Box plot with min, 25%, median, 75% and max observed runoff in episodes.

(December–February), precipitation was dominated by snow and was on average 156 and 183 mm in the first (2009–2014) and second (2014–2021) part of the experiment, respectively. The retention on GR1 and GR3 were 36 and 34%, respectively, while REF withholds only 18%. In the spring (March–May) snow from the winter was melting. In addition, precipitation came as rain and thereby accelerated melting rates. As a result, a net loss of water was observed at REF, while the losses were approximately nil for GR1, GR2, and GR3. The large difference between REF and the vegetated roofs is one obvious reason for investigating the performance of the green roofs in the cold part of the year. During summer (June–August), 36–44% of water is lost due to ET from the green roofs. Additionally, REF has some properties of water retention during summer. This is expected as minor rain events on a hot, black roof make the rain evaporate. During the autumn (September–November), temperature drops, vegetation prepares for winter dormancy, and less water is lost through ET.

When summing up the first 5 years of the study (Figure 3, upper panel), we see that a standard black roof does not contribute to the overall retention of water, while the extensive, green roofs do.

In Oslo, the snow-covered periods (SCPs) of the year will typically not coincide with the previously defined seasons. Hence, to address the functionality during SCPs solely, it is necessary to evaluate the characteristics of the winters and the roof performances with respect to water retention during periods when snow was observed on the roof. The experimental site had durations of SCPs approximately 5 months per year, usually ending in April. Snow could melt several times through the winter season resulting in a runoff. The first five SCPs were colder than the six that followed (average −3.3 and −0.5 °C, respectively; Table 1). Through the eleven SCPs, the average temperature increased by 0.46 °C annually ($r^2 = 0.38$ and $p = 0.02$). Temperature sensors below the roofs followed the average daily air temperatures.

Table 1 | Days between first snowfall to the last sign observations of snow, including maximum snow depth and air temperature. Precipitation and runoff in real and relative numbers on each of the three roofs

SCP	09/10	10/11	11/12	12/13	13/14	14/15	15/16	16/17	17/18[a]	18/19	19/20
Observations											
Days with snow	119	113	121	172	104	168	136	190	166	192	154
Precipitation (mm)	142	181	206	338	366	350	286	325	340	417	349
Runoff roof 2	143	210	218	415	456	312	251	271	209	327	368
Air average (°C)	–5,8	–5,8	–0,7	–3,5	–0,6	0,7	–0,8	0,1	–2,2	–1	0
Air min. (°C)	–20,3	–17,5	–14,7	–15,4	–12,3	–13,3	–14,4	–12,3	–13,1	–12,3	–6,9
Air max. (°C)	5,4	5,7	11,3	6,7	5,3	14,4	7,9	15,1	8,8	8,1	4,3
Max snow depth											
REF (cm)	48	30	54	41	37	–	–	–	–	–	–
GR1	52	30	64	50	38	38	29	28	80	46	19
GR2	–	–	–	–	–	30	20	25	75	39	14
GR3	42	30	49	40	27	28	23	24	74	34	18
Runoff in rel. nu.											
Precipitation	99	86	95	82	80	112	114	120	163	128	95
REF	*100*	*100*	*100*	*100*	*100*	–	–	–	–	–	–
GR1	98	72	83	75	92	110	107	104	106	119	106
GR2	–	–	–	–	–	100	100	100	100	100	100
GR3	95	66	81	79	83	107	111	114	111	118	108

Note: Precipitation and runoff from roof 2. Roof 2 had no vegetation (REF) during the first 5 years. Relative runoff compared to runoff from roof 2 (e.g., runoff in SCP 14/15 was 312 mm from GR2 and is set to 100). Runoff was 10 and 7% higher from GR1 and 3, respectively. Precipitation was 350 mm, which is 12% more than runoff for GR2.

[a] Half of the snow height had to be removed because the snow load could harm the roof.

The wind occasionally blew some of the snow from GR3 towards GR1, making the maximum snow depth 23 and 8% higher on GR1 and GR2, respectively (Table 1). As a result, we could expect that runoff from GR1 would exceed runoff from GR3, which is the case for the spring (Figure 3). However, on average, GR1 performed better than GR3 (approximately 3%). This is a surprise since GR3 is more sun exposed than GR1. The difference is, however, not statistically significant.

