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Comparing experimentally measured runoff coefficients with field observations for detention-based roofs

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Background

In cities, where surfaces of detention-based roofs are higher and increasing, this will be a more important factor for the stormwater calculations. The rational method is one of the most commonly used design tools for urban runoff calculation, as described by Mulvaney in 1851 and later by Kuichling in 1889. The runoff coefficient is an essential part of this formula, mainly given as the relationship between precipitation and runoff. More knowledge is needed on the runoff coefficient for detention-based roofs in order to improve design calculations. This thesis compares laboratory and experimental field studies to investigate runoff coefficients for different layered detention-based roofs. Further it is discussed in what extent the runoff coefficients from detention-based roofs is an appropriate tool in the overall stormwater management plan.

Research Questions

1. What are the runoff coefficients of different types of detention-based roofs?
2. How does laboratory measured runoff coefficients compare with field observations?
3. How to incorporate runoff coefficients from detention-based roofs in the overall stormwater management plan.

Collaboration partners: Klima2050

Location: Department of Civil and Environmental Engineering, SINTEF Byggforsk laboratory, Trondheim

Advisors: Tone Merete Muthanna and Birgitte Gisvold Johannessen

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU), as a product of the course TVM4905, Water and wastewater engineering, Master's thesis. The thesis is about detention-based roofs in a storm water management design context. It compares laboratory measured runoff coefficients with field observations. The study was conducted at the Department of Civil and Environmental Engineering. Laboratory measurements was conducted in the SINTEF Byggforsk laboratory, directed by Klima 2050 - Centre for Research-based Innovation.

I would like to express my sincere gratitude to my supervisor, associate professor Tone Merete Muthanna. Thank you for your guidance, great interest and motivation through the process of this thesis. I would also like to thank PhD candidate Birgitte Gisvold Johannessen for helping me and for locating the collected field data, and Senior Engineer at Sintef byggforsk Jan Ove Busklien, for guidance and assistance in the laboratory.

Trondheim, June 10, 2018

Lotte A. Schärer

Lotte Askeland Schärer

Sammendrag

Laboratoriemålte avrenningskoeffisienter for fordrøyningsbaserte tak, sett opp mot feltmålinger.

Dagens behov for overvannsløsninger har samtidig økt interessen for fordrøyningsbaserte tak. For å kunne optimalisere disse takene, trengs det mer kunnskap om takenes hydrauliske egenskaper. Denne studien har sett nærmere på dette.

Figur 1: Mye forskning blir gjort både i laboratoriet og i felt. Her testes ulike fordrøyningsbaserte tak i fullskala for et kaldt og vått klima.
Foto: Lotte Askeland Schärer

Den rasjonelle metoden er en av de mest brukte beregningsmetodene for overflateavrenning. Avrenningskoeffisienten er en viktig faktor i denne formelen, og er gitt som forholdet mellom nedbør og avrenning. I denne studien blir avrenningskoeffisienter brukt til å undersøke de ulike takenes hydrauliske kapasitet, med fokus på fordrøyningsegenskaper. Studien er utført i samarbeid med Klima 2050.

Fordrøyningsbaserte tak

En av hovedgrunnene til et økt ytelsesbehov for overvannsløsninger er urbanisering. Øket andel tette flater gir øket overflateavrenning. Ettersom tak står for en stor del av de tette flatene i byer, har det blitt populært med takløsninger som kan infiltrere og forsinke avrenningsvannet. Den vanligste typen av fordrøyningsbaserte tak er "grønne", men det finnes også varianter uten vegetasjon. Mye forskning er allerede blitt gjort innenfor feltet, og det blir stadig bevist at de beste løsningene avhenger av oppbygging og lokasjon. Mindre forskning har blitt gjort for å se hvordan de enkelte lagenes bidrag til reduksjon og forsinkning er. Derfor ble det i denne studien utført tester for å finne avrenningskoeffisienter for ulike typer fordrøyningsbaserte tak. Tester ble også utført på enkelte materialer, for å kunne se bidraget fra hvert enkelt lag.

Laboratorietester

Testene ble gjort etter en tysk standard metode. Her påføres en simulert nedbørshendelse på et test-tak, med en intensitet på 27 mm i løpet av 15 minutter. Avrenning blir målt kontinuerlig, slik at avrenningskoeffisienten kan beregnes etter 15 minutter. Testmaterialet skal være ved feltkapasitet før start, og må derfor gjennomvannes før tre etterfølgende tester blir kjørt i 24-timers intervaller.

Ti ulike oppbygginger ble testet, hvor to av disse også ble testet med redusert nedbørsmengde. Tre hovedfunn ble gjort. 1) Leca Media ga en klart lavere avrenningskoeffisient enn de andre lagene. Dette gjenspeiles også i kombinasjonene der Leca Media er inkludert. 2) Ved å sammenlikne avrenningskoeffisientene, både mot hverandre og enkeltlagene, kommer det frem i hvilket lag den horisontale strømningen foregår. 3) Reduksjon av nedbørsmengde ga lavere avrenningskoeffisient, dog ikke i samme skala som nedbørsmengden.

Feltmålinger

Feltmålinger ble brukt for å kunne sammenlikne og vurdere laboratorietestene mot virkelige hendelser. Registrert data fra test-tak lokalisert i Trondheim, Oslo, Sandnes og Bergen ble benyttet, da disse byene representerer et typisk norsk varierende kystklima. De utvalgte hendelsene ga svært varierende avrenningskoeffisienter for samme tak. Alle de valgte felthendelsene ga en betraktelig lavere avrenningskoeffisient enn tilsvarende takkombinasjon ga i laboratoriet.

Bruken av avrenningskoeffisienten som en dimensjonerende faktor

I denne studien blir det vist at avrenningskoeffisienten kan være svært kompleks. Det kan være utfordrende, nærmest umulig, å finne en passende avrenningskoeffisient ved beregninger. Laboratorieresultatene gir en mer kontrollert hendelse, med gitte forhold som gjør det mulig å sammenlikne testene med hverandre, og en bedre forståelse for vannets bevegelse gjennom lagene. Da fordrøyningsbaserte tak er laget for å håndtere små til medium hendelser, kan en lavere intensitet ved laboratorietester være en bedre tilnærming til det norske klima.

Dette sammendraget er skrevet i byggeindustriens format.

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Thesis structure

This thesis is written in a manuscript based format. The work in this thesis has been accepted for presentation at Nordic Water conference, which takes place in Bergen, 13th – 15th of August 2018. A paper will subsequently be submitted to the International Water Association (IWA) journal, Hydrology Research. The structure of this thesis is therefore based on the instructions for the manuscript given by Hydrology research.

Laboratory measurements are the main part of this thesis. The results are compared to field observations, which introduce the varying Norwegian climate. This makes up the discussion about the relevance of this type of laboratory measurements in urban storm water management design. The Appendix includes climatic information of Norway which was used to describe the Norwegian varying climate, pictures and more detailed data from the measurements in the laboratory and in the field.

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Comparing experimentally measured runoff coefficients with field observations for detention-based roofs

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Department of Civil and Environmental Engineering, The Norwegian University of Science and Technology (NTNU), 2018

Abstract

Predicted climate changes combined with urbanization increases the performance demand on urban stormwater management structures. The rational method with the runoff coefficient (C) is one of the most commonly used design tools in urban stormwater design. In Norway, detention-based roofs are gaining popularity as a stormwater management measure. More knowledge is needed on the runoff coefficients from these roofs in order to improve design calculations. This thesis compares laboratory and experimental field studies to investigate runoff coefficients from different types of detention-based roofs. The laboratory measured runoff coefficients are found by the standard German method given in the "FLL Guideline". Runoff coefficients for both single layers and combinations of these layers are found. The Leca-based roof systems gave the lowest runoff coefficients, with C = 0,33 and C = 0,29. The two other detention-based roof systems got higher values of C = 0,84 and C = 0,74. By comparing these values to the coefficients for the single layers, it becomes clear that the value of the runoff coefficient is mostly determined by in which of the layers the horizontal flow occurs. The runoff coefficients from the field were calculated using observed precipitation and runoff from existing green roofs in Oslo, Trondheim, Sandnes and Bergen, all cities representing a cold and wet Norwegian costal climate. The single events chosen as most comparable to the laboratory events based on precipitation, gave significantly lower and varying runoff coefficients. In this way, the study shows the runoff coefficient as a complex value, and highlights the challenge, if not the impossible task, 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

Keywords – Detention performance, Detention-based roof, Rational Method, Runoff Coefficient, Urban Storm Water

1 Introduction

An increased performance demand on urban stormwater management structures is a worldwide challenge. As a result of climate changes, more frequent rainfall events with higher intensity are expected in the following years (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 been nationally adopted. Step one; infiltration of all small events, step two; detain 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 (NOU, 2015, p. 67). As rooftops make up about 50 % of the paved surfaces in developed cities, it makes detention-based roofing a promising solution (Hamouz et. al., 2018; Sobczyk & Mrowieck, 2016; Berretta et.al, 2014; Stovin et. al., 2012).

Rooftop detention can be accomplished through different solutions where green roofs are the most common. However, detention can also be achieved through various non-vegetated detention substrates and media (Andenæs et.al, 2018). Green roofs are made to collect, store, and evapotranspirate precipitation on building rooftops. By converting impermeable roofs to something more similar natural landscape, one can achieve a significantly reduction and delayed runoff (WEF, 2012, p. 326). Typical components of these roofs are plants, soil media, root barrier, drainage layer and an impermeable membrane. As vegetation, sedums are commonly used plants. The robustness of these plants requires little maintenance and less soil. These types of green roofs are called extensive green roofs, and are characterized by their thinner profile (WEF, 2012, p. 326; Berretta et.al, 2014).

A review article on the topic by Andenæs et.al. (2018), found retention performance as one of the most studied hydrological properties of green roofs. The detention capacity was also found to be frequently studied, though not investigated as broadly. Detention-based studies study detention performance with focus on peak flow reductions for single events, while the retention-based studies investigate water retention in form of evapotranspiration over a longer period of time. There is a vast literature base for hydrologic performance of green roof. In the following section a selection relevant to this study has been reported. Studies reporting on both retention and detention has been prioritized. A study by Johannessen et.al. (2017) investigates 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. As more robust option, Hamouz et.al. (2018) presents a LECA-based roof system, covered with a permeable concrete pavement instead of vegetation. As expected the retention was lower than a typical green roof, but the detention capacity was particularly encouraging. Stovin et.al. (2015) performed an outdoor study in Sheffield - UK, based on nine test beds with different substrate and vegetation. Rainfall- and runoff data over a four-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 performance for extensive green roofs in different Norwegian locations. The event based approach was particularly challenging, resulting in large variability in metrics, even with 3-8 years of collected field data. Summarized: Design of green roofs should be geographical site specific. Little research has been conducted on the separate components of the layers that make up detention-based roofs. To optimize layer composition for different climatic zones, more knowledge is needed coupling local climate with detention metrics.

In cities, where surfaces of detention-based roofs are higher and increasing, this will be a more important factor for the stormwater calculations. The rational method is one of the most commonly used design tools for urban runoff calculation, as described by Mulvaney in 1851 and later by Kuichling in 1889. 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. A typical way to find this value, is by the relationship between the intensities of the peaks or based on the volumes (Ødegaard et.al.,2014, p. 48-49). More knowledge is needed on the runoff coefficient for detention-based roofs in order to improve design calculations. This thesis compares laboratory and experimental field studies to investigate runoff coefficients for different layered roof with focus on the detention. Further it is discussed in what extent the use of runoff coefficients from detention-based roofs is an appropriate tool in the overall stormwater management plan.

(1) What are the runoff coefficients of different types of green roofs?
(2) How does laboratory measured runoff coefficients compare with field observations?
(3) How to incorporate runoff coefficients from detention-based roofs in the overall stormwater management plan.

2 Study area and data

This study is based on data from a set of laboratory experiments and four test roofs at different locations in Norway. It compares data from a standardized method against observed events at the four locations. To make the study relevant to cold and wet regions, data collected from four roofs at different locations in Norway are used. These green roofs are located in Oslo, Trondheim, Sandnes and Bergen. All four locations are characterized by coastal climate, but with some distinct differences, giving a representation of a varying Norwegian climate. Intensity, Duration and Frequency (IDF) curves, given by Norwegian centre for climate services (NCCS), show that the climate in Oslo stands out the most. Shorter and intense precipitation events occur here more often. The IDF-curves for Bergen, Sandnes and Trondheim show events of lower intensity with less variation between the different recurrences. Both Trondheim and Oslo are situated in fjords; Oslo at the bottom of Oslofjord, and Trondheim midway in the Trondheimsfjord. Climatic charts by NCCS, show that these cities have more varying temperatures, including more temperatures below zero than the two other cities. The most northern of the cities, Trondheim, experiences about three months with temperatures below zero each year (Johannessen et.al. 2018). Of the four cities, Bergen experiences most precipitation annually, followed by Sandnes (NCCS, 2018).

