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The effect of ventilated air cavities on the hydrological performance of green roofs in Nordic countries.

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Thea Sophie Johannessen

Master of Science in Civil and Environmental Engineering
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Supervisor: Tone Merete Muthanna
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Preface

This master thesis is a result of the course TVM4905, Water and wastewater engineering, Master's thesis and is awarded 30 credits. The study has been carried out in the spring of 2020 and the final product is submitted to the Norwegian University of Science and Technology (NTNU). The work was supported by the Department of Civil and Environmental Engineering in corporation with SINTEF and Klima2050. The thesis investigates the effect ventilated green roofs may have on the evapotranspiration in cold and wet climate. Laboratory tests were initially planned to be performed in order to examine the effect of ventilated air cavities on green roofs. Laboratory tests were ready to be conducted when university campus and the connected laboratories were closed 12. March 2020 due to Covid-19. The initial tests were therefore not possible to perform. As it was impossible to predict when the laboratories would open up for students, a new way to approach the problem was necessary. It was therefore decided to perform a model simulation in WUFI. Laboratory measurements are planned to take place later in 2020.

I would like to express a deep appreciation to my supervisor, associate professor Tone Merete Muthanna. Thank you for all the hours you have put aside to discuss issues relating to this thesis and for all the help and motivation you have given me through this process. I also want to thank my co-supervisor, senior researcher at SINTEF, Edvard Sivertsen, for you guidance and ideas. I would like to especially thank you both for extra motivation and excellent problem solving during some chaotic weeks after the lockdown of the laboratory. In addition, I would like to express my appreciation to Researcher Scientist Stian Bruaset for helping me to prepare for the laboratory test, Senior Research Scientist Lars Gulbrekken for suggesting WUFI as simulation program as well as providing valuable information about ventilated air cavities, and PhD candidate Vincent Pons for providing valuable moisture and climate information from Høvringen, Trondheim.

Wolbrechtshausen, 10. July 2020

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Sammendrag

Grønne tak kan forbedre overvannshåndtering ved å forsinke og redusere flomtoppen ved en nedbørshendelse. Dette vil avlaste det offentlige avløps- eller overvannsnettet og kan redusere risikoen for flom. Flomtoppen blir forsinket ved at taket holder tilbake nedbør og blir redusert ved at regnvannet blir ført tilbake til atmosfæren gjennom evapotranspirasjon. Evapotranspirasjon påvirker i stor grad fordrøyningseffekten av det grønne taket og hvor stor evapotranspirasjonen er i et område påvirkes av klimaet. Viktige faktorer som påvirker størrelsen på evapotranspirasjonen er temperatur, luftfuktighet, vindhastighet og solstråling. Klimaet i Nordiske land er sesongbasert og evapotranspirasjonen, og dermed kapasiteten til grønne tak, varierer derfor fra årstid til årstid. I Nordisk klima, som i Norge, er evapotranspirasjonen nesten neglisjerbar i vintermånedene. Dette kan implisere at vindhastigheten muligens i større grad påvirker regenerereringen av kapasiteten i grønne tak. Det er så vidt forfatteren bekjent ingen tilgjengelig forskning som omhandler luftede grønne tak. Denne studien vil derfor undersøke den potensielle effekten lufting av grønne tak har på fordrøyningkapasiteten i taket. Prinsippet fra lufting av isolerte skrå tretak ble brukt som inspirasjon og overført til flate ekstensive grønne tak. Ved å bygge det grønne taket med en luftespalte vil en tillate luft utenfra til å sirkulere mellom det grønne taket og takmembranen. For å undersøke effekten lufting av grønne tak har på evapotranspirasjonen ble det planlagt å gjennomføre laboratorietester i klimarommet i SINTEF Byggforsk sin lab på Gløshaugen. Testene ble planlagt gjennomført på grønne tak moduler med og uten luftespalte. Modulen med luftespalte skulle ha en 73 mm luftespalte og begge modulene skulle påføres de sammen tre vindhastighetene. Klimarommet tillater at temperaturen blir kontrollert. Dersom det viste seg at lufting av grønne tak kunne øke evapotranspirasjonen, og dermed fordrøyningskapasiteten, skulle modulene også testes for ulike temperaturer for å undersøke effekten i kaldt klima. Laboratorietestene var planlagt og klargjort, men ettersom Covid-19 førte til at campus og laboratoriet stengte, ble det ikke mulig å gjennomføre de planlagte testene. Simuleringer i det numeriske simuleringsprogrammet WUFI ble i stede brukt.

WUFI er et hygrotermisk simuleringsprogram som i hovedsak blir brukt til å simulere varme og fuktighet i bygningskomponenter. Fuktighetsdata fra testfeltet på Høvringen i Trondheim ble brukt til å validere simuleringsmodellen. Modellene i WUFI ble derfor konstruert med samme oppbygging som testtaket på Høvringen og simulert for klimatiske forhold målt på Høvringen. Flere av materialparameterne påkrevd av WUFI er ikke vanlige å teste for materialer brukt til overvannsløsninger. Dermed måtte flere av materialparameterne for dreneringslaget (leca) og sedummatten brukt i modellen estimeres basert på begrenset tilgjengelig forskning på liknende materialer. Ukorrekt materialdata er derfor en stor usikkerhetskilde ved simuleringene. En modell uten lufting ble konstruert og brukt som referansetak. Modellen med luftespalte ble simulert for 50, 70 og 100 mm spaltehøyde og for

minimum, median og maksimum vindhastighet for Høvringen målt over tre år. De ble også simulert for en 0,33 m/s vindhastighet.