Relative retention

For some SCPs runoff from the roofs exceeded the precipitation measured in the rain gauge (seen as numbers less than 100 in Table 1 for the first 5 years). It is well known that rain gauges usually measure less precipitation than the real precipitation, due to turbulence around the instrument (e.g., Muchan & Dixon 2019). Collecting snow precipitation is even more difficult (e.g., Sandsborg 1972; Rasmussen *et al.* 2012); under catch of solid precipitation range from 20 to 50% under windy conditions. Consequently, the experimental site has two possible sources of error: both related to wind. The experimental site has no wind observations. However, the building is close to the forest, and local trees and two-storey houses give some shield. Still, for the first 5 years (Table 1), runoffs from the green roofs were from 2 to 34% less than REF. The difference between REF and the green roofs were statistically significant ($p < 0.04$), however, the difference between the two green roofs was not (16 and 19% for GR3 and GR1, respectively). The rain gauge had an under catch from 1 to 20% compared to REF. On average, the difference between the rain gauge and REF was 12%, and statistically significant ($p < 0.02$).

In SCPs, the average runoff was higher from REF than from the green roofs (Table 1). This changed to the opposite when REF was covered with vegetation. For the last six winters, GR2 had less runoff than GR1 and GR3 (8 and 12%, respectively), and was statistically significant ($p < 0.006$). This could be due to a higher substrate depth of GR2 than GR1 (i.e., 125 and 65 mm and water storage). The difference between GR1 and GR3 was not statistically significant. In summary, between 16 and 31% of the SCP-precipitation did not reach the downspouts and enter the sewage system, for GR3 or GR2 (Table 1). This implies that green roofs can assist in reducing water discharged to the combined sewerage system also during SCPs. This effect is important, not only to reduce the risk of combined sewer overflows (CSO) but also to reduce the amounts of clean and cold-water entering biological wastewater treatment plants that may result in operational difficulties (Metcalf & Eddy 2003).

It is expected that mild winters give more days with snowmelt and thereby runoff from roofs. In addition, precipitation would come as rain or slush, and not as snow. Through the 11 winters of observations, days with runoff could vary from 21 days in the 'cold' SCP of 2009/10, up to 121 days in the 'mild' SCP of 2014/15 (Table 1). This corresponds to 18 and 72% of the SCP, respectively. As a result, the roofs could be snow-free for periods. On average, half of the SCP had some melting, and 20% of the period had more than 1 mm/day runoff from the roofs. It was as suspected that the relationship between days with runoff and average daily winter temperature over 0 °C was statistically significant ($r^2 = 0.8$ and $p < 0.001$).

Highest daily runoff

The greatest runoff intensity during SCPs was measured on November 11 in 2018 from the GR1 and GR3 (Table 2). At this event the roofs did not have any snow-cover and rain (41.9 mm) was the main source of runoff. The greatest runoff intensity was when snow accumulated on the roofs occurred in mid-April during the SCP of 2012/13 on REF (Table 2 and Figure 4). The runoff was readily generated via snowmelt as only 7 mm of rain was observed.

GR1 and GR3 performed somewhat similarly for the maximum daily runoff throughout the study (Table 2, average 29,8 and 29,4 mm/day, respectively). In comparison, the highest daily runoff from the green roofs through the 11 years of investigation happened on August 29 in 2011, and was 49.7 mm/day. Precipitation was 54.1 mm.

Table 2 | Highest daily runoff in the SCP from the three green roofs and the reference roof (first 5 years of roof 2)

SCP no.	**09/10**	**10/11**	**11/12**	**12/13**	**13/14**	**14/15**	**15/16**[a]	**16/17**	**17/18**	**18/19**[a]	**19/20**[a]
GR1 (mm/d)	35.5	22.9	18.1	31.2	32.9	26.8	29.2	22.8	25.5	46.1	36.6
GR2 (mm/d)	–	–	–	–	–	21.4	29.1	23.6	24.6	42.5	36.7
GR3 (mm/d)	33.8	23.4	21.2	26.9	30.3	22.8	30.1	29.4	25.1	45.5	34.7
REF (mm/d)	*37.4*	*29.6*	*30.2*	*44.8*	*35.8*	–	–	–	–	–	–

[a] Rain on not snow-covered roof.