The four roofs chosen for the study are constructed to be suitable for field studying. The data collection, described by Johannessen et.al. (2018), are logged continuously to get the best basis for evaluating the hydraulic performance of the roofs. The roofs consist of four different sections with test beds made up of varying layers, making 16 different roof sections in total. In this way, the roofs made up of different layers within one geographical site can be compared and evaluated to each other. In this thesis, only one of the four roof sections at each location was used. This is the roof consisting of a 10 mm felt mat underneath a layer of sedum for all four locations. This type of build-up is also tested in the laboratory. The area of the roof in Oslo is 2 m x 4 m, with a slope of 5,5 %. In Trondheim the area is 7,5 m x 2 m and in Bergen is 4,9 m x 1,6 m. Both with a slope of 16 %. The area and in Sandnes 5,4 m x 1,6 m with a steeper slope of 27 %. Climatic data from a period of three years are collected in Trondheim, Sandnes and Bergen. For the roof in Oslo, data are collected over a period of eight years. (Johannessen et.al., 2018).

3 Methods

A German standardized method (FLL, 2008) was used to determine the runoff coefficient for the different layers, which make up typical detention-based roof solutions. Field observations from four different locations in Norway were used to be compared with the laboratory measured values.

3.1 Laboratory measurements

The basis for the material selection being tested in this study is based on commonly used layers of typical combinations of green or LECA-based roof solutions (Hamouz et al. 2018). The details of the materials used are presented in Table 1.

Table 1. Presentation of the materials being tested in the laboratory. The type of material, producer of the material, the materials purpose as a layer of a detention-based roof and the thickness of the layer is given for each component. The combination description denoted with R# refers to the different runs in which the specific material is used.

Material	Producer	Purpose	Thickness [mm]	Combination	Comment
Leca Media	Leca Norge AS	Drainage	100	R1, R8, R10	Fraction of 0 mm – 6 mm K_{sat} = 105 cm/hour*
Felt I	Bergknapp	Root protection	7	R2, R4, R7, R8	
Felt II	Veg Tech	Root protection	10	R3	
Sedum	Grasrota	Infiltration, evaporation	50	R4, R7, R8	
Drainage board I	Isola	Drainage	40	R5	3 mm holes on the bottom of the cups**
Drainage board II	Isola	Drainage, storage	40	R6, R7, R8	
Leca concrete pavers	Multiblokk AS	Protection	70	R9, R10	
Grout material	Multiblokk AS	Infiltration	70	R9, R10	To stay in place; higher density than LECA Media
Geotextile	Dupont Plantex	Separation	1	R9, R10	

*Saturated hydraulic conductivity (K_{sat}) is found by using a Constant head permeameter test based on Smoltczyk (2003) description. Here it is modified to be applied on columns. The test was performed 3 x 3 times on each material, with cores that fill the columns with a length of 40 cm and a diameter of 10 cm.

**To determine the holes on the bottom of the Isola DE40, a flow through test was executed. The time for a full cup to be emptied was measured for holes with a diameter of 2 mm, 3 mm and 4 mm. Each dimension was tested in five cups, three times each.

To find the runoff coefficient (C), for the different roof configurations, both single layers and combinations of layers were tested. These combinations make up the different runs referred to as (R), shown in Figure 2.

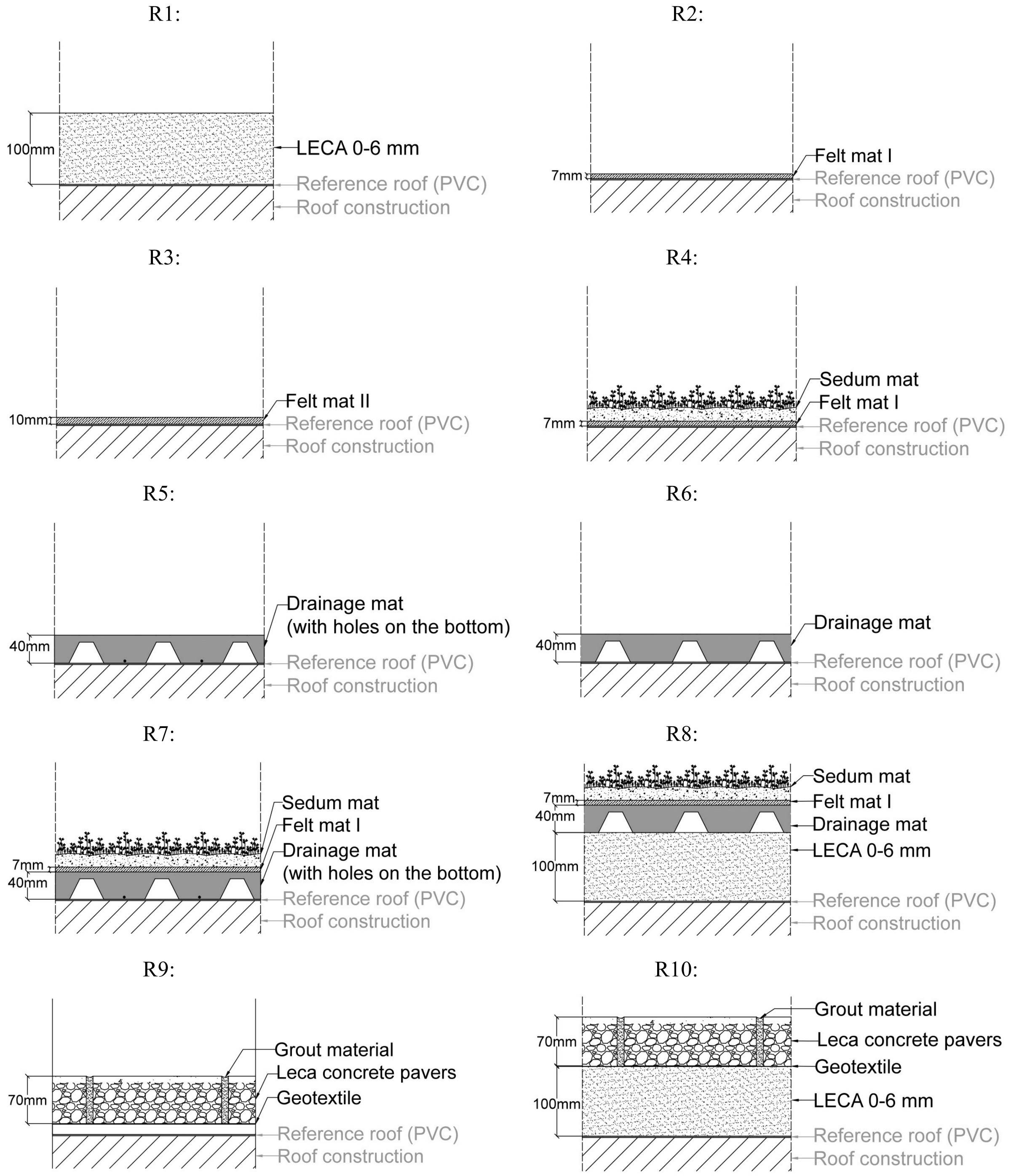
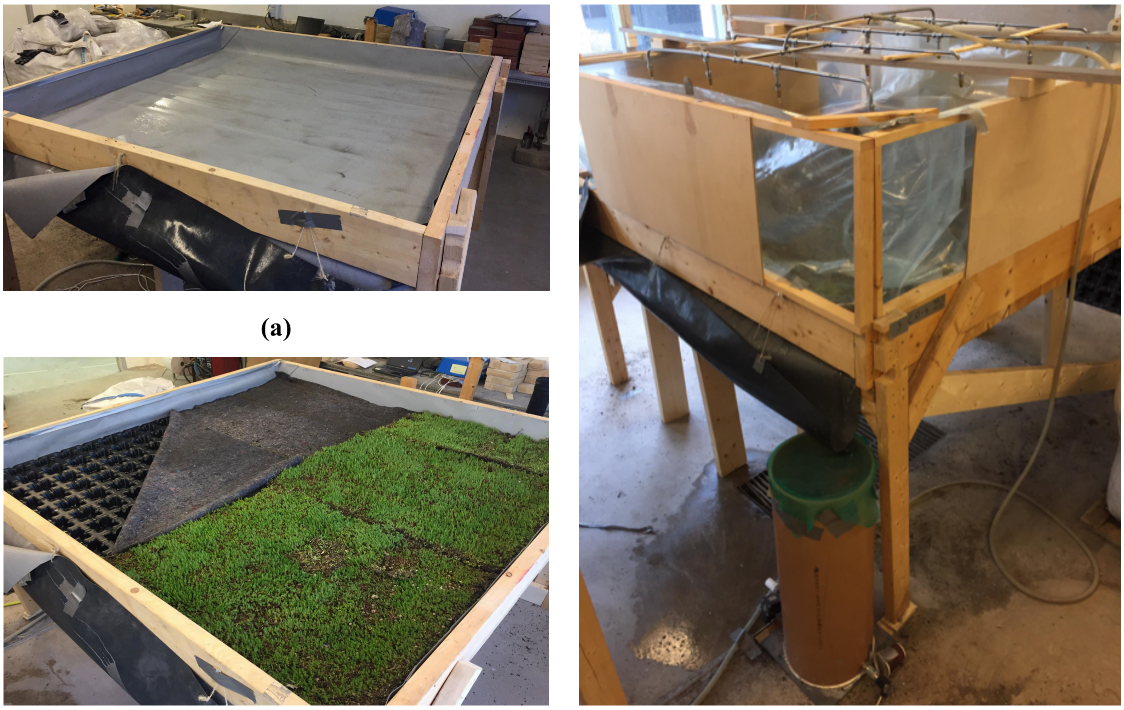


Figure 2. Section drawings for the composition of the different runs; R#.

The German method used to determine the runoff coefficient for the different roof layers and combination of layers, is in this study based on the 2008-edition of FLL's guidelines for planning construction and maintenance of green roofing (FLL, 2008, p. 100). The guidelines say that the test roof should be constructed with a 2 % drainage gradient, and a width of 1 m and placed inside a wind- and rain-protected testing hall. The method specifies a block rain of 27 mm over a duration of 15 minutes. Prior to the test, the roof material should be pre-wetted to saturation by continuous irrigation for ten minutes beyond reaching a constant runoff rate. This is followed by a subsequent 24-hour drainage time, at which field capacity is assumed. The method then prescribes three repetitions for each test with 24-hour intervals. The C-value is then given by the ratio between the total runoff measured after 15 minutes and the total volume of water added.

Specific for this study is the area of the modelled roof: 2 m x 2 m. There are 16 nozzle tubes placed about 80 cm above the roof construction that adds the given amount of water in 15 minutes. This is calibrated to occur after 88 cycles, eight seconds with constant and uniform distribution of block rain, followed by two seconds without distribution. This calibration gives a total amount of 27,4 mm in 14,67 minutes. The runoff from the roof is measured by an instrument that registers the hydraulic pressure over time when the runoff data is logged every two seconds. Further information about the measurements are given by Busklien et.al. (2014), who used the same laboratory layout. For R2, R3, R5, R6 and R9 the measurements did not have to be in periods of 24 hours. These layers reached field capacity earlier. The permeable pavement (R9), was lifted 1,5 cm by using steel rods. This is because the water flows vertically through the joints, and not horizontally trough the Leca concrete pavers. To get the method better suited to the Norwegian coastal climate, R8 and R10 are also tested with a reduced amount of water, calibrated to 11,4 mm in 16,67 minutes. This is calibrated as 88 cycles of 3 seconds with constant and uniform distribution of block rain, followed by 7 seconds without distribution. Illustration pictures from the measurements are presented in Figure 3.



(a)

(b)

(c)

Figure 3. Illustration pictures from the laboratory; (a) Reference roof; (b) Example of built up, R7; (c) Running the simulation. There are pictures of all the runs in Appendix B.1

To create a graphical representation, data registered for every minute, or closest minute - plus/minus 1 second, are picked out from the single runs. This is because the data are not logged precisely every two seconds. In this way, it is possible to make average curves for each sample roof. Runoff curves and intensity curves are made based on the minute data, to compare the detention performance of the different layers. The layers can also be compared to the low friction based reference roof (Fig. 3. a), to see the effect of the tested build up.

