Limitations in using runoff coefficients for green and gray roof design

Lotte Askeland Schärer, Jan Ove Busklein, Edvard Sivertsen and Tone M. Muthanna

ABSTRACT

Climate change combined with urbanization increases the performance demand on urban drainage systems. Green roofs are one of the most used green infrastructure measures to alleviate the pressure on the urban drainage system through the detention and retention of runoff. The rational method with the runoff coefficient (*C*) is one of the most commonly used design tools for stormwater design in Norway. This method relies on a runoff coefficient being available for green roofs, which is typically not the case. This paper compares laboratory and experimental field studies to investigate runoff coefficients from different types of detention-based roofs. The methodology described in the German 'FLL Guideline', one of the world's most commonly used green roof standards, was used to measure the runoff coefficients for the different components making up a typical green roof. The contribution from each layer is reflected in the runoff coefficients. The runoff coefficients from the field experiments were calculated using observed precipitation and runoff from existing green roofs in Oslo, Trondheim, Sandnes, and Bergen, Norway. Events that had a cumulative precipitation comparable to the laboratory events, but longer durations, were selected. These events gave significantly lower and varying runoff coefficients, clearly demonstrating the limitation of choosing a suitable runoff coefficient for a given roof. However, laboratory experiments are important in understanding the underlying flow processes in the different layers in a detention-based roof.

Key words | detention, green roof design, laboratory scale, rational method, runoff coefficients

Lotte Askeland Schärer
Tone M. Muthanna (corresponding author)
Department of Civil and Environmental Engineering,
The Norwegian University of Science and Technology (NTNU),
S.P Andersens vei 5, 7491 Trondheim,
Norway
E-mail: *tone.muthanna@ntnu.no*

Jan Ove Busklein
Edvard Sivertsen
SINTEF Building and Infrastructure,
Høgskoleringen 7b, 7034 Trondheim,
Norway

INTRODUCTION

An increased performance demand on the urban drainage system from climate change and urbanization is a worldwide challenge. Climate change leads to a change in rainfall frequency, a general increase in the intensity and frequency of extreme events (Intergovernmental Panel on Climate Change [IPCC] 2013; Hanssen-Bauer *et al.* 2015). Combined with urbanization, damaging rain-induced flood events will increase in frequency (Norges Offentlige Utredning [NOU] 2015, p. 30). In Norway, a three-step approach to stormwater management has nationally been adopted. Step one: infiltration of all small events; step two: detention of medium events; and step three: ensure safe flood ways for the larger events. The first two steps are mainly about reducing the impermeable surface area, and increasing infiltration and evapotranspiration. Rooftops typically make up as much as 40–50% of the paved surfaces in cities, which

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make detention-based roofing a promising solution (Stovin et al. 2012; Berretta et al. 2014; Sobczyk & Mrowieck 2016; Hamouz et al. 2018).

Rooftop detention can be accomplished through different solutions where green roofs are the most common. Green roofs are made to collect, store, and retain precipitation through evapotranspiration and detention in the substrate. By converting impermeable roofs to something more akin to natural landscape, one can achieve a significantly reduced and delayed peak runoff (WEF 2012, p. 326). The typical buildup of a green roof consists of plants, substrate, root barrier, drainage layer, and an impermeable membrane. For the vegetation sedums, plants are commonly used. The robustness of these plants requires little maintenance and less soil. These plants are robust and require little maintenance and little soil. These types of green roofs are called extensive green roofs and are characterized by their thin profile thickness of less than 100–150 mm (WEF 2012, p. 326; Berretta et al. 2014). However, detention can also be achieved through various non-vegetated detention substrates and media. These types of roofs commonly use an extruded clay aggregate layer to achieve detention caused by the porous media the water flows through. In addition, a top layer of pavers is needed to keep the detention layer in place (Andenæs et al. 2018).

Retention of water through evapotranspiration and detention through temporary storage and peak flow delay in the substrate and drainage layers are the two most commonly studied hydrologic functions of green roofs, according to a review article by Andenæs et al. (2018). Detention-based studies investigate detention performance with focus on peak flow reductions for single events, whereas the retention-based studies investigate water retention in the form of evapotranspiration over a longer period of time. A study by Johannessen et al. (2017) investigated the green roof performance potential in cold and wet regions. The evapotranspiration was found to be a limiting factor for the green roof retention capacity, with almost negligible values in the winter. Hamouz et al. (2018) presented an extruded clay aggregate-based detention layer overlaid with lightweight concrete pavers to keep the extruded clay in place (wind protection). The retention on this roof was found to be lower than a typical green roof, as this system does not offer any transpiration, and evaporation can only occur in the slits between the pavers. Though the retention was less in the extruded clay aggregate roof system, it showed very promising detention capacity. Stovin et al. (2015) performed an outdoor study in Sheffield, UK, based on nine test beds with different substrates and vegetation. Rainfall- and runoff data over a 4-year period were collected. This study provides both lower retention and detention on the non-vegetated test beds, as well as for the large-pored and permeable substrate. Johannessen et al. (2018) studied retention and detention performances for extensive green roofs in different Norwegian locations. In order to investigate detention metrics, it was necessary to identify single events in the continuous time series. This was particularly challenging in a coastal climate with a more or less continuous stream of low-pressure weather systems from the Atlantic. This resulted in large variability in metrics, even with 3–8 years of collected field data. This variability showcases the need for geographical site-specific design of green roofs. However, there is a need to understand the water detention in the various components and layers of green and gray roofs in order to improve performance prediction for use in design. Currently, this information is to a large extent unknown and not available. Further, with more knowledge of the performance of each layer, it will be possible to optimize layer composition for different climatic zones, as well as meeting local discharge regulations and building restrictions.