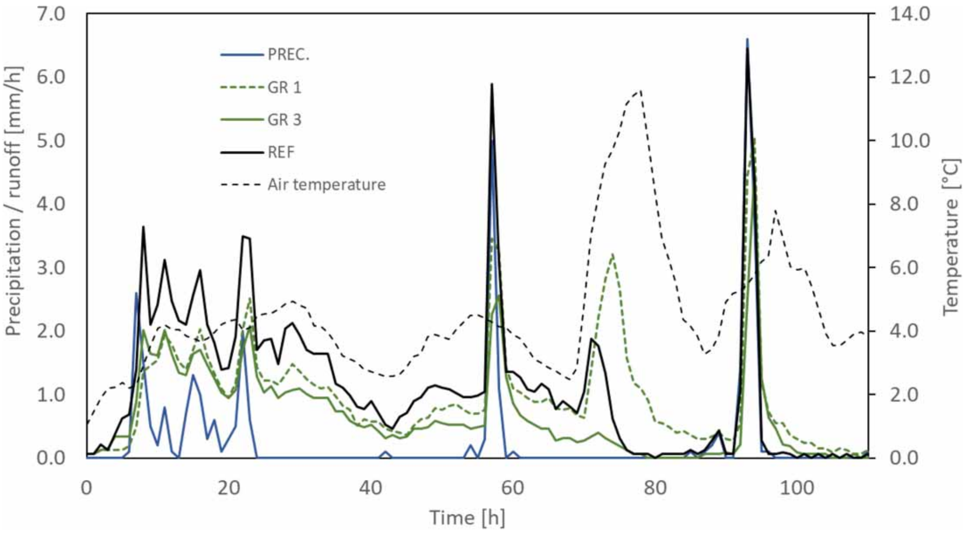


Figure 4 | Runoff from the snowmelt episode in mid-April 2013 was boosted by precipitation as rain. Snow depths on the roofs were 30 cm at the beginning of the episode and reached 0 cm at approximately 70 h (i.e., GR3) and 80 h (i.e., GR1 and REF). The last peak was an effect of precipitation alone. Even though the GRs are saturated, there is some peak reduction. The total runoff was 15 and 40% less than from GR1 and GR3, respectively, compared to the REF-roof.

The maximum runoff from REF consistently exceeded the runoff from the green roofs in the same period (average 34 mm/day compared to 25 mm/day) and was statistically significant ($p < 0.02$). For GR2, which was established after the SCP of 2014/15, the roof typically had less maximum runoff compared to GR1 and GR3. However, the difference was minor (average 29.7 mm/day compared to 31.2 mm/day), and not statistically significant.

During SCPs, GR2 also had the lowest runoff when compared to GR1 and GR3 (Table 1). The theoretical water holding capacity are 19, 24, and 13 mm for GR1, GR2, and GR3, respectively (Johannessen *et al.* 2018). GR1 and GR3 have the same manufacturer. The main difference is the drainage layer below the vegetation mat and the fabric. The drainage layer had no statistically significant effect during SCPs probably due to the rather slow runoff in winter. GR2 has a buildup depth of 2–3 times higher than the other roofs. If runoff for GR1 and GR3 is 16–19% less than a standard bitumen roof (Table 1), and runoff from GR2 is 8–12% less than the other two; an extensive green roof with a depth of 125 mm can withhold 24–31% of the precipitation through the snow period.

Detention of peak runoff during SCPs at temperatures below and above freezing

Figure 5 shows cumulative frequencies of hourly precipitation and runoff intensities from the roofs throughout the SCPs which includes snow-free periods with temperatures above and below 0 °C. The plots include all observations (i.e., both with and without precipitation and runoff) and only the upper percentiles are shown. Table 3 shows the precipitation and runoff from percentiles 95, 99, and 100% from Figure 5. As expected, the distributions of intensity frequency are highly dependent on whether air temperatures are below or above the freezing point during SCPs. While only modest amounts of runoffs are generated from the roofs during periods with $T < 0$ °C, the runoff intensities exceed that of precipitation in periods with $T > 0$ °C (Figure 5 and Table 3).