Darcy's and Manning's formulas are used to explain the horizontal flow occurring in the drainage layers. In the permeable layers the drainage layer will appear as a filter. The flow may be described by Darcy's formula, given by WEF (2017, p. 296) as:

$$Q = \frac{K(h_{sf} + d)}{d} A_{SF} \qquad (1)$$

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, described in WEF (2017, p. 278) as:

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

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.

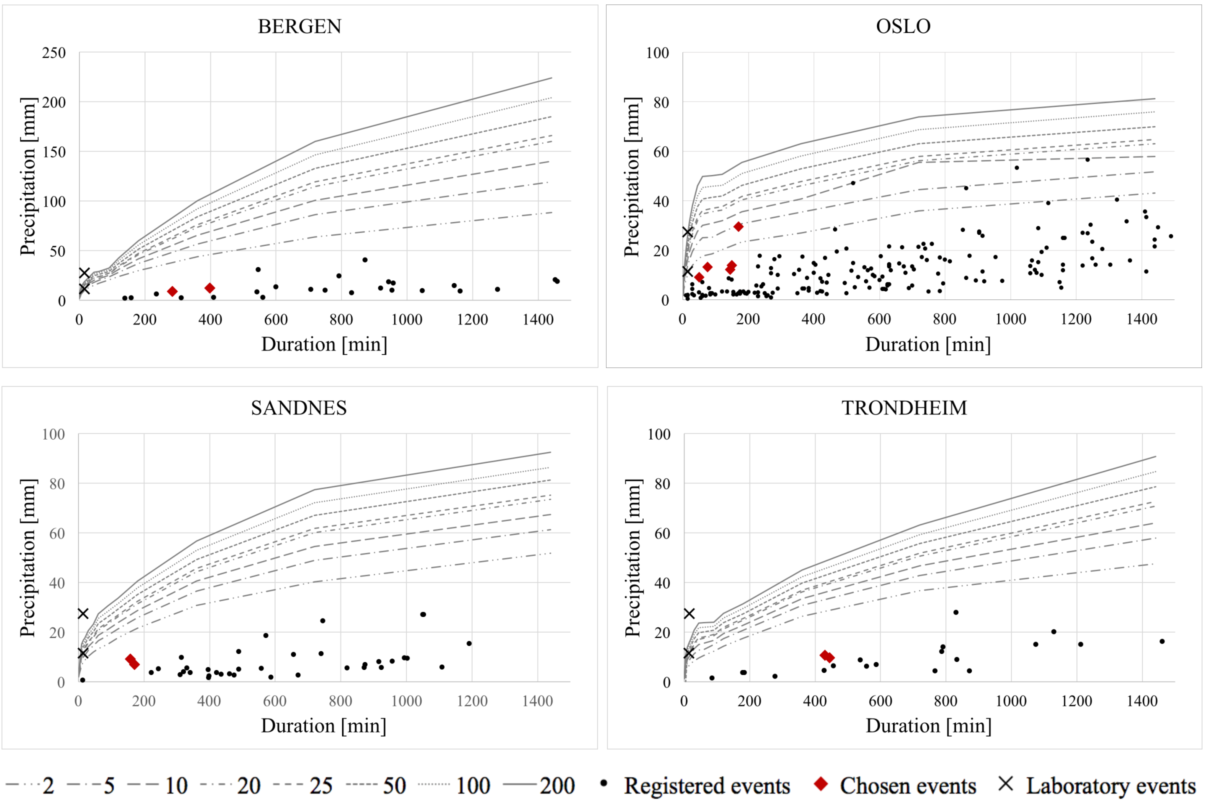
3.2 Field measurements

To find events comparable to the laboratory measurements the data on precipitation and runoff are used. To be able to calculate the runoff coefficient there must be single events, with registered runoff. To avoid data from snow covered roofs, which may appear in Oslo and Trondheim, only data from May to October are evaluated. These eliminations are displayed in Table 2.

Table 2: Elimination of events. (1) number of single events, (2) number of single events with runoff, (3) number of single events with runoff in May - October, (4) single events with runoff in May-October, with a duration within 1440 minutes

	Period	(1)	(2)	(3)	(4)
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 (4), are plotted in IDF-curves for the common areas. The events are selected based on the amount of precipitation and time of duration. To get events with the same amount of cumulative precipitation as in the laboratory simulated event, the duration time expands. IDF-curves with protracted duration up to 24 hours are therefore used. Figure 4 shows the IDF-curves with plots of the registered data.



Figur 4: IDF-curves and precipitation events from the field measurements. Larger scale and information about the IDF-curves in Appendix A.2.

After picking out the most current events, more detailed data from these events must be retrieved from the logged field data. Precipitation and runoff data over time will be used to calculate the runoff coefficients for the roofs. To make the calculation as similar to the laboratory as possible, the runoff coefficients is calculated by dividing the total precipitation with the total collected runoff at the time the precipitation stops. In the events where the precipitation starts off very small, almost negligible, the events are set to start when the precipitation picks up.

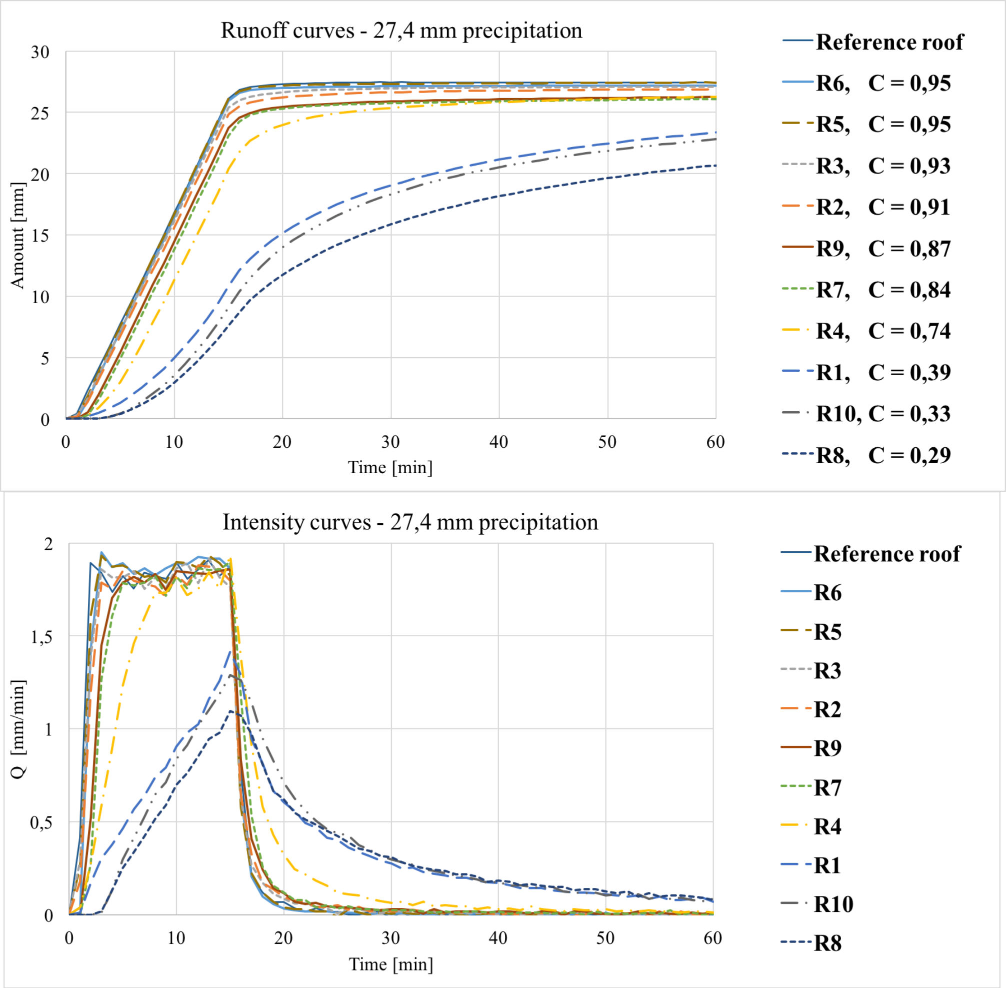
To look for trends for the runoff coefficients for the field events they are plotted in graphs: runoff coefficients/humidity, runoff coefficients/intensity precipitation, runoff coefficient/lag start, runoff coefficient/runoff, runoff coefficient/precipitation and runoff coefficient/duration precipitation.

4 Results and discussion

The runoff coefficients from the different layers and layered roofs are given by the data collected in the laboratory. The measured values from the laboratory are compared to the events from the field. This makes up the discussion on the importance of the runoff coefficient for use in urban stormwater management design.

4.1 Laboratory measured runoff coefficients

The laboratory tests had little variance between the three repetitions for each run (denoted with an R# and a number for each type in Figure 2) and a high repeatability. Due to small weaknesses in the modeled roof construction, collecting system and the measuring equipment, the method gave a standard deviation smaller than 0,017 for the calculated runoff coefficients (Appendix B.2). The average curve of the three repetitions of each run was therefore used. For an overview, all average runoff- and intensity-curves from each of the runs exposed to 27,4 mm precipitation are presented in Figure 5.



Figur 5: Average runoff curves, intensity curves and runoff coefficients, C for the repetitions, representing each run.

In addition to the logged data, some observations were made during the runs. In several runs, a free water surface above the layer occurred (R1, R2, R3 and R4), and it is unknown if all the water flow trough the material. The drainage board with extra drainage holes at the bottom (R5) was nearly empty through the irrigation. The cups on the other drainage board (R6) were full at start and through the irrigation. A deterioration of the sedum was observed as the experiments progressed.

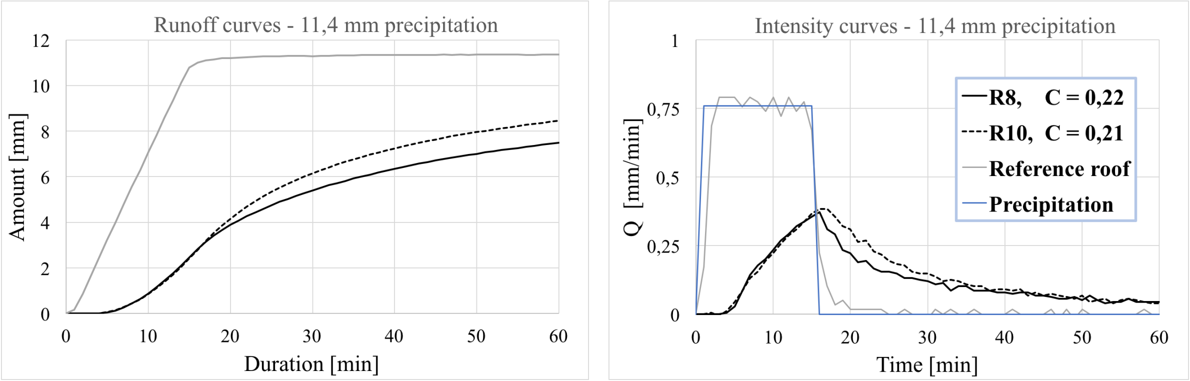
It can be seen from the curves represented by the single layers (R1, R2, R3, R5, R6), that the 10 cm layer of LECA Media (R1), stands out the most. With a lower and later peak flow. Here the runoff coefficient is considerably lower than the other four individually tested layers, which appear to be more similar the reference roof. The two felt materials from the different producers (R2, R3), have only small differences in the hydraulic behavior. It was somewhat unexpected that the thinnest felt mat had the greatest detention with the smallest runoff coefficient. This may be due to a more tightly packed material, with less pore volume inside. The drainage boards with and without the extra drainage holes on the bottom (R5, R6) gives the same runoff coefficient. This indicates that the extra drainage holes of three millimeters does not increase the detention of this layer. 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. This leads to a high runoff coefficient, at the same value as the reference roof.

Green roofs are represented by the combinations tested with sedum. Three different runs including sedum were executed in the laboratory. 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 Leca Media. The combination in R4 gives a lower runoff coefficient than the combination in R7, although R7 is thicker consisting of one more layer. This 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, including LECA media gives the lowest coefficient of runoff. It also gives a substantially lower runoff coefficient than the LECA layer alone. Here, it is possible that the horizontal flow occurs in both the sedum layer and in the LECA media layer. It is unlikely that a free surface flow will occur on the LECA-surface.