One possible and commonly used metric to capture the detention performance is the runoff coefficient from the rational method (Kuichling 1889). The rational method is one of the most commonly used design tools for urban runoff calculations, where the runoff is found as a function of the area times the rainfall intensity times a runoff coefficient. The runoff coefficient is given as the relationship between precipitation and runoff. It can be calculated either by the ratio between the intensities of the peaks or the volumes. This ratio is typically applied at the outlet of a watershed. In order to improve design calculations, more knowledge is needed on the runoff coefficient for detention-based roofs, broken down to the individual layers in the roof systems. Hence, the objective of this paper is to compare laboratory and experimental field installations to investigate runoff coefficients for different layered roofs with focus on the detention. Further, it is discussed to what extent the use of runoff coefficients from detention-based roofs is an appropriate tool. More specifically, we wanted to answer the following research questions:

1. What are the runoff coefficients of different types of detention-based roof systems?
2. How does laboratory measured runoff coefficients compare with field observations?
3. How appropriate is the use of runoff coefficients for detention-based roof design?

STUDY AREA AND DATA

This study is based on data from a set of laboratory experiments and four field test roofs at different locations in Norway. The green roofs are located in the cities of Oslo, Trondheim, Sandnes and Bergen in Norway. Three of the four locations are characterized by a coastal climate, classified as temperate oceanic climates (Cfb) in the Köppen-Geiger classification, while Oslo, located in eastern Norway, is classified with warm summers and a humid continental climate (Dfb) in the Köppen-Geiger classification (Peel Finlayson & McMahon 2007). Intensity, Duration, and Frequency (IDF) curves, given by the Norwegian Center for Climate Services (NCCS, www.klimaservicesenter.no), show that the climate in Oslo differs most from the other locations, with more frequent, shorter, and more intense precipitation events compared to the other sites. The IDF curves for Bergen, Sandnes, and Trondheim show events of lower intensity with smaller differences in intensities between the different return periods.

The four roofs chosen for the study were constructed for field research, described by Johannessen et al. (2018). The roofs consist of different sections with test beds from three to five test beds, made up of varying commercial green roof solutions. This study focused on one of the four roof sections at each location, namely the roof consisting of a 10 mm felt mat underneath a layer of sedum, which is equivalent to R4 in Figure 1. The area of the roof in Oslo is 2 m × 4 m, with a slope of 5.5%. In Trondheim, the area is 7.5 m × 2 m, and in Bergen, the area is 4.9 m × 1.6 m, both with a slope of 16%. The area in Sandnes is 5.4 m × 1.6 m, with a steeper slope of 27%. Climatic data from a period of 3 years are collected in Trondheim, Sandnes, and Bergen. For the roof in Oslo, data are collected over a period of 8 years (Johannessen et al. 2018).

METHODS

For the laboratory part of the investigations, the German standardized method (FLL 2008), which has standardized the procedure for investigating the runoff coefficients of green roofs, was used. In order to understand the behavior of each individual layer making up the different roof configurations, the runoff coefficients for individual layers were tested first, and subsequently, the different roof configurations were tested as a complete solution. In order to relate the results from the laboratory to field observations from four different locations in Norway were compared to the runoff coefficients measured in the laboratory.

Laboratory measurements

The method used to determine the runoff coefficient for the different roof layers and the combination of layers is in this study based on the 2008 edition of German FLL's guidelines for planning construction and the maintenance of green roofing (FLL 2008, p. 100). There is no national guideline available in Norway. The FLL standards have previously been used in Norway by Busklein et al. (2014). Using the FLL standards in the current study enables an easy comparison to previously conducted studies and thereby facilitated the discussion of the results

The materials tested in this study are typical components of green or extruded clay aggregate-based roof solutions. To find the runoff coefficient (C), for the different roof configurations, in total 10 single layers or combinations of the layers were tested. Configurations for each experiment (run, R) are shown in Figure 1. In addition to these ten runs, a reference roof test was added, which tested the plain roofing material without any additions. This was used to compare the results to standard black roof, denoted reference roof from hereon.

The FLL guideline requires that the test roof should be constructed with a 2% drainage gradient, a width of 1 m, and be placed inside a wind- and rain-protected testing hall. The method specifies a block rain of 27 mm over the