Interestingly, while the 1% greatest intensity for precipitation and green roof runoffs were about the same for this period (about 2 mm/h), the reference roof consistently had greater runoff intensities. In fact, the 1% greatest runoff intensity from the traditional roof during SCPs with $T > 0$ °C (2.8 mm/h) was the same as the 1% greatest

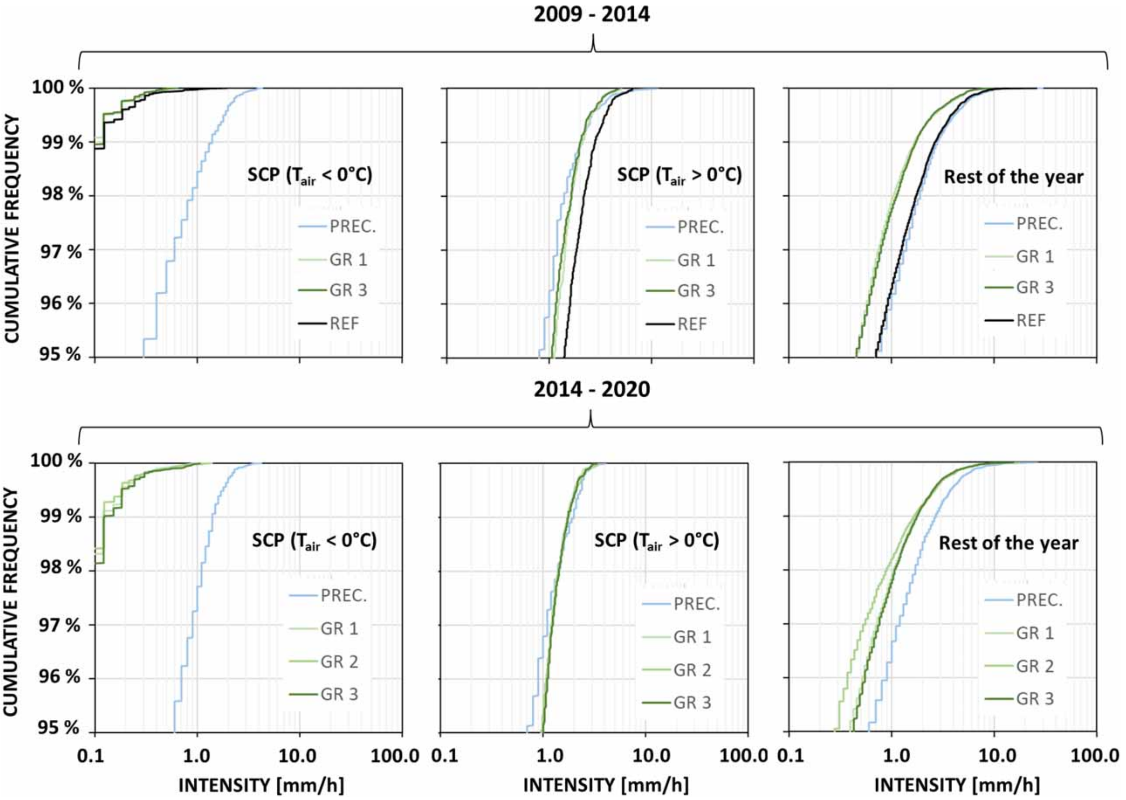


Figure 5 | Cumulative frequencies of hourly precipitation and runoff intensities from the roofs for various periods and situations. SCP is the periods from the first snowfall to the last snow had melted in the winter half-year. $T > 0$ °C includes episodes where the average air temperature is positive. 'Rest of the year' is more or less the summer-half-year.