Non-vegetated roofs are in this study represented as the LECA based roof system with the permeable pavement (R10 = R1 + R9). The runoff coefficient of the system, C = 0,33, is to a large degree influenced by the drainage layer of 10 cm LECA Media with C = 0,39. The cover of the roof is permeable, and the water flows vertically through this upper layer, before it flows laterally in the LECA based layer. The test of the pavement alone (R9) gave a runoff coefficient C = 0,89, contributing to increase the detention capacity of the system presented as R10. A possible connection in this case, is to multiply the layers combined in the roof system R10. This gives a total runoff coefficient of 0,34, which is 0,01 larger than what the laboratory measurements gave the system. This may be due to of the delay between the two layers which is not taken into account when multiplying the runoff coefficients.

Of all the measurements in the laboratory, the LECA Media based systems (R8 and R10) gave the lowest runoff coefficients. These are the most complex systems, and seem to have the main drainage in the Leca-layer. In the comparison of the hydraulic performance of the vegetated and the non-vegetated roof systems, the event-based detention performance is higher for the vegetated one. For event based detention the evapotranspiration can be ignored as insignificant in the time period measured. The runoff coefficient found in this study, can be seen as detention-based. This is because the calculations are not based on the total runoff, which is measured to be close to the added volume of water (Appendix B.5).

A simulated rain event of 11,4 mm was applied on two of the roof systems (R8 and R10), to get a measurement more suitable to the Norwegian climate. The reduction of precipitation amount, also leads to a decreasing runoff coefficient. With a standard deviation of less than 0,006 for the runoff coefficients of each repetition (Appendix B.4), the average curves of the repetitions, represents the runs. The runs with a reduced precipitation event are presented below in Figure 6.



Figur 6: Runoff curves, intensity curves and runoff coefficients, C for a reduced precipitation event on the LECA-based roof systems; R8 and R10

These two tests gave a quite similar runoff coefficient, given as 0,22 for the roof system with vegetation (R8) and a coefficient equal 0,21 for the non-vegetated roof system (R10). This makes up about 2/3 of the runoff coefficients found for the same layered roofs with higher intensity of the block rain. This is not in the same range as the 60 % reduction of precipitation. The reduced differences of the runoff coefficient between the two roofs for the lower intensity event, can possibly be explained by that these runs were performed at the end of the experimental work. At this stage, the sedum mats were in significantly poorer state than at the start of the experiments. This means that the reduction of the runoff coefficient may be the same for the two runs. It should also be mentioned that the runoff intensity for the two runs are not the same after the peak flow, even though the runoff coefficients are quite similar.

For the layer of Leca (R1) and the Leca based systems (R8 and R10), it is observed a similarity of the time of peak flow, despite the different compositions of layers and intensities of events. Time to peak flow for these runs occurs in about 15 minutes, which is the duration time for the simulated precipitation event. In this scenario, the added block rain equals the time of peak flow and time of concentration (Tc). When T_c equals the duration-time, it makes up the worst-case scenario, defined by the Rational Formula (Butler & Davies, 2011)

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 executed in this study, the runoff coefficients are most governed by the layers where horizontal flow occurs. In the runs where horizontal flow occurs trough the porous medias, as Leca (R8 and R10) and Sedum (R4) the flow is governed by Darcy's equation. This means that the flow through the media, among other things, are based on the hydraulic conductivity and the size 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 detention capacity may be explained by friction and slope of the roof.

4.2 Runoff coefficients based on field data

The events chosen as the field observations (figure 4) most comparable to the events simulated in the laboratory based on total precipitation are presented as curves in Figure 7. Due to dissimilarities, the events are presented in individual graphs.

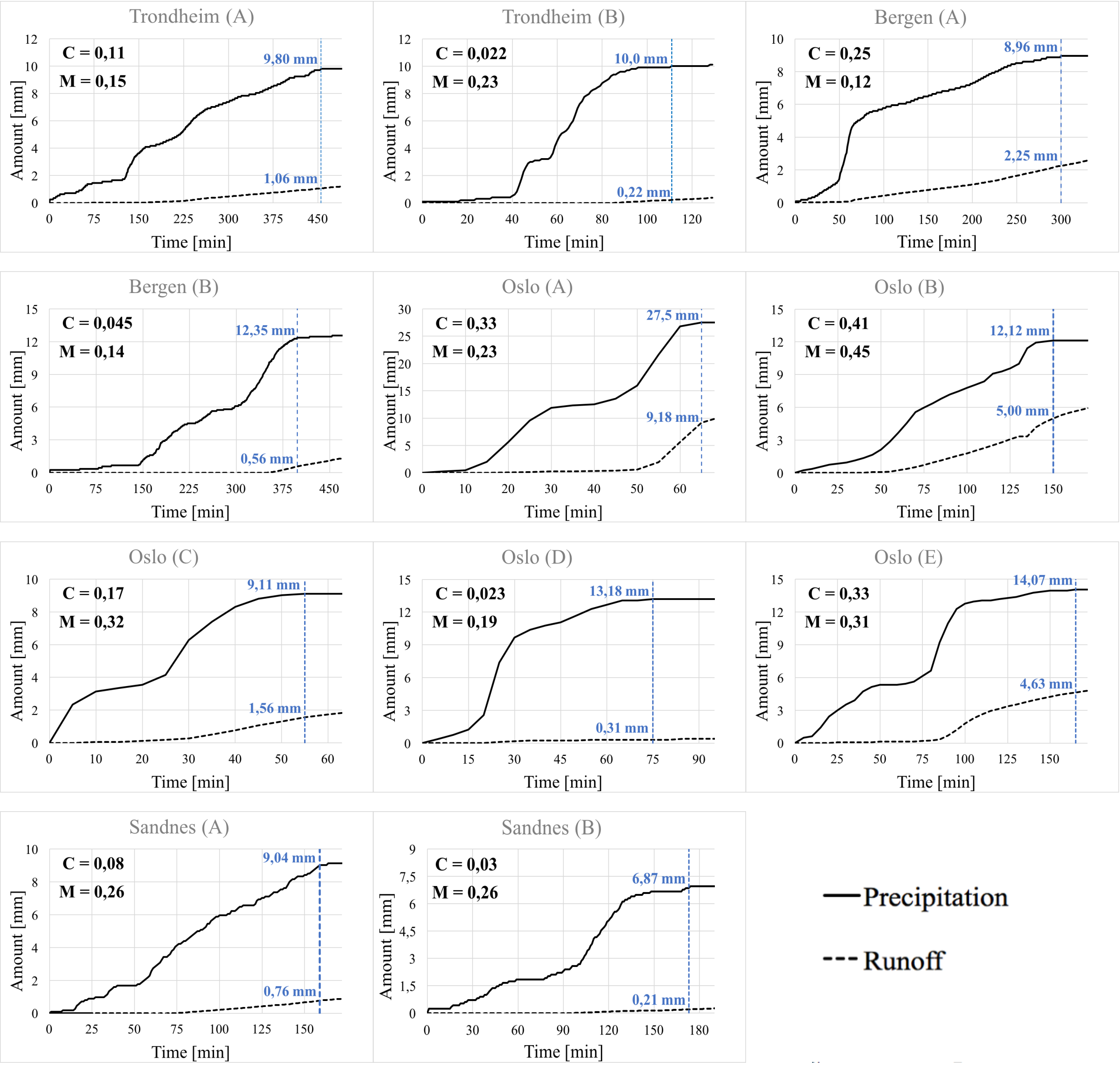


Figure 7: Precipitation- and runoff curves for the chosen events, runoff coefficient (C) and moisture (M) at start of precipitation. The blue represents the calculation of the runoff coefficient. More detailed data of the events, and the same curves of a larger scale are presented in Appendix A.3 and A.4.

The graphs illustrate a varying hydrologic performance of the same layered roof consisting of 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 the curves from the laboratory measurements. The detention performance variates for the events, when lag times varies between 1 and 351 minutes. Runoff at the end of precipitation variates between 0,21 and 9,18 mm. This gives a variation in the calculated detention-based runoff coefficients between 0,023 and 0,41. Compared to the laboratory measured runoff coefficient for the same layered roof, these field observations give a much lower value.

In the field, the state of the roof is not necessarily always the same before the precipitation events occur, which could affect the hydraulic performance. The soil moisture levels at the start of precipitation vary for all the events. Lower soil moisture levels will make the roof capable of storing more water, which will lead to an increase in lag times, and an increased detention performance. 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 after a longer duration than in the laboratory. The longer duration results in lower average intensity of precipitation in the field than in the laboratory, as measured in the laboratory measurements.

To look after trends for the values of the calculated runoff coefficients, plots of the runoff coefficients versus runoff, lag time, moisture, duration, precipitation and average intensity of precipitation was made (Appendix A.5). The only trend that emerges is the increase of runoff coefficient when runoff increase. However, this is expected due to the use of this value in calculations of the runoff coefficient.

4.3 The runoff coefficients as a factor in urban stormwater management

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

Results from the laboratory measurements gave a variation in the runoff coefficient dependent on the materials and compositions of the layers. It also gave a variation dependent on the intensity of the added event. This confirms the studies by among others (Stovin et.al., 2015; Johannessen et.al., 2018; Hamouz et.al., 2018). The different runs (R#) gave runoff coefficients with small errors for the repetitions, which indicates that the testing method is robust and reliable. These laboratory analysis aids our understanding of how water moves through the layers. This makes it easier to compare the layers and evaluate the contribution of each layer when planning a detention-based roof construction. The fact that this is a standard method also makes the results comparable to other studies using the same standardized method.

The challenge with a standardized method, is the results suitability to the location they may be used. The laboratory measurements are conducted in a state which may not be realistic for a given location. This is the case for the Norwegian climate (Figure 4), where the intensity of an event of 27,4 mm in 15 minutes rarely occurs. Lack of suitability is especially an issue for detention-based roofs which are established to handle small to medium events, as defined in the strategy of three steps (NOU, 2015, p. 67), and not the larger events with rare recurrences. However, these laboratory measurements are more suitable for downstream stormwater calculations dimensioned for larger events. The Leca-based runs gave a contribution for detention, even for larger events.

Measurements from the four roofs in the field resulted in runoff coefficients of a smaller order (Figure 7). There are many variables that affect the runoff peaks such as variable soil moisture content, variable intensities, and physical roof design. The collected data for a 4-8-year period was naturally difficult to match up with the events simulated in the laboratory, due to the recurrences of these large events. But there was also a challenge lying in the finding of similar events to compare, leading to the various runoff coefficients. As an alternative to the typical event based metrics used for evaluating detention performance, Johannessen et. al. (2018) presents flow duration curves based on time series, which gives valuable information on the runoff pattern from the roofs, and can be used in relation to local requirements.

5 Conclusion

In this study, the runoff coefficients for different layered detention-based roofs has been investigated. The results highlight the complexity of the runoff coefficient. The laboratory measurements gave a varying runoff coefficient due to the compositions of the roofs and intensity of the added block rain. In addition, the field measurements gave a smaller and more varying runoff coefficient for the same roof composition.

From the laboratory measurements, the two runs containing LECA Media, clearly makes up the lowest measured runoff coefficients: the LECA-based non-vegetated roof system (R10) with a runoff coefficient equals 0,33 and the LECA-based sedum-roof (R8) with the runoff coefficient equals 0,29. Higher runoff coefficients were calculated for the other two roof-combinations, with 0,74 for the combination of sedum and felt mat (R4) and 0,84 for the combination of sedum, felt and drainage board (R7). The time and the reduction of the peak flows are reflected by the runoff coefficients in this study.

The evaluated events from Trondheim, Oslo, Sandnes and Bergen gave runoff coefficients between 0,023 and 0,41 for the same layered roofs. In comparison, the same layered roof (R4) gave an almost doubled coefficient in the laboratory. There are many variables that affect the runoff, which could not all be accounted for in the experimental setup, such as variable soil moisture content, variable intensities, and physical roof design. Unlike the laboratory measurements, it is challenging to find events comparable enough to give the same runoff coefficients.

The results of this study clearly shows the challenges of choosing a suitable runoff coefficient for a given roof in the calculations of stormwater runoff. However, laboratory analysis aids our understanding of how water moves through the layers. Laboratory experiments are important in understanding the underlying flow processes in the different layers in a detention-based roof. In the thicker layers, like the LECA, there will be flow through porous media, which is governed by Darcy's equation, while for example flow across the drainage boards, overland flow may occur, which 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.