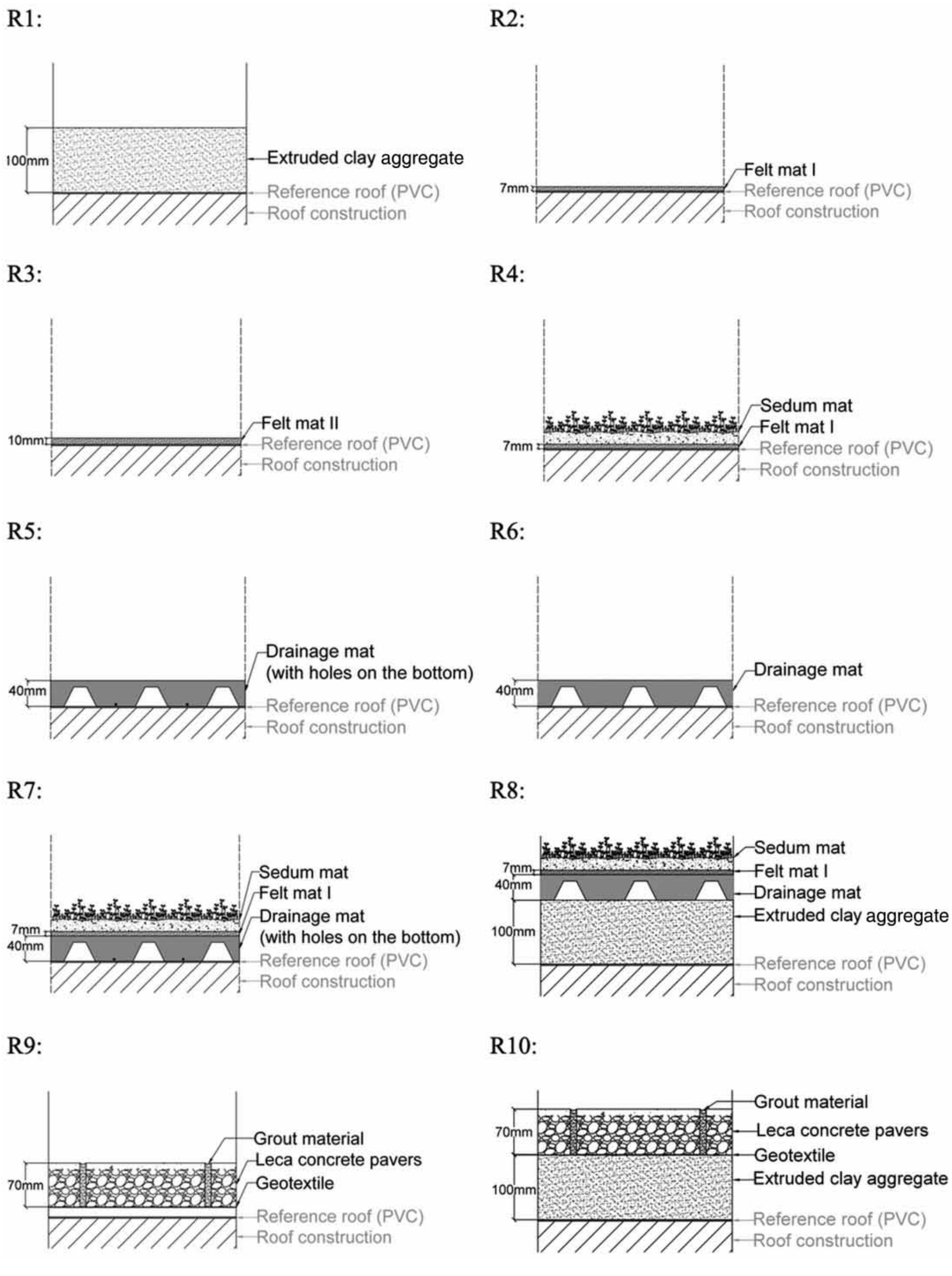

Figure 1 | Section drawings for the composition of the different runs; R#.

duration of 15 min. This is a high intensity event for the locations in this study, which exceeds the 100-year event for all the locations in the study. As green roofs are predominantly designed to handle the smaller events, described as a step 1 solution in the three-step approach to stormwater management in Norway (Lindholm *et al.* 2008), it was decided to include a more relevant and moderate event for comparison between the field and laboratory results. The four locations are located in different climatic classification regions, as described in the case study section; however, a 11.4 mm event over 15 min was chosen to represent a more typical event which should be handled by green roofs. This represents a 5-year event in Bergen, a 10-year event in Sandnes, and between a 2- and 5-year event in

Oslo (10.3 mm/15 min for 2 years and 14.1 mm/15 min for 5 years), while, in Trondheim, it is equivalent to a 50-year return event. Trondheim observes significantly lower intensity events compared to the three other locations. The runs using this event were tested on the two complete roof configurations denoted in R8 and R10 in Figure 1.

Prior to the test, the roof material should be pre-wetted to saturation by continuous irrigation for 10 min beyond reaching a constant runoff rate. This is followed by a subsequent 24-h drainage time, after which field capacity is assumed. The method then prescribes three repetitions for each test with 24-h intervals. The runoff coefficient C is then given by the following equation:

$$C = \frac{R}{V} \tag{1}$$

where V is the total volume of water added in liters and R is the volume of runoff in liters at the time when the precipitation ends, in this case 15 min.

In this study, the area of the modeled roof was 2 m × 2 m. The precipitation was supplied using 16 nozzle tubes placed 80 cm above the roof construction. The system was calibrated to give a total amount of 27.4 mm in 14.67 min, which was considered accurate enough to the 15 min prescribed treatment time. The runoff was measured with a 0–100 mBAR PTX1400 pressure transducer in a collection tank at the downstream end with a two second time resolution (Figure 2). For R2, R3, R5, R6 and R9, the prescribed 24-h period between the pre-wetting and the test was omitted, as these were single-layer runs where a 24-h period would have completely dried them up. For these runs, field capacity was assumed at the end of runoff from the pre-wetting phase. The permeable pavement (R9) was lifted 1.5 cm by using steel rods since the water flows vertically through the joints but not horizontally through the concrete pavers.

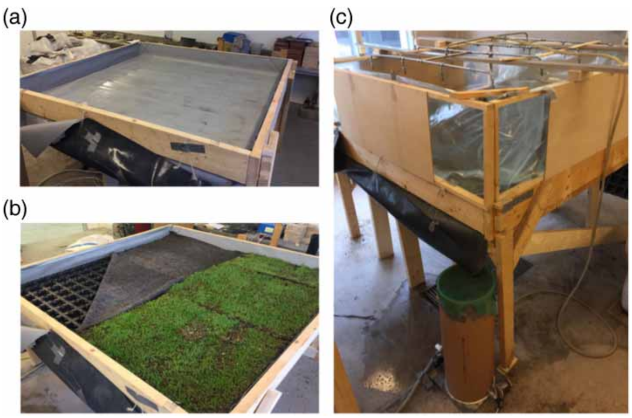

Figure 2 | Illustration pictures from the laboratory: (a) reference roof; (b) example of built up, R7; and (c) running the simulation.