Table 3 | Precipitation and runoff intensities (mm/h) for frequencies and various periods and situations

		SCP ($T_{air} < 0$ °C)			**SCP ($T_{air} > 0$ °C)**			**Rest of the year**		
		95%	**99%**	**Max**	**95%**	**99%**	**Max**	**95%**	**99%**	**Max**
2009–2014	Precipitation	0.30	1.40	4.30	0.80	2.10	11.50	0.70	2.80	29.70
	GR1	0.00	0.06	0.55	1.12	2.08	5.06	0.45	1.67	19.03
	GR3	0.00	0.12	0.64	1.07	2.01	4.82	0.46	1.74	15.35
	REF	0.00	0.12	1.94	1.39	2.81	6.51	0.71	2.69	25.89
2014–2020	Precipitation	0.60	1.40	4.20	0.70	2.00	4.10	0.60	2.70	26.20
	GR1	0.06	0.12	1.15	0.97	1.72	3.43	0.39	1.73	17.26
	GR2	0.06	0.12	1.39	0.96	1.76	3.58	0.28	1.67	16.80
	GR3	0.06	0.12	1.07	1.01	1.76	3.35	0.43	1.77	15.34

Note: Details in tabletop; see Figure 5.

precipitation intensity during the period where the rain intensities are the greatest (i.e., 'rest of the year'). The greater runoff intensities from the reference roof during melt periods typically coincide with the separate observations for each melt event as exemplified in Figures 6 and 7. The phenomena may be explained by the low albedo of the reference roofing (i.e., bitumen membrane). When parts of the roofing are exposed, the low albedo may have given positive feedback that accelerated snowmelt. For a green roof, a higher albedo is expected and hence the effect is less prominent. Additionally, under the assumption that temperatures below the roofs (i.e., in the garage) are greater than surrounding air temperatures, one would expect accelerated snowmelt at the reference roof due to the isolation effects of green roofs (Lundholm *et al.* 2014).

When considering the 'rest of the year', runoff intensities from the reference roof coincide with precipitation intensities. In contrast to this, runoff intensities from the green roofs are skewed towards the left hence showing the green roof's effect on reducing high precipitation intensities (Figure 5). For example, the 1% greatest precipitation intensities in the 'rest of the year' were 2.7 and 2.8 mm/h, while the 1% greatest runoff intensities in the same period varied from 1.7 to 1.8 mm/h (Table 3). The detention effect of green roof on high precipitation intensities is supported by findings in previous studies (Johannessen *et al.* 2018).

When comparing the two experimental periods (*i.e.*, 2009–2014 and 2014–2020) the dampening effects of green roofs appear consistent and runoff intensities from the individual green roofs typically coincide. One exception is GR2, which during the 'rest of the year', has somewhat lower intensities than GR1 and GR3 (Figure 5 and Table 3). This may be an effect of the larger water holding capacity of GR2. Nevertheless, the larger capacity of

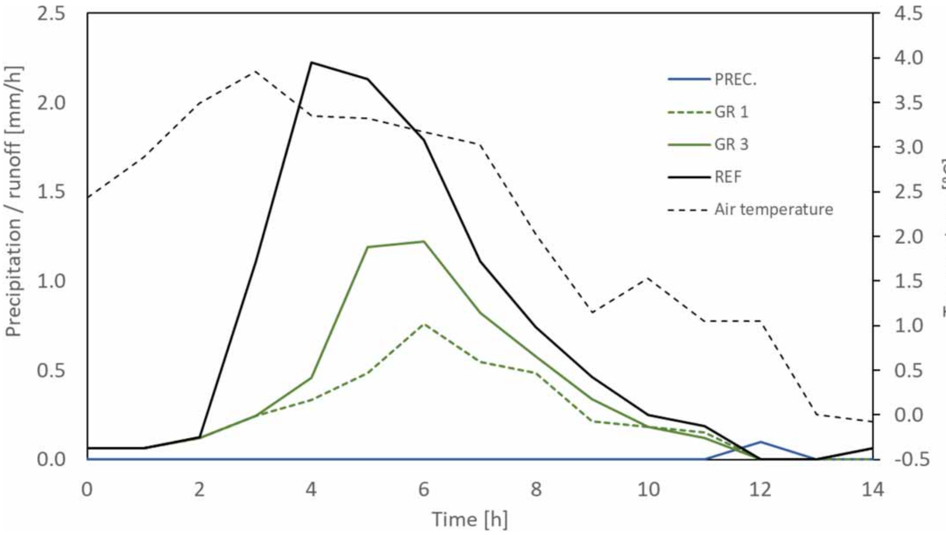


Figure 6 | Snow melting and runoff from the traditional roof (REF) and the two green roofs (GRs) followed air temperatures rather closely. Snow depth decreased from 5 cm in the beginning of the episode to 0 cm at the end. The relative runoff peak reduction was 66% for GR1 and 45% for GR3. The average water content in the substrate was 20 and 25% for GR1 and GR3, respectively. The substrate field capacities of the green roofs were reached since runoff had started before the runoff peaks.