Acknowledgements

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Appendix A – Field measurements

The climatic chart and the IDF-curves are given by the Norwegian Centre for Climate Services (NCCS). Available at: https://klimaservicesenter.no [Accessed March, 2018]. The data from the field measurements are Extracted with help from Birgitte Gissvold Johannessen.

A.1 Climatic charts

These charts presents the varying Norwegian climate, and are used for the description in chapter 2.

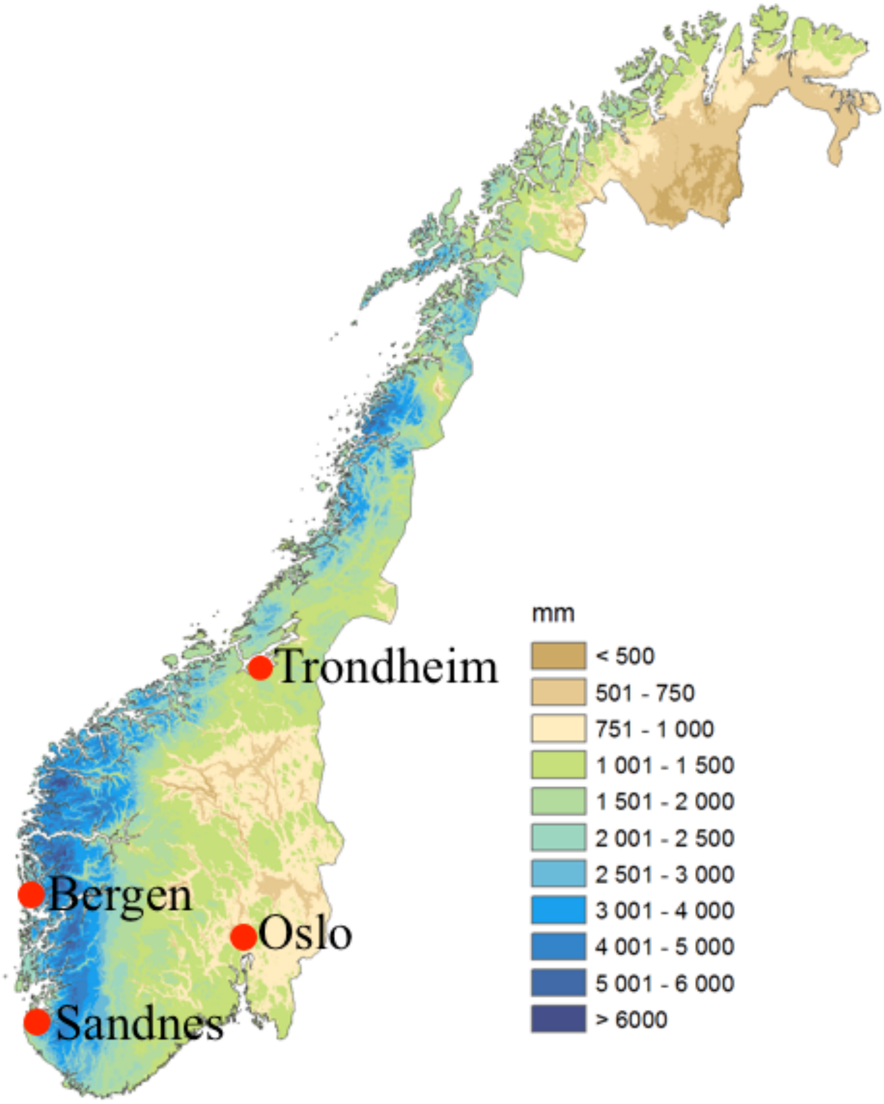


Figure 8: Average precipitation (mm) trough a year, based on data from 1985 to 2014. (NCCS, March 2018)

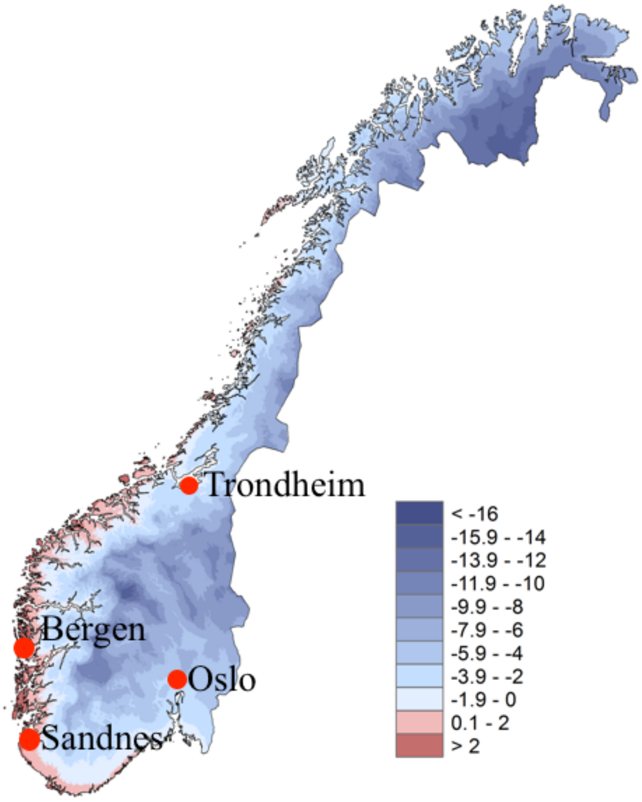
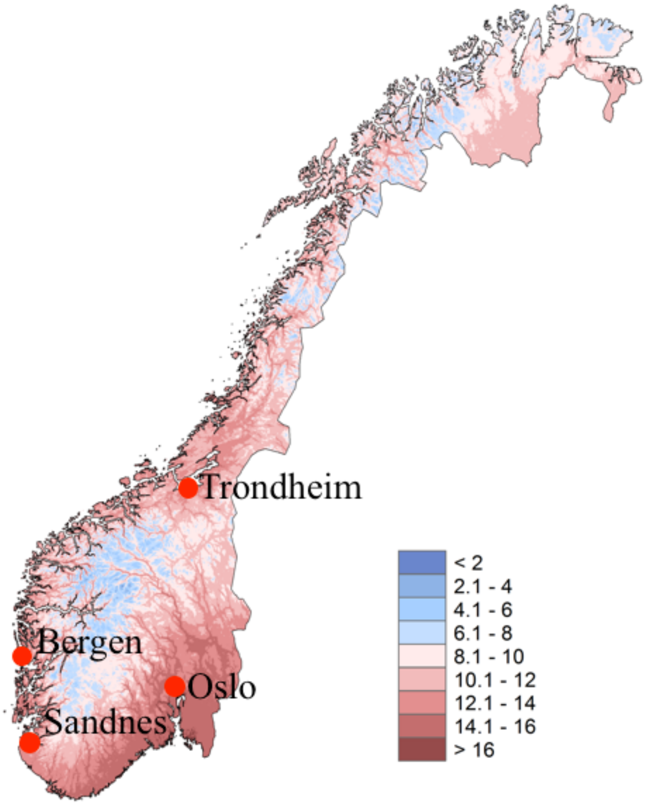


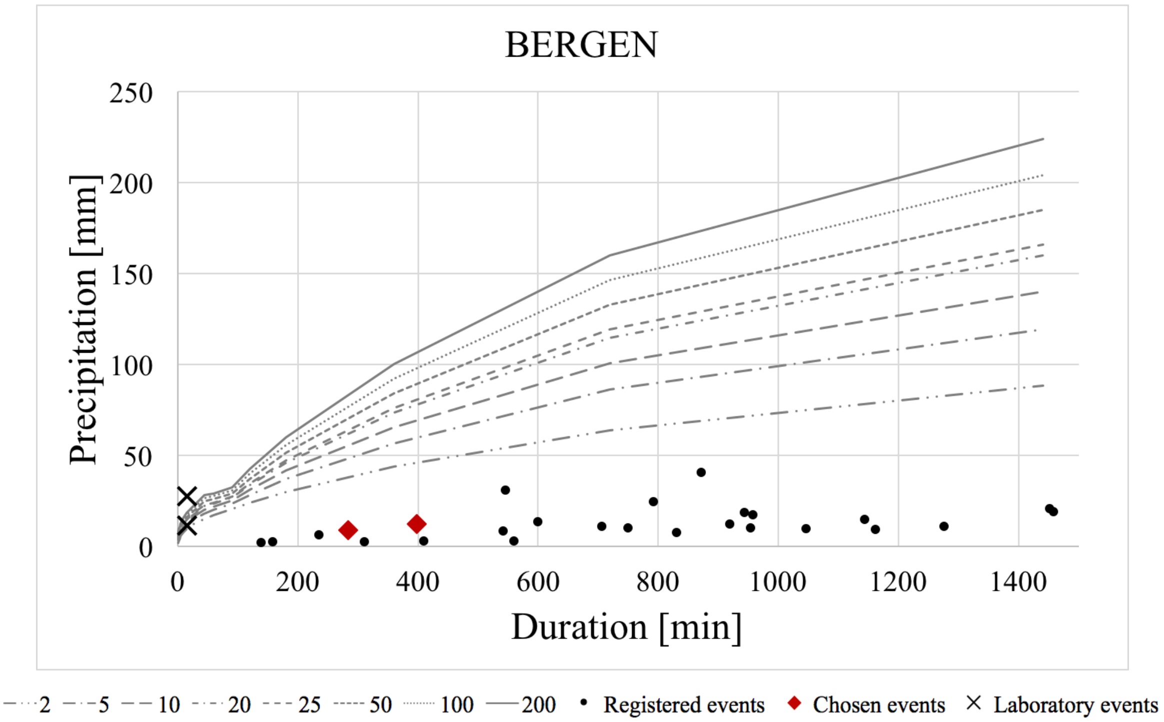
Figure 9*:* Average temperatures (°C) in winter conditions based on measurements from 1985-2014 *(NCCS, March 2018)*



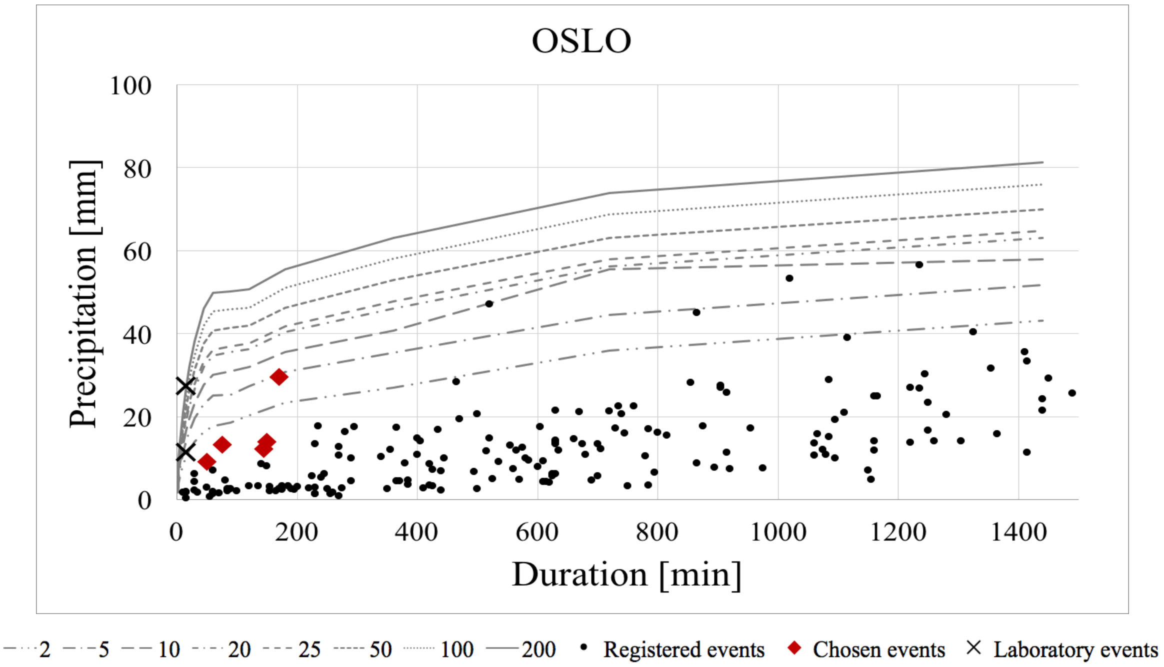
Figur 10: Average temperatures (°C) in winter conditions based on measurements from 1985-2014 (NCCS, March 2018)