Darcy's and Manning's formulas are used to calculate the horizontal flow occurring in the different drainage layers. The permeable layers and the drainage layers can be described as a filter with flow across the filter. The flow may be described by Darcy's formula:

$$Q = \frac{K(h_{sf} + d)}{d} \times A_{sf} \tag{2}$$

Q (V/T) is the flow through the media, K (L/T) is the hydraulic conductivity, h_{sf} (L) is the depth of ponding over the filter media surface, d (L) is the thickness of the filter media, and A_{sf} (L^2) is the surface area of the filter media. When a free surface flow occurs, the flow can be described by Manning's formula as:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \tag{3}$$

Q (V/T) is the flow, n is the Manning's roughness coefficient, A (L^2) is the cross-section of the flow, R (L) is the hydraulic radius, given as flow depth for wide 'channels', and S (L/L) is the slope.

Field measurements

Data from selected precipitation events at the four field locations were used for comparison with the laboratory results. The events were selected from continuous precipitation records at each location. A precipitation event was defined as precipitation after a minimum of 6 h of -antecedent dry weather period. From these, only events producing runoff were selected. In a final step, only events from May to October were selected in order to avoid data from snow-covered roofs, which may appear in Oslo and Trondheim. The outcome of the selection procedure is displayed in Table 1.

Table 1 | The selection of events from the total number of single events in the continuous data series from the field observed green roofs

Observation period		Total number of observed precipitation events	Events resulting in runoff	Events from May to October (excluding winter)	Events with a duration less than 1,440 min (1 day)
Bergen	01.01.15–21.08.17	122	47	35	26
Oslo	02.09.09–06.12.17	655	263	192	179
Trondheim	01.01.15–18.12.17	201	47	29	20
Sandnes	22.04.15–21.10.17	158	72	47	38

The remaining events, ranging from 26 in Trondheim to 179 in Oslo, were plotted in IDF curves for each respective area (NCCS 2018) (see Figure 3). From the events displayed in Figure 3, we selected a small subset where cumulative precipitation is similar to the laboratory events, and the duration is as short as possible. To get events with similar cumulative precipitation as in the laboratory experiments, it was necessary to select events with duration up to 450 min. Figure 3 shows the IDF curves together with the initial set of events, the final set of selected events, and the simulated laboratory events.

Precipitation and runoff data from each event were used to calculate the runoff coefficients for the roofs based on the same definition as in Equation (1), which means that the