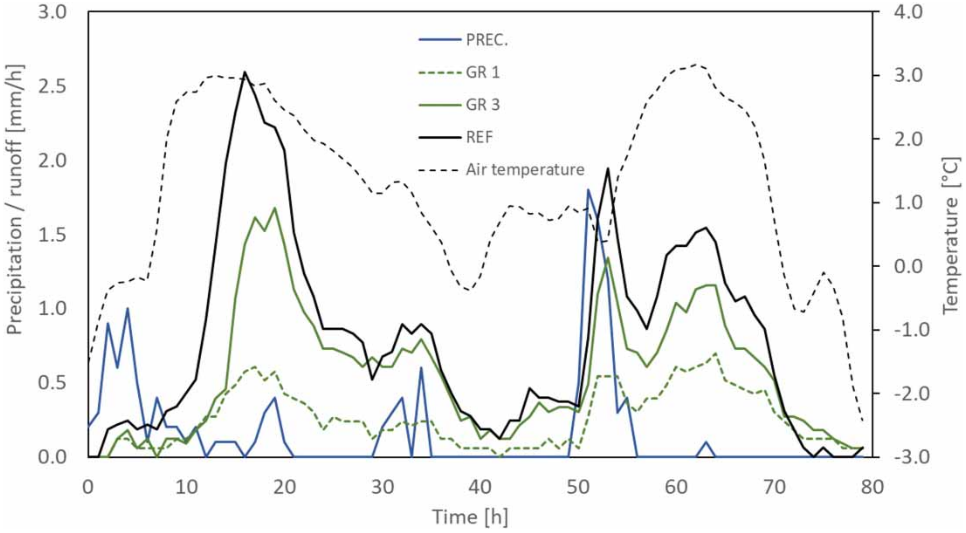


Figure 7 | Precipitation as snow (first 5 h) and rain (rest of the period) influenced the runoff intensities from the experimental site. Air temperatures appear to have a great influence on runoff intensities. Snow depth was 40 cm at the beginning of the episode, and 10–15 cm at the end. The total runoff volume was 68 and 30% less from GR1 and GR3 compared to REF. The substrate water content was 14% at the beginning of the episode in GR1, and 40% at the end. The respective were 17 and 45% for GR3. The substrate is totally saturated at a water content of 40–45%.

GR2 does not appear to affect the roofs' detention during periods dominated by snow-cover and melting snow (SCP).

From Table 3, it is also evident that the highest recorded runoff intensities occurred during the 'rest of the year'. This is expected as heavy rains during summer have the greatest intensities in Oslo. Nevertheless, the 5% greatest runoff intensities were not associated with this period but rather SCPs with temperatures above freezing. While the summer rains may cause a costly urban flood, high runoff intensities during spring can nevertheless be critical in drainage systems that are prone to thaw-freezing issues (e.g., frozen drains), and frozen soil with little infiltration. The dampening effect of the green roofs on these high runoff intensities is therefore not only a novel finding but can also be important to reduce the risk of melt-induced incidents in the drainage system. In summary, results show that green roofs, when compared to traditional roofs, reduce the runoff intensities throughout the year in cold climates.