A.2 IDF-curves

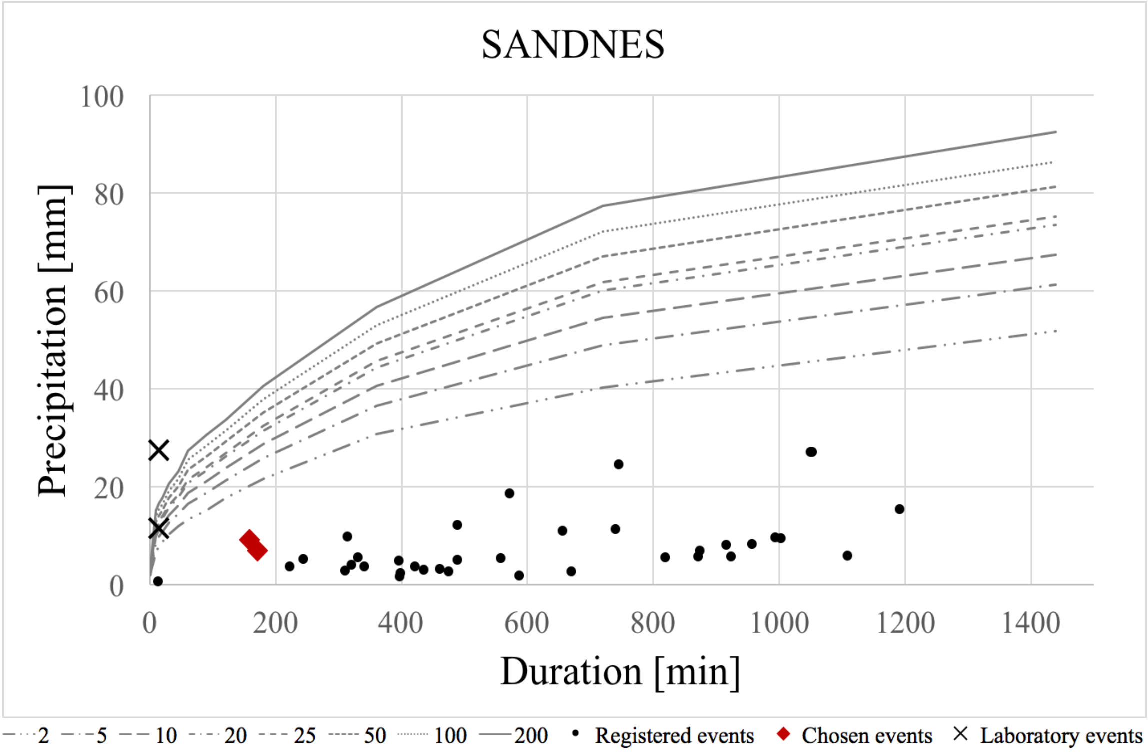
IDF-curves used to describe the varying Norwegian climate in chapter 2, and to choose events for the study of field events in chapter 3.



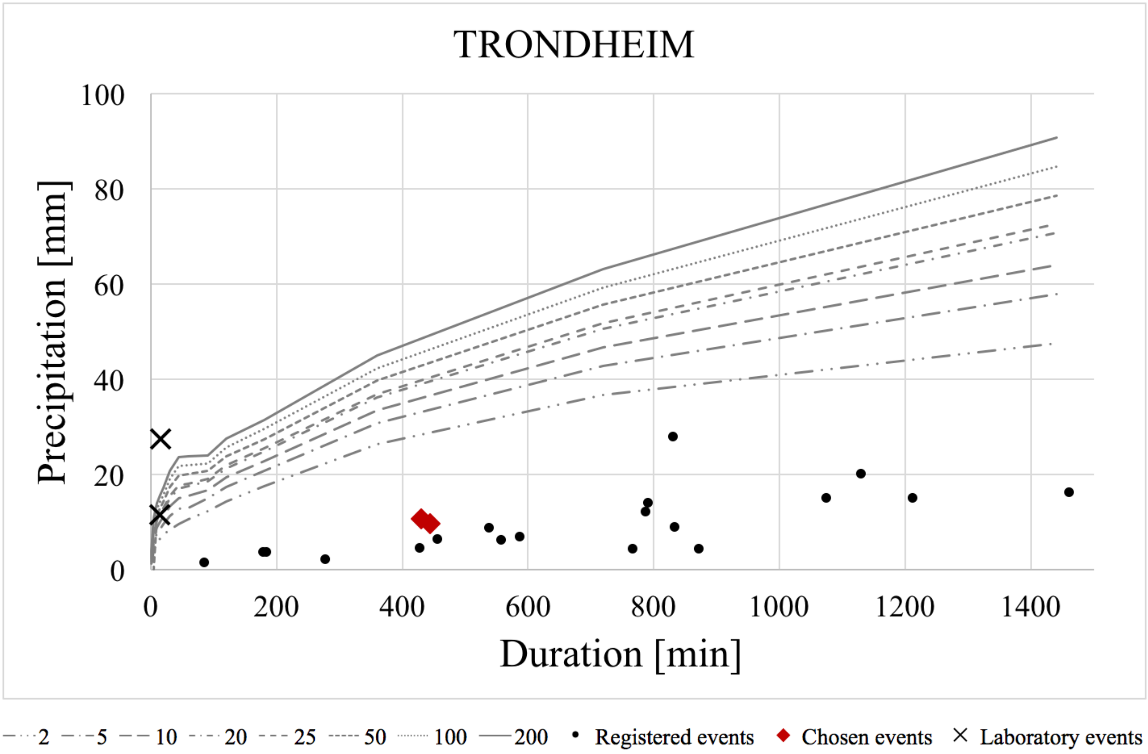
Figur 11: IDF-curve based on data collected since 17.06.03 at Florida UIB weather station in Bergen (NCCS, Accessed May 14, 2018). Plots of events from field studies at testing roof (Johannessen, 2018).



Figur 12: IDF-curve based on data collected since 01.01.1968 at Blindern PLU weather station in Oslo (NCCS, Accessed May 14, 2018). Plots of events from field studies at testing roof (Johannessen, 2018).



Figur 13: IDF-curve based on data collected since 20.06.1974 at Florida UIB weather station in Sandnes (NCCS, Accessed May 14, 2018). Plots of events from field studies at testing roof (Johannessen, 2018).



Figur 14: IDF-curve based on data collected since 11.12.1986 at Risvollan weather station in Trondheim (NCCS, Accessed May 14, 2018). Plots of events from field studies at testing roof (Johannessen, 2018).

A.3 More detailed data from the chosen events

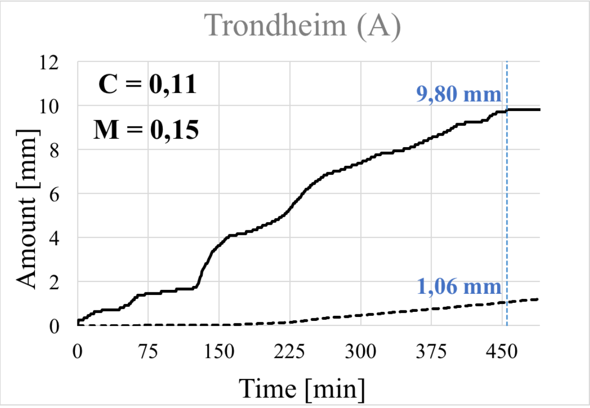
Table 3: Data from the events collected in the field

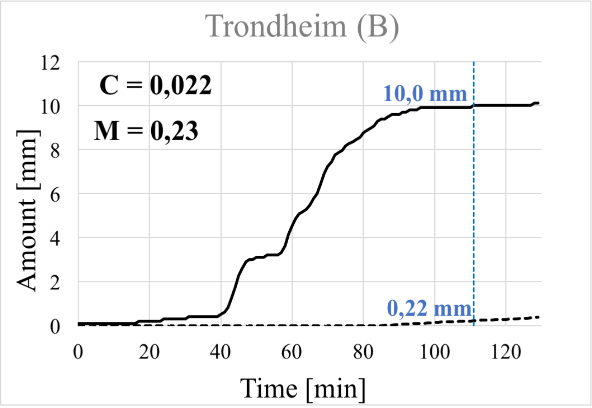
		Date and time of start precipitation	**Duration precipitation**	**Total prec.**	**Runoff ***	**Lag start**	**Moist. Start**	**Runoff Coeff ****
Bergen (1C)	A	15.09.15 13:59	299	8,96	2,25	1	0,12	0,25
	B	07.07.17 15.10	398	12,35	0,56	351	0,14	0,045
Oslo (3C)	A	07.06.11 07.10	65	27,51	9,18	15	0,23	0,33
	B	29.09.12 00.00	150	12,12	5,00	40	0,45	0,41
	C	04.08.13 17.25	55	9,11	1,56	5	0,32	0,17
	D	17.07.14 20.30	75	13,18	0,31	20	0,19	0,023
	E	12.08.13 11.35	165	13,97	4,63	20	0,31	0,33
Sandnes (1C)	A	05.05.15 19.27	159	9,04	0,76	75	0,30	0,08
	B	11.05.17 14.26	173	6,87	0,21	96	0,26	0,03
Trondheim (1C)	A	29.06.15 03.16	455	9,8	1,06	137	0,15	0,11
	B	28.07.16 11.40	111	10,01	0,22	85	0,23	0,022

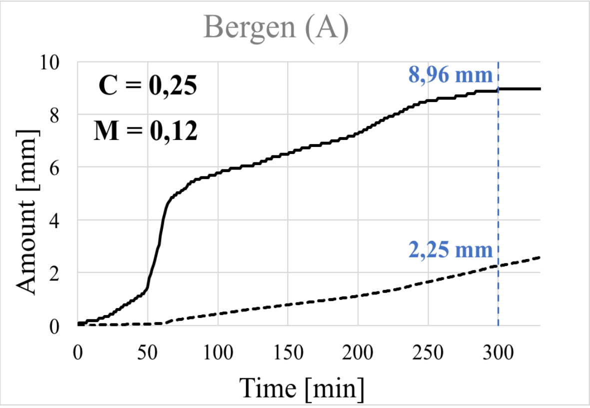
*Total amount runoff when precipitation has ceased
**Runnoff coefficient calculated as the relationship between Runoff* and total precipitation

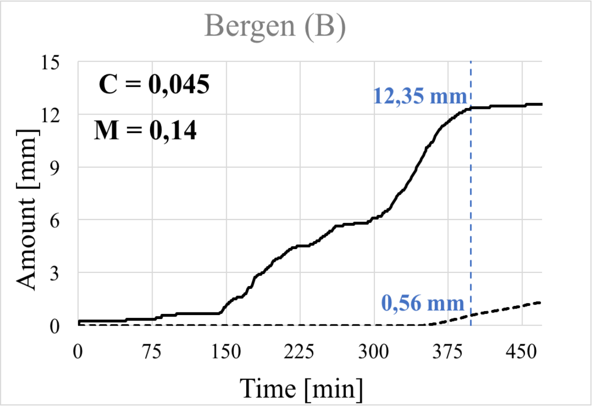
A.4 Precipitation and runoff curves

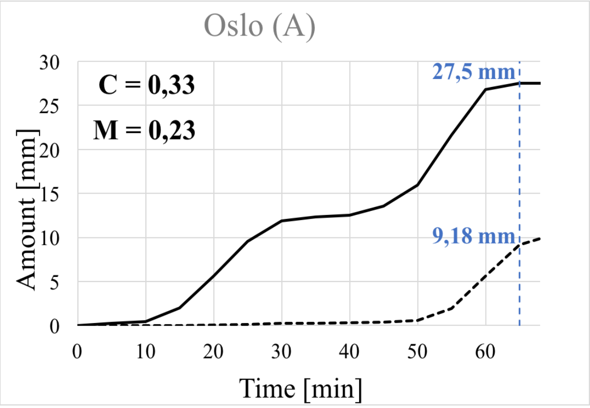
Precipitation and runoff curves from the collected events for the outdoor testing roofs consisting of sedum and felt. The same curves as in chapter 4.2 in a larger scale.