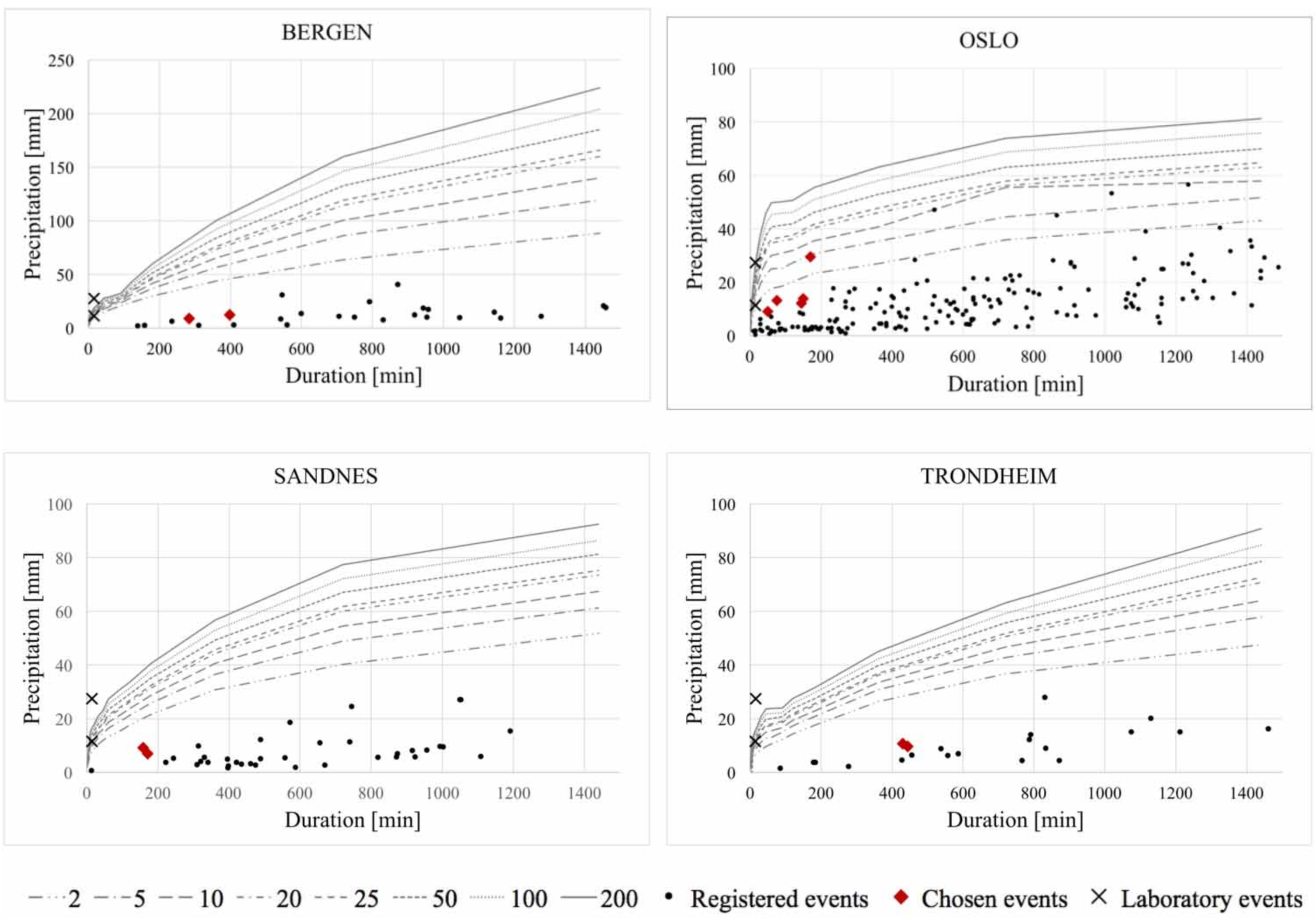

Figure 3 | IDF curves and precipitation events from the field measurements, where X for laboratory events includes both the FLL prescribed precipitation event of 27 mm/15 min and the 11.4 mm/15 min selected based on the field locations.

runoff coefficients for the field cases were calculated as the runoff volume over the total precipitation volume for the time span covered by the precipitation event. This makes the duration different for all the events as it is based on the actual duration of the event. In the events where the precipitation starts off very small, almost negligible, the events were set to start when the precipitation exceeded 0.5 mm.

RESULTS AND DISCUSSION

In this section, the results from the laboratory and field measurements are presented and compared.

Laboratory measured runoff coefficients

The laboratory conducted tests showed small variance between the three repetitions for each run (denoted R1 through R10 in Figure 1), which indicates that the set-up had a satisfactory reproducibility, with a standard deviation of 0.02 for calculated runoff coefficients. For further analysis, a simple average of the three repetitions is used. Average runoff and intensity curves from each of the runs exposed to 27.4 mm precipitation are presented in Figure 4.

For several runs, a free water surface above the layer being tested occurred (R1, R2, R3, and R4). This results in that runoff flows as overland flow on the surface of the layer and directly into the collection tank, which would affect the runoff coefficient calculation. The drainage board with extra drainage holes at the bottom (R5) was nearly empty through the irrigation, indicating that the holes were not serving to detain the runoff. The holes were made to function as a slow draining of the storage volume in these drainage boards. The cups on the drainage board without these extra drainage holes (R6) were full at the start of the run because of the pre-wetting in the procedure. This

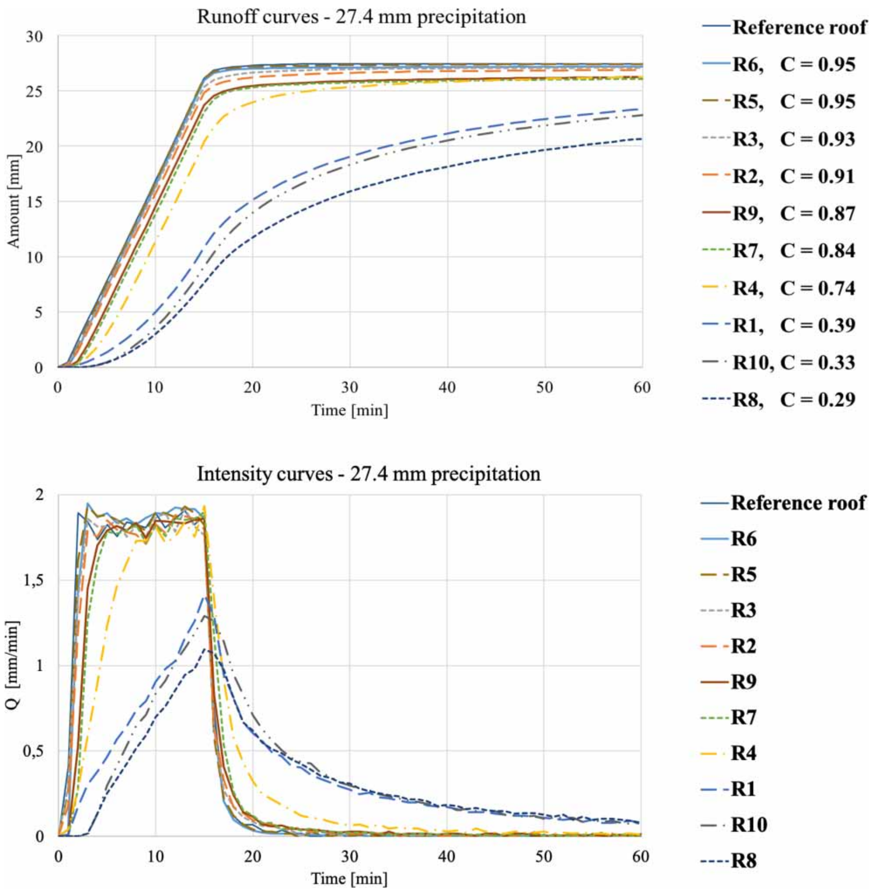

Figure 4 | Average runoff curves, intensity curves, and runoff coefficients, *C*, for each run.

caused the initial storage to be full at the onset of precipitation. A general deterioration of the sedum was observed as the experiments progressed through different configurations, as the sedum mats were reused for several runs, which resulted in multiple moving operations of the sedum. This was accounted for by the fragile mats that serve as a placeholder for the substrate and the sedum, which really is not made to be moved between the different configurations.