Variables influencing the maximum runoff during SCPs

A total number of 505 runoff episodes during SCPs were identified. Variable statistics for the episodes are summarized in Table 4. The statistical analyses indicated that some of the independent variables were correlated. After rejecting the highly correlated variables, the total number of variables in the model was reduced from 17 to 10. The stepwise regression resulted in the following linear relationship:

$$Q_{\max} = 0.34 - 0.39 \cdot RT + 0.52 \cdot P_{\max} + 0.12 \cdot T_{\max} - 0.07 \cdot T_{\min} - 0.01 \cdot h_{\min} + 0.02 \cdot dh \tag{1}$$

where $Q_{\max}$ is the maximum runoff (mm/h), RT is the roof type (0 for REF and 1 for green roof), $P_{\max}$ is the maximum precipitation intensity (mm/h), $T_{\max}$ and $T_{\min}$ is the maximum and minimum air temperatures, respectively (°C), $h_{\min}$ is the minimum snow depth (cm), and dh is the reduction in snow depth snow during the episode (cm). The R^2 and R^2_{adj} for Equation (1) were both 0.72 and all variable coefficients were significant.

As expected, it can be seen from Equation (1) that maximum precipitation intensity, maximum air temperature, and reduction in snow depth all increase $Q_{\max}$. Furthermore, green roofs, minimum air temperature, and minimum snow depth decrease $Q_{\max}$. By evaluating the coefficient values in terms of the variable intervals given in Table 4, some interpretations of the effect of green roofs for $Q_{\max}$ can be evaluated. Using median observed values in Equation (1) gives $Q_{\max}$ 0.81 mm/h with GR, and 1.2 mm/h with a black roof. A decrease of 33%. For mean and maximum, the effect of GR is 24 and 6% detention, respectively. There is an effect of using green roofs, however, the effect decreases especially as precipitation and air temperature increase. Minimum

Table 4 | Variables used to predict and explain the maximum runoff from the roofs

Variable	Symbol	Unit	Min.	Median	Mean	Max.
Maximum runoff intensity	$Q_{\max}$	mm/h	0.1	0.6	1.0	6.5
Episode duration	t_d	h	2	17	37	331
Total precipitation	P	mm	0.0	0.5	7.4	72.3
Precipitation as snow	P_s	mm	0.0	0.0	1.2	14.6
Precipitation as rain	P_r	mm	0.0	0.4	6.1	69.7
Maximum precipitation intensity	$P_{\max}$	mm/h	0.0	0.3	1.0	6.8
Mean precipitation intensity	P_{mean}	mm/h	0.1	0.6	0.6	1.6
Precipitation duration	t_r	h	0	2	11	139
Mean air temperature	T_{mean}	°C	−6.8	2.6	2.8	14.5
Minimum air temperature	$T_{\min}$	°C	−8.0	0.0	0.5	12.0
Maximum air temperature	$T_{\max}$	°C	−6.0	4.7	4.9	16.1
Mean air temperature 24 h before	T_{24}	°C	−7.8	0.3	0.4	8.3
Mean air temperature 48 h before	T_{48}	°C	−6.4	0.1	0.1	8.1
Mean snow depth	h_{mean}	cm	0	9	14	64
Minimum snow depth	$h_{\min}$	cm	0	7	12	64
Maximum snow depth	$h_{\max}$	cm	1	12	15	64
Reduction in snow depth	dh	cm	0	1	3	34

Note: Observations are from the 505 episodes. Details on each variable is presented in 'Methods'. Equation (1) is valid for the observations in the table.

temperature, snow-cover, and snow melting usually have less effect on the runoff according to Equation (1). Overall, the effect of green roofs in reducing $Q_{\max}$ is consistent with the results of Figure 5 and Table 3.

'Snow ageing' is an effect of snow crystals changing. Temperature and liquid water are important in this process. New snow has often a density of 0.1 kg/L (1 cm snow = 1 mm water). However, as winter goes by the density increases as shown in Table 5. When density is close to 0.4 kg/L, liquid water runs through the snowpack (Otnes & Ræstad 1978). On the other hand, as this investigation shows, runoff may happen even when snow density is less. Runoff was usually going on from late February to the beginning of April, with the largest peak late March.

Density measurements were not done on a regular basis, since snow-cover was often unstable, especially in the last years of the investigation. As a result, it was not possible to make a mass-balance based on snow water equivalents and measured runoff to find the possible effect of sublimation.

As snow may work as a reservoir for precipitation fallen as rain, we had expected reduced runoff during SCPs. Equation (1) suggests that the snowpack could have this effect, even though minor. In general, this effect is expected to increase with the degree of insulation of the roof (Lundholm *et al.* 2014).