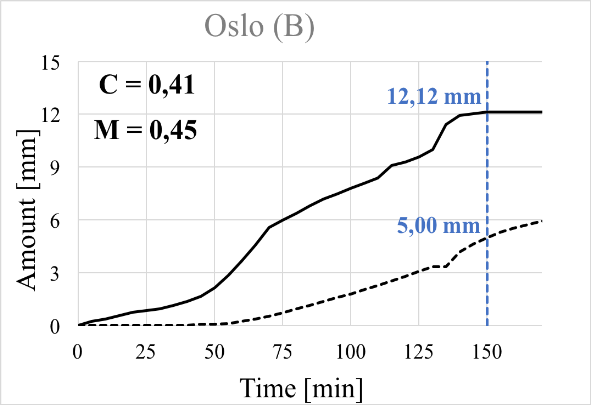


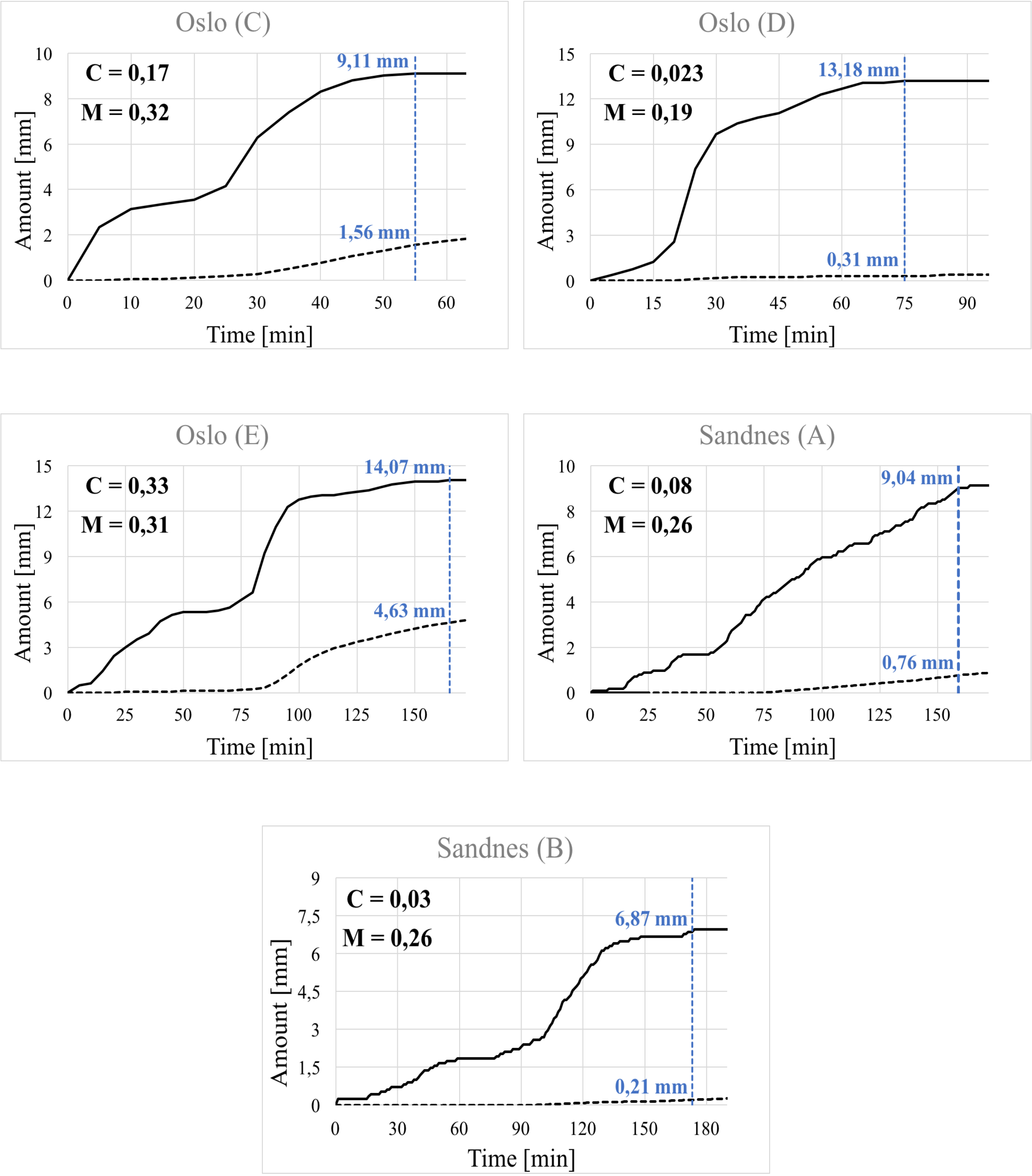








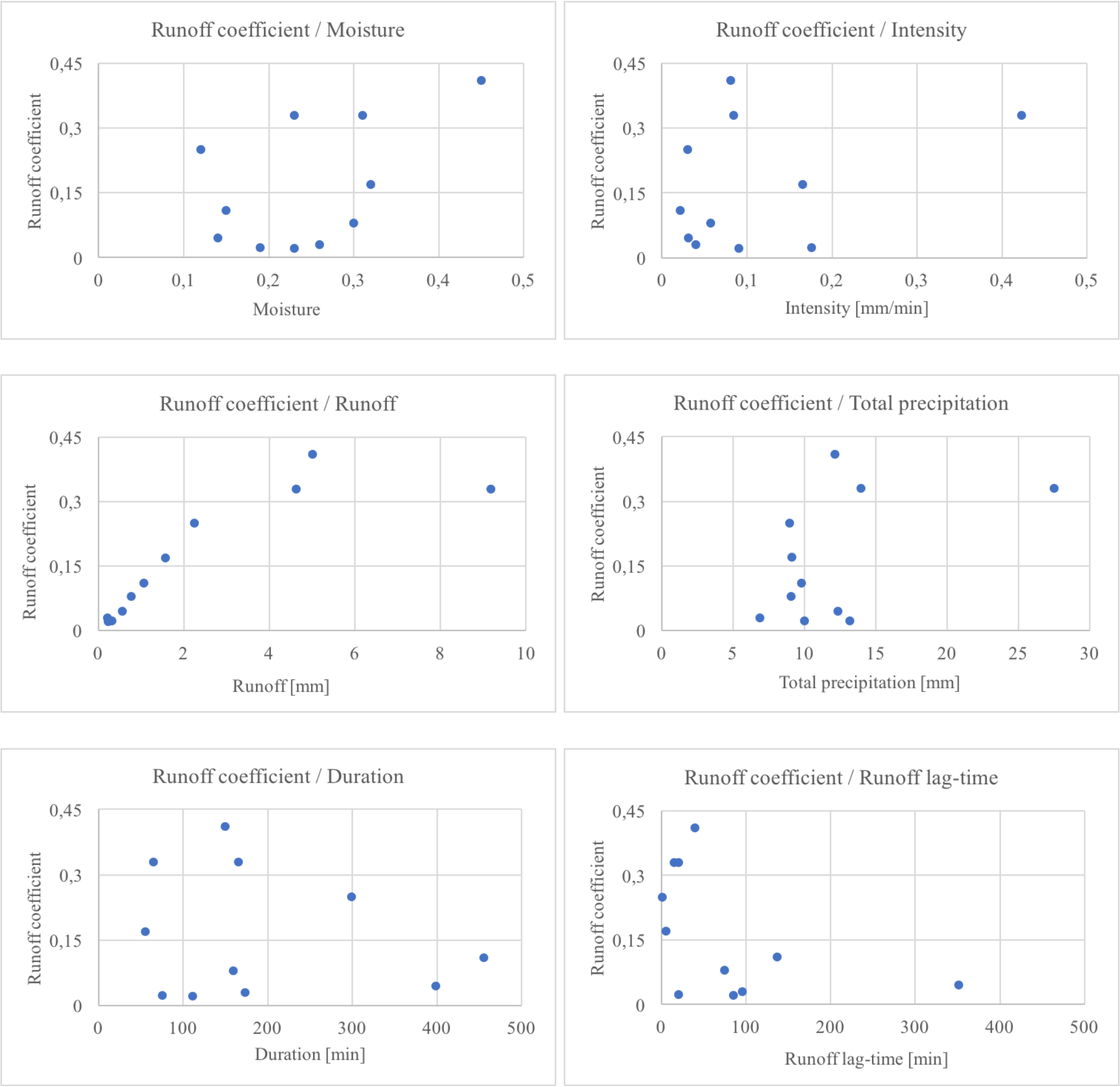




Figur 15: Precipitation- and runoff curves for the chosen events, runoff coefficient (C) and moisture (M) at start of precipitation. Blue describes the values for calculating the runoff coefficient at the end of precipitation.

A.5 Plots

Plotted data from the collected field events. Used to look after trends for the runoff coefficients.



Figur 16: Plots of the runoff coefficient to factors influencing the value

Appendix B – Laboratory measurements

B.1 Pictures from the runs

R1: Leca Media 0 – 6 mm, 10 cm

R2: Felt mat I, Bergknapp, 7 mm

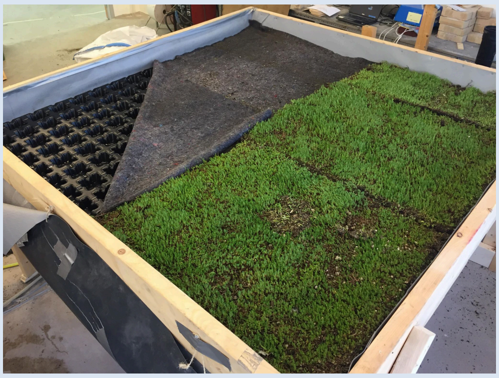
R3: Felt mat II, Veg Tech, 10 mm

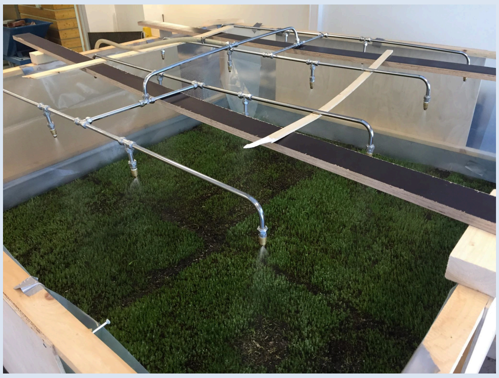
R4: Sedum mat and felt mat I

R5: Drainage mat I, Isola DE40 with 3 mm extra drainage holes

R6: Drainage board II, Isola DE40

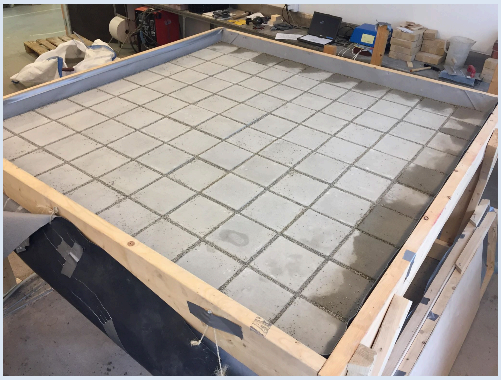
R7: Sedum mat, felt mat, Isola DE40 with 3 mm drainage holes

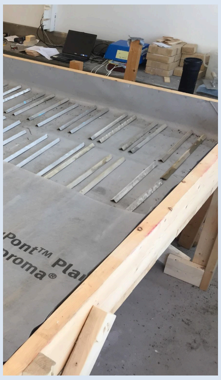




R8: Leca Media, Isola DE40, Felt mat I, Sedum mat

R9: Leca concrete pavers with grout material as filler, geotextile, lifted 1,5 cm