It can be seen from the curves represented by the single layers (R1, R2, R3, R5, and R6) that the 10 cm layer of an extruded clay aggregate medium (R1) stands out as the single-layer component with the highest detention capacity both with respect to volume and peak flow reduction. It had a considerably lower runoff coefficient than the other four individually tested layers, which all appear to be more similar to the reference roof. The two felt materials tested, from the different producers (R2 and R3), have only minor differences in the hydraulic behavior. It was somewhat unexpected that the thinner of the two mats had the greatest detention and the smallest runoff coefficient. This may be due to a more tightly packed material, with less pore volume inside for the thicker mat. The drainage boards with and without the extra drainage holes on the bottom (R5 and R6) resulted in the same runoff coefficient, indicating that the extra drainage holes of 3 mm does not increase the detention. Smaller drainage holes may have an increasing effect on the detention, but at the same time smaller holes are more vulnerable to clogging. Since the cold and wet coastal climate leads to lower evapotranspiration (Johannessen *et al.* 2017), water stored in the layers of the roof may never evaporate. This reduces the retention capacity and the layer only works as a 'one time retention volume'. In this detention-based testing method, the drainage board without the extra holes used in the laboratory was always full while testing, and the runoff is a function of the surface friction and rainfall intensity. This leads to a high runoff coefficient comparable to the reference roof, as there is a higher friction in the roofing reference than the slick plastic surface of the drainage boards.

Green roofs are represented by three different combinations of layers tested with just the sedum, R4; sedum and felt mat, R7; sedum, felt mat over-the-drainage mat with extra drainage holes and R8; sedum, felt mat, drainage board and an extruded clay aggregate medium. The combination in R4 gives a lower runoff coefficient than the combination in R7, although R7 is thicker consisting of one more layer. The difference is most likely explained by the vertical movement of the water through the sedum and felt layers, followed by horizontal flow movement through the drainage board, which gave a low detention performance when it was tested alone. In R4, with the combination only consisting of a sedum mat and a felt mat, the water flows laterally through the layers. R8, which includes an extruded clay aggregate medium, gives the lowest coefficient of runoff. It also gives a substantially lower runoff coefficient than the extruded clay aggregate layer alone. This showcases the importance of understanding the interactions between the layers in the design phase. Here, it is possible that the horizontal flow occurs in both the sedum layer and the extruded clay aggregate media layer. It is unlikely that a free surface flow will occur on the extruded clay aggregate surface, as the vertical infiltration rate is much higher than the maximum intensity of 27 mm/15 mm, which is a rather high intensity event.

The non-vegetated roof was made up of the extruded clay aggregate with concrete pavers on top ($R10 = R1 + R9$). The runoff coefficient of the combined system was $C = 0.33$. This was to a large degree influenced by the 10 cm extruded clay aggregate layer with a runoff coefficient equal to 0.39. The concrete pavers covering the extruded clay layer made the runoff flow laterally over the pavers, entering the media in the cracks between the pavers before it flows laterally in the extruded clay aggregate-based layer. The test of the concrete pavers alone (R9) gave a runoff coefficient equal to 0.89, which, to a lesser extent, contributes to the detention capacity of the combined system (R10). Since the flow directions are the same for the layers in the combined system as for the single layers, multiplying the individually obtained runoff coefficients gives a runoff coefficient equal to 0.34 for the combined roof system R10. This is in good agreement with the value obtained directly for the combined system and within the standard deviation of the method. The runoff coefficients found in this study can be seen as detention based. Of the measurements in the laboratory, the extruded clay aggregate medium-based systems (R8 and R10) gave the lowest runoff coefficients.

The applied standard with 27 mm in 15 minutes is an extreme event in the study locations in this study. A

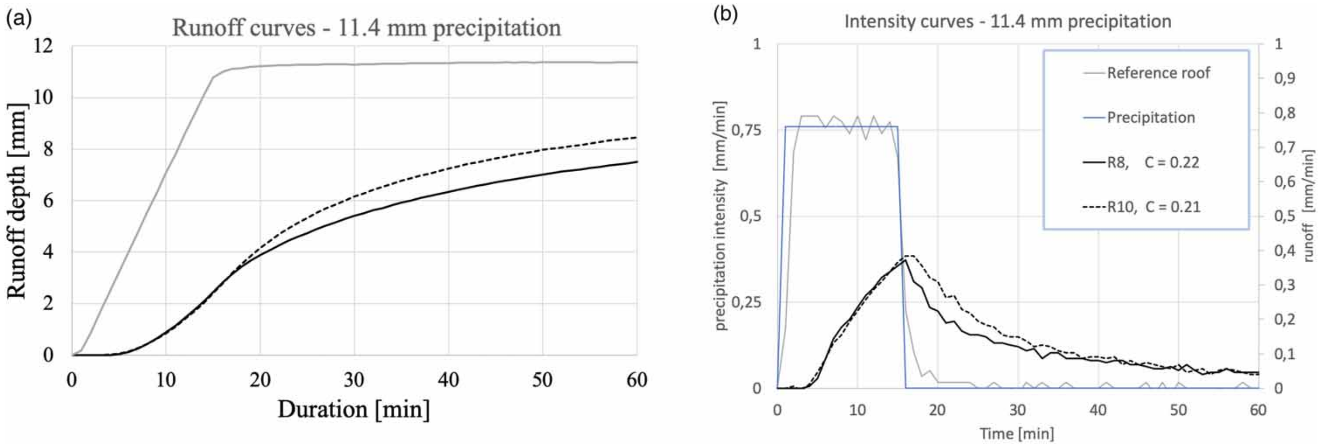

Figure 5 | Runoff curves (a), intensity curves and runoff coefficients (b) for the reduced precipitation event on the extruded clay aggregate-based roof systems; R8 and R10.

simulated rain event of 11.4 mm with a duration of 15 minutes was applied on the R8 and R10 roof systems, in order to obtain a rainfall event more suitable to the Norwegian climate. It can be seen that a reduction in applied precipitation depth leads to a reduced runoff coefficient (Figure 5).