Altering the buildup for improved retention

The substrate used for vegetation growth typically has a high porosity. Crushed bricks, Leca®, pumice, and other similar ingredients have in addition an inner volume for water to infiltrate. As a result, the water storage capacity can be rather high. This extra volume could be used to increase the detention if water is restricted from draining the roofs easily.

The initial water content (IWC) was measured through two different systems (see methods). In the frosty part of the SCPs the water content, probably as ice, was usually 18–20%, according to the Vegetronix, but only 3–5% according to the Decagon. As far as we know, neither system was made for measuring solid water. However,

Table 5 | Snow water equivalents (SWE) through the SCP 2017/18

Date	Feb. 13	Mar. 10	Mar. 25	Mar. 29	April 7	April 9
Density (kg/L)	0.17	0.24	0.22	0.26	0.37	0.40

Kuoppamäki (2021) found similar results and interpreted it as the amount of ice that can be built up in the coarse substrate is low. As temperature increases and melting starts, the soil is saturated often to 45% according to the Vegetronix. The Decagon system gives a more detailed result:

- For GR1, the water content was usually between 8 and 30% under melting, with 38% as a maximum.
- For GR2, the water content never surpassed 16%. The typical water content was 15%.
- For GR3, the water content varied usually 8–45% under melting, with 48% as a maximum.

The highest water content was usually measured in the spring, at the end of the melting season.

The water content is reflected by the way the green roofs are constructed. GR1 and GR2 are drained. Hence, less water bypasses the sensors under snowmelt. GR1 and GR3 have a 10 mm RTF below the vegetation mat. The fabric slows down the drainage of water. As a result, GR3 is usually wetter than GR1 and GR2. GR2 with no drainage obstacle contain the least water of the three. If a fabric was put between the substrate and the drainage system, the GR2 system would use more of the available space in the substrate for water retention. It could be a volume of 40–50%.

According to Teemusk & Mander (2007), vegetation may have some importance under snow melt. The authors reported that the runoff intensities and volumes during a period of melting, were lowest from the green roof with the highest vegetation cover. They did not try to explain why this was the case. Could a greater root volume in the 100 mm Leca® substrate be of some importance, increasing the organic content?

CONCLUSION

Green roofs reduce runoff even in the cold part of the year with minor evaporation. Results show that the green roofs are significantly reducing and slowing the runoff, hence reducing the volume of cold-water entering treatment plants and the risk of exceeding the capacity of the downstream sewer system during this period.

A non-vegetated reference is needed to monitor the effect of green roofs in the SCP of the year since precipitation gauges usually have a significant under catch. On our site, it was an average of 12%.

In SCPs, there is no runoff from the roofs in 98% of the time as long as the air temperature is below zero. For air temperatures over zero, snow is melting, and the 1% highest runoff intensities (1.7–2.1 mm/h) could be greater than the similar 1% highest runoff intensities in the summer, even though the precipitation in summer is larger and more intense. The maximum runoff was, however, several times higher in 'rest of the year' (summer-half-year).

GR1 and GR3, with only 2–3 cm substrate over a textile fabric often had similar average runoff intensities. Runoff volumes decreased by 16–19% compared to the traditional black roof. GR2 had a deeper substrate, a drainage system with a higher water holding capacity, and less runoff. As a result, the average retention through the SCP was 24–31%. This buildup could be developed to perform better, e.g., by putting a fabric between the substrate and the drainage to prevent an easy loss of water.

Precipitation as rain and *air temperature* are the most important factors influencing the runoff intensities from snow-covered roofs with or without vegetation. However, extensive green roofs always dampen the runoff compared with a traditional black roof. The effect of detention decreases as the precipitation and air temperature increase.

With climate change, snow melting occurs more frequently. As much as runoff episodes have high variability, it is difficult to predict a certain retention or detention performance from the green roofs. However, this investigation has shown that even thin substrate, and extensive green roofs may make a difference.

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AUTHOR CONTRIBUTION

B.C.B. has designed the experimental set up, built the green roofs, followed up the field observations, and controlled the data. B.C.B. and K.H.P. have done the analyses and written the manuscript together.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details. Data are available on request to Braskerud.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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