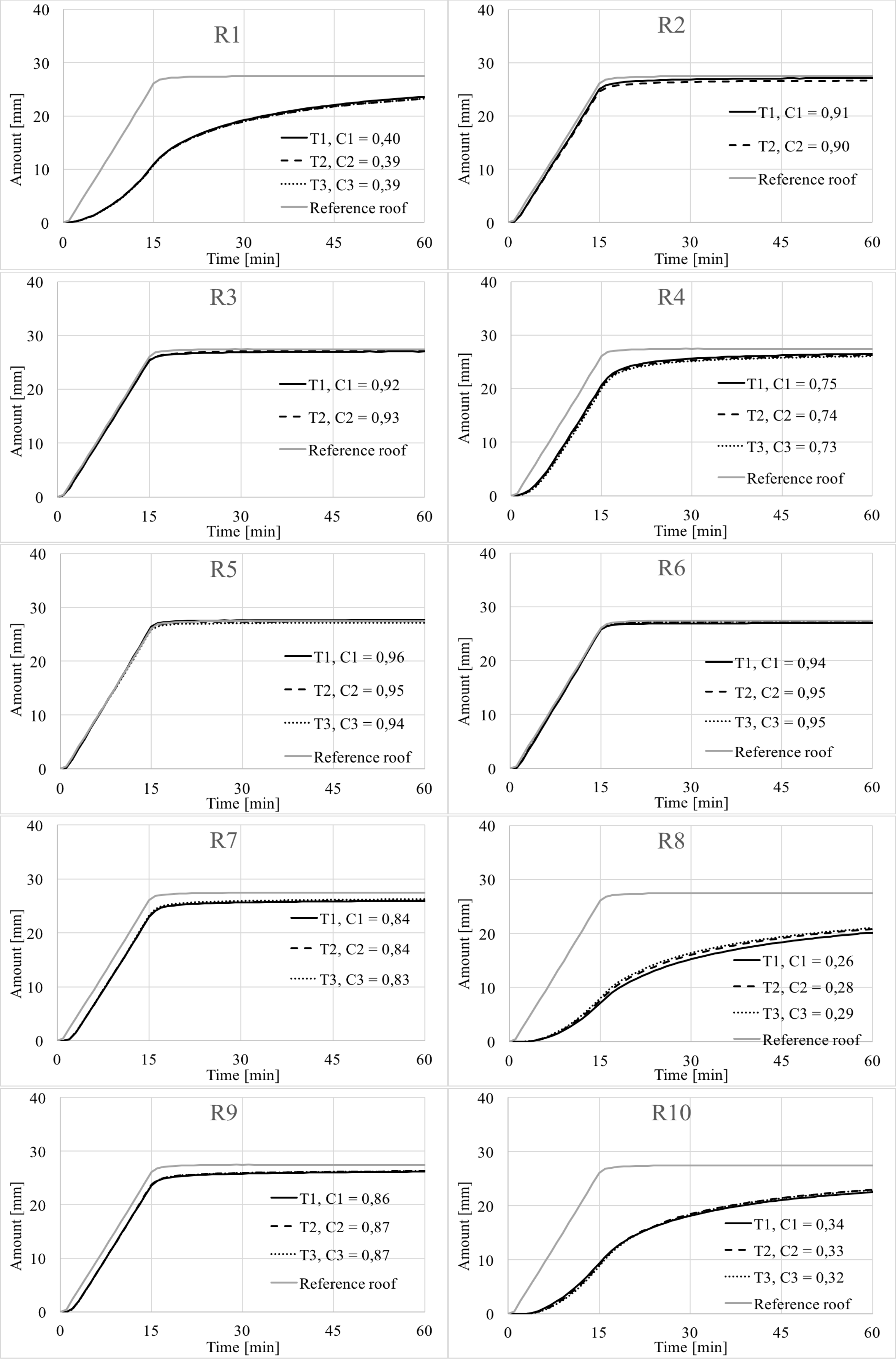


R10: Leca media, geotextile, leca concrete pavers with grout material

Referance roof: Low friction PVC mat

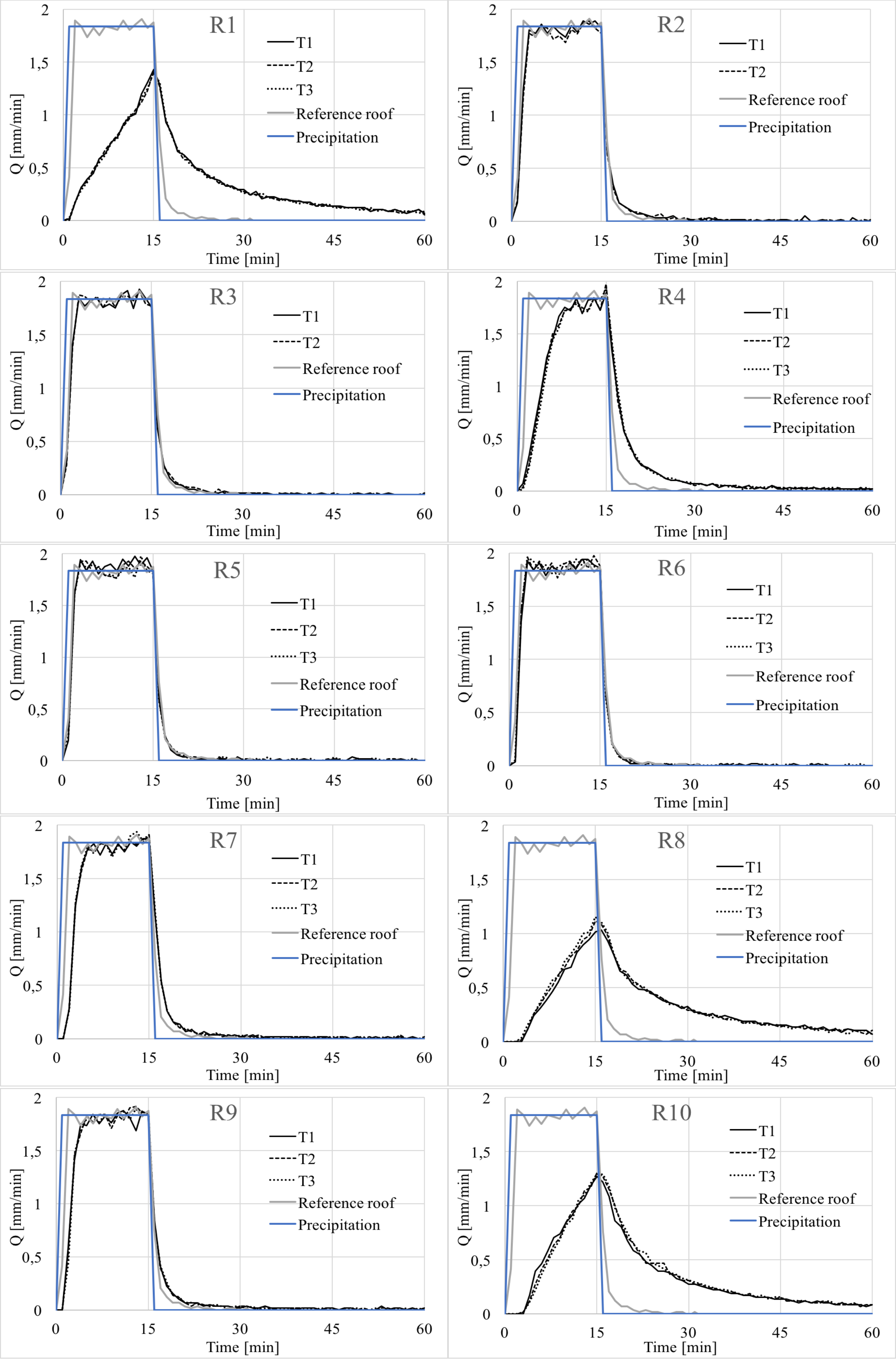
Laboratory setup and collecting system

B.2 Runoff curves



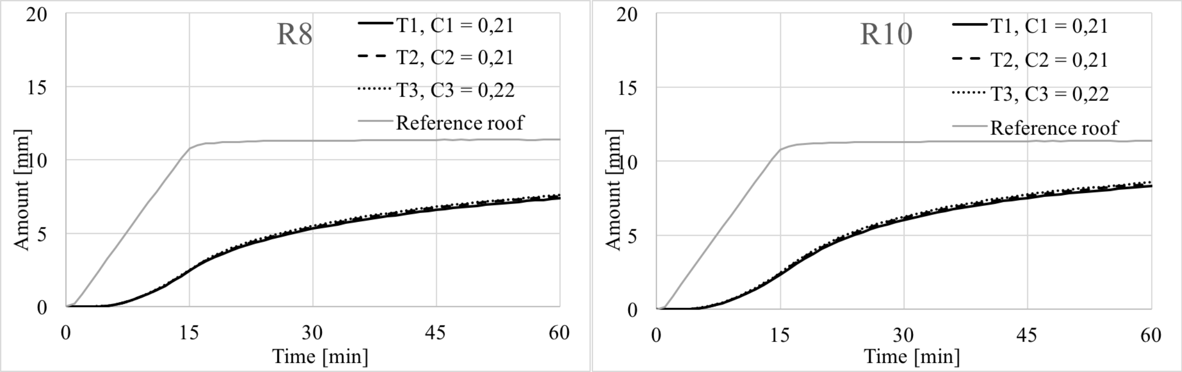
Figur 17: Runoff curves for 27,4 mm precipitation, including runoff coefficients (C) for all the repetitions

B.3 Intensity curves

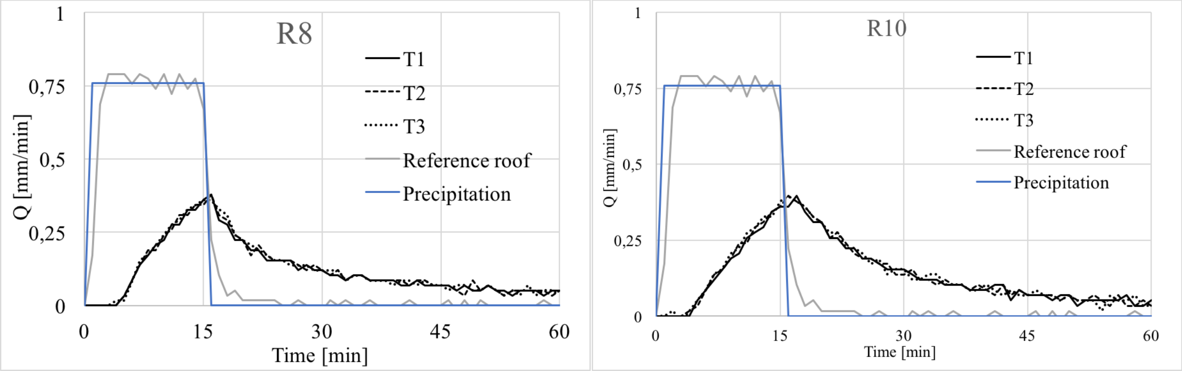


Figur 18: Intensity curves for 27,4 mm for all the repetitions

B.4 Curves from the reduced precipitation



Figur 19: Runoff curves for 11,4 mm precipitation and runoff coefficients for all the repetitions



Figur 20: Intensity curves for 11,4 mm precipitation for all the repetitions

B.5 More detailed data from the measurements

Table 4: Data from the laboratory measurements

	Run	Precipitation [mm]	Runoff, 15 min [mm]	Runoff, total [mm]	Lag time [s]	Peak flow [mm/min]	Runoff coeff.
R1	1	27,4	10,92	27,27	58	1,43	0,40
	2	27,4	10,79	26,68	67	1,42	0,39
	3	27,4	10,79	26,76	50	1,40	0,39
R2	1	27,4	25,06	27,17	23	1,89	0,91
	2	27,4	24,62	26,75	22	1,89	0,90
R3	1	27,4	25,34	27,08	16	1,93	0,92
	2	27,4	25,41	27,25	19	1,91	0,93
R4	1	27,4	20,68	27,36	37	1,89	0,75
	2	27,4	20,38	27,09	53	1,98	0,74
	3	27,4	20,02	26,97	56	1,93	0,73
R5	1	27,4	26,42	27,74	39	1,97	0,96
	2	27,4	26,16	27,50	33	1,93	0,95
	3	27,4	25,86	27,32	44	1,98	0,94
R6	1	27,4	25,76	27,12	55	1,94	0,94
	2	27,4	26,06	27,43	53	1,98	0,95
	3	27,4	26,06	27,42	55	1,96	0,95
R7	1	27,4	22,96	26,88	89	1,87	0,84
	2	27,4	23,01	26,95	89	1,91	0,84
	3	27,4	23,25	27,19	86	1,94	0,85
R8	1	27,4	7,10	25,92	189	1,03	0,26
	2	27,4	7,67	25,89	180	1,12	1,28
	3	27,4	8,05	26,13	170	1,15	0,29
	1	11,4	2,42	10,08	261	0,38	0,21
	2	11,4	2,44	10,33	264	0,38	0,21
	3	11,4	2,49	10,40	259	0,36	0,22
R9	1	27,4	23,61	26,93	66	1,88	0,86
	2	27,4	23,80	26,98	78	1,92	0,87
	3	27,4	23,73	27,05	78	1,89	0,87
R10	1	27,4	9,35	26,42	187	1,27	0,34
	2	27,4	9,08	26,79	175	1,31	0,33
	3	27,4	8,82	26,76	175	1,29	0,32
	1	11,4	2,34	10,56	241	0,40	0,21
	2	11,4	2,41	10,71	239	0,40	0,21
	3	11,4	2,48	10,78	231	0,40	0,22