Both tests gave similar runoff coefficient for the vegetated (R8) and non-vegetated roof (R10) systems, 0.22 and 0.21, respectively. For the higher intensity event, the 27 mm event, the non-vegetate roof had a slightly better detention, 0.29 versus 0.34 for the runoff coefficient. The change for the lower intensity event could be a result of a poorer vegetation mat towards the end of the experiments and the previously mentioned progressive deterioration of the vegetation mat due to all the handling configuring the different combinations. However, it can be concluded that the runoff coefficient increases with increasing intensity.

Laboratory experiments are important in understanding the underlying flow processes in the different layers in a detention-based roof. As interpreted from the laboratory experiments performed in this study, the runoff coefficients are mostly governed by the layers where horizontal flow occurs. In the runs where horizontal flow occurs through the porous media, as for the extruded clay aggregate (R8 and R10) and the sedum (R4), the flow is governed by Darcy's equation. This means that the flow through the media, among other things, is based on the hydraulic conductivity and the particle size distribution of the porous media. When the water flows across the drainage board (R7), overland flow may occur, which is governed by Manning's equation. Here, the shorter detention time may be explained by the friction and the slope of the roof.

Runoff coefficients based on field data

The selected events (cf. Figure 3) are presented as cumulative precipitation and runoff in Figure 6. These observations are considered most comparable to the events simulated in the laboratory based on total precipitation.

The graphs in Figure 6 indicate a varying performance response of a similar layered roof at the four locations (i.e. sedum spices and a felt mat of 10 mm). Due to varying intensities within the events, it can be observed that the curves from the field measurements are less smooth than those from the laboratory measurements. The detention performance varies between the events, whereas lag times vary from 1 to 351 min. The ratio between accumulated precipitation and runoff at the end of each precipitation event results in detention-based runoff coefficients varying between 0.023 and 0.41. Compared to the laboratory measured runoff coefficient for the same layered roof (R4), these field observations give a significantly lower value than the measured runoff coefficient of 0.74 for the 27 mm event.

In the field, the state of the roof at the onset of each precipitation event will vary, which could affect the performance. The moisture in the roof will vary for the field events, while it is constant at field capacity for the laboratory

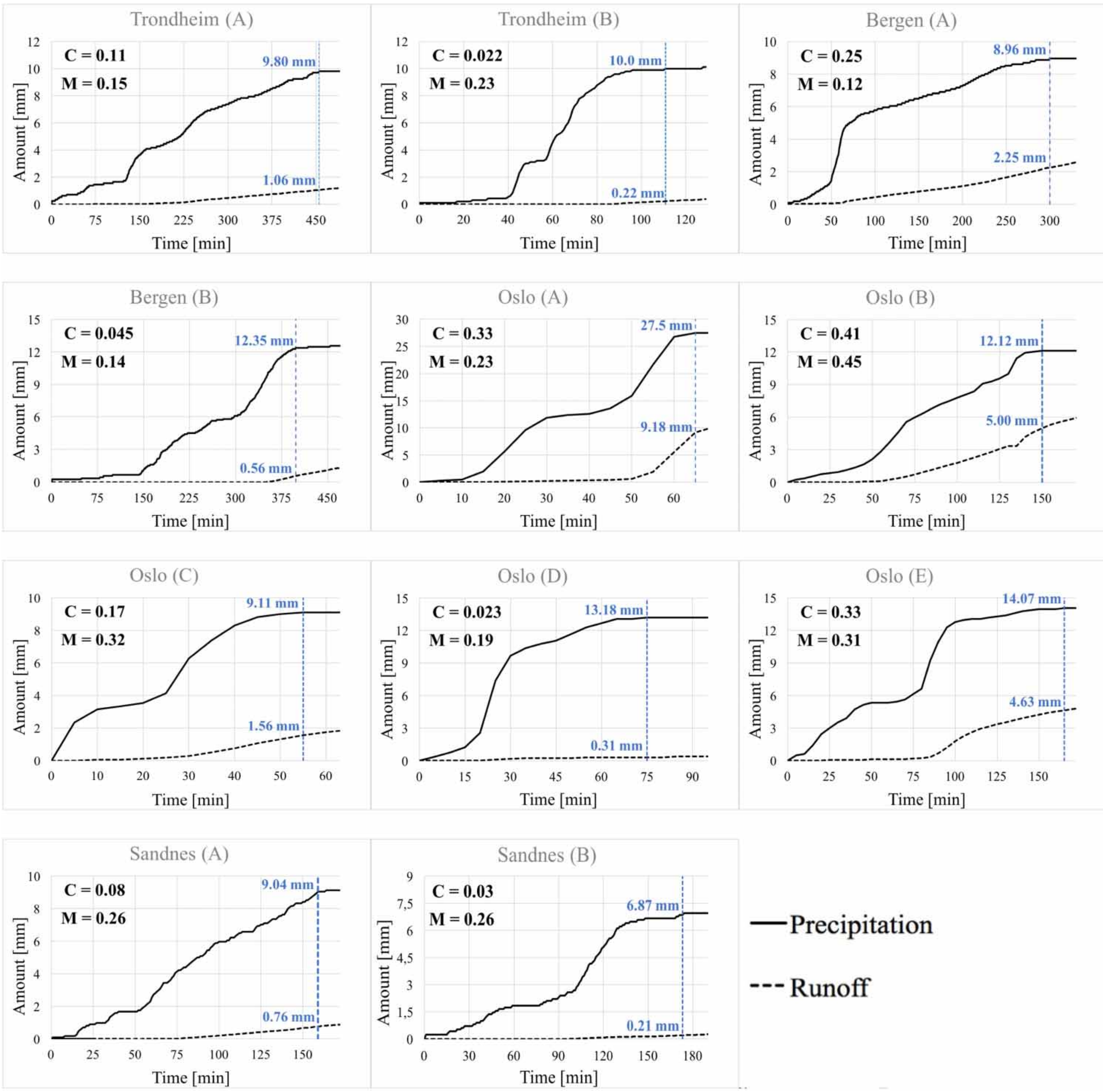

Figure 6 | Precipitation and runoff curves for the chosen field events, runoff coefficient (*C*) and moisture (*M*) at the start of precipitation. The blue represents the values used in the calculation of the runoff coefficient. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2020.049.

experiments. Lower soil moisture levels will make the roof capable of storing more water, which will lead to an increase in lag time and a decrease in runoff coefficient, *C*. This differs from the laboratory measurements, where the roof was at field capacity at the onset of precipitation. The events were selected based on the amount of precipitation. In all the chosen field events, this occurred over a longer duration than in the laboratory. Longer duration results in the lower average intensity of precipitation in the field than in the laboratory.

Runoff coefficients as a variable in designing detention-based roofs

In urban areas, where roofs are a large part of the impervious surfaces, the runoff from roofs is an important factor when dimensioning urban stormwater structures (Stovin et al. 2012; Berretta et al. 2014; Hamouz et al. 2018). As more detention-based roofs are established in the cities, the importance of including the effect of these in the runoff calculations increases (Sobczyk & Mrowiec 2016). The variations in the runoff coefficients calculated in this study prove the challenge of using a suitable value for a given roof.

Results from the laboratory measurements gave a variation in the runoff coefficient depending on the materials and compositions of the layers. It also gave a variation depending on the intensity of the added event which confirms the results from other studies (Stovin et al. 2015; Johannessen et al. 2018; Hamouz et al. 2018). The laboratory test method gave runoff coefficients with small standard deviations and high reproducibility, which indicates that the testing method was robust and reliable. In addition, the laboratory analysis improves the understanding of how water moves through the layers, making it easier to compare the layers and evaluate the contribution of each layer. However, the discrepancy to the field observations raises an important concern in using the laboratory measured runoff coefficients for design. The laboratory experiments were conducted at field capacity, which will be a conservative approach, still the resulting runoff coefficient was higher than the field comparisons for all the roofs.

The challenge with a standardized test method is the results' suitability to the location they may be used. The laboratory measurements are conducted in conditions which may not be realistic for a given location. The lack of suitability is especially an issue for detention-based roofs which are established to handle small-to-medium events, as defined in the three-step approach (NOU 2015, p. 67), and not the larger events with rare recurrences. Hence, these laboratory measurements, with 27 mm in 15 min, are more suitable for downstream stormwater calculations dimensioned for larger events and the performance of step 1 solutions in extreme events.

Measurements from the four roofs in the field resulted in significantly lower runoff coefficients than the values obtained from the laboratory test. There are many variables that affect the runoff peaks such as soil moisture content, intensities, and physical roof design. The field data record of 4–8 years can be considered substantial; however, it was still difficult to find events that could be compared with the laboratory experiments as there are many variables that may influence the performance. This clearly demonstrates that this approach is not well suited to capture the performance of detention-based roofs, such as green roofs. As an alternative to the typical event-based metrics and runoff coefficient focus on urban stormwater management is used for evaluating detention performance, Johannessen et al. (2018) presents flow duration curves based on time series as an alternative approach. Flow duration curves give valuable information on the runoff pattern from the roofs, which can be used in relation to local requirements. A volume of storage-based approach would also complement a pure peak flow approach that today is still very commonly used. Both these methods would shift the focus from a pure peak flow focus to a total water management focus, where detention-based roofs are part of a series of solutions.

CONCLUSION

In this study, the runoff coefficients for different layered detention-based roofs have been investigated. The results highlight the complexity of using a runoff coefficient approach to design of these roofs. The laboratory measurements gave a varying runoff coefficient due to the compositions of the roofs and the intensity of the added block rain. However, it was the roof systems with an extruded clay layer (R1, R8, and R10) that had a significant lower runoff coefficient than all the other types, which indicates the need for a porous flow-based layer for the detention of precipitation.

The field measurements gave a smaller and more varying runoff coefficient for the same roof configurations compared to the laboratory setups. The soil moisture level on the onset of precipitation can explain this variation, which also can be derived as the single most important parameter for the performance of a green roof system.

The results of this study demonstrate the challenge of using a suitable runoff coefficient measured in the laboratory for a given roof in the calculations of stormwater runoff. However, laboratory analysis aids our understanding of how water moves through the layers and is important to understand the underlying flow processes in the different layers in a detention-based roof. In the thicker layers, like the extruded clay aggregate, there will be flow through porous media, which is governed by Darcy's equation, while flow across the drainage boards is governed by Manning's equation. Characterizing the differences in the flow through the different media can aid our understanding of the field observations and by this improve design calculations in urban stormwater management. Further, moving towards a flow characteristic volume-based approach will improve the design of these systems.

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