Valideringen av modellen viste at det målte fuktighetsinnholdet og det simulerte fuktighetsinnholdet ikke ga perfekt korrelasjon. Det simulerte fuktighetsinnholdet fulgte derimot samme trend som det målte fuktighetsinnholdet. Modellen pålagt en luftespalte ble derfor brukt videre i simuleringene.

Resultatene fra simuleringene indikerer at fuktighetsinnholdet i dreneringslaget er lavere for lavere luftespalte. De viser også indikasjoner på at lavere vindhastighet gir lavere fuktighetsinnhold, ned til en viss hastighet. Det kan også se ut som at endring i vindhastighet påvirker fuktighetsinnholdet i dreneringslaget i større grad for taket med 100 mm luftespalte enn for taket med 50 mm luftespalte.

For å undersøke effekten av luftede grønne tak nærmere, ble fuktighetsinnholdet fra de ulike spaltehøydene påført medianvind sammenliknet og analysert. Regenereringsraten av fordrøyningskapasiteten og den prosentvise forskjellen i ET ble funnet for de ulike spaltehøydene. Funnene viser tendenser til at lavere luftespalte gir høyere regenereringsrate og høyere evapotranspirasjon. Dette kan gi en indikasjoner på at lavere luftespalte gir bedre uttørking av taket.

Det er fremmet et forslag om implementering av skatt på overvann fra eiendommer i Norge. Skattesatsen vil da delvis baseres på hvor mye avrenning det er forventet fra eiendommen. Det kan dermed bli mer attraktivt å håndtere overvann lokalt, også for privatpersoner, slik at skattesatsen blir lavere. Det kan følgelig være nyttig å beregne mengde avrenning som kan reduseres ved implementering av ventilerte grønne tak. Det er predikert at både gjennomsnittstemperatur og nedbør vil øke i fremtiden og dermed kan det også være fare for økt tørke av sedumtaket ved implementering av luftespalte. Dette ble videre undersøkt.
Norge er et land med store variasjoner i klima og det kan se ut som at luftet grønt tak ikke nødvendigvis er en god løsning i områder som allerede står ovenfor en økt risiko for tørke. Dette kan typisk være i området hvor det kun er forventet en liten økning i nedbør. I områder som allerede opplever store nedbørsmengder, hvor det også er forventet en økning i nedbør kan det derimot være hensiktsmessig å implementere luftede grønne tak. Ved å fange avrenning fra taket i våte perioder, kan det oppsamlede vannet bli brukt til irrigasjon i tørre perioder og dermed unngå at vegetasjonen visner.

Simuleringene gjennomført i denne oppgaven gir indikasjoner på at luftede grønne tak kan øke kapasiteten i taket. Det er i midlertidig mange potensielle feilkilder ved simuleringene og resultatene gir kun indikasjoner og ikke noen nøyaktige resultater. Det er dermed nødvendig å gjennomføre laboratorietester av konstruksjonen for å få mer pålitelige resultater.

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Thesis structure

This thesis is presented in concise article-form, comprising both simulations and laboratory tests which were developed but not performed due to the Covid-19 Pandemic. The intention behind adopting this format was to enable publishing. The result of this work was initially planned to be presented at the International Low Impact Development Conference, which should have taken place in Bethesda, Maryland 19th -22nd of July 2020. The conference was however cancelled due to the Covid-19 pandemic. A paper will later be submitted to an as of yet unspecified journal. The Norwegian summary is intended to be presented in the Klima2050 newsletter.

The effect of ventilated air cavities on the hydrological performance of green roofs in Nordic countries.

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Abstract

Green roofs can improve stormwater management through retention of rainfall and detention of runoff. Evapotranspiration has a large impact of the retention performance of green roofs. Temperature, relative humidity, wind speed and solar radiation are important factors for evapotranspiration which are seasonable variable in Nordic climates. In Nordic climate, such as Norway, the evapotranspiration can be almost negligible during winter implying that the wind speed may play a larger role in regeneration of retention capacity. There is however limited research concerning the effect of wind on evapotranspiration. This study aims to investigate the potential retention performance benefit of an air ventilated green roof system. The new construction method allows for air circulation between the green roof and the roof membrane. The hygrothermal simulation programme WUFI was used for the simulations and a model of a traditional green roof build-up was used as reference roof. Comparisons of the results from measured and simulated moisture content showed that the simulated moisture content followed the same tendencies as the measured moisture values. There are however several limitations by using WUFI as a tool to simulate the moisture condition in ventilated green roofs. In order to investigate the effect of the ventilated air cavity on the evapotranspiration, the models were tested for different wind speeds. The simulations showed that by allowing wind to flow under the configuration a higher evapotranspiration was achieved, increasing the regeneration rate of the expanded clay aggregate layer and hence increase the hydrological performance.

Keywords – Green roof, Ventilated air cavity, evapotranspiration, hygrothermal simulation, retention

1. Introduction

Green roofs are becoming increasingly popular as a stormwater solution, since they offer a wide range of environmental, economic and social benefits reported by several reviews (Andenaes et al., 2018, Eckart et al., 2017, Getter and Rowe, 2006). In areas with natural landscape and a big portion pervious area, precipitation gets infiltrated into the ground or evaporated back to the atmosphere (Dingman, 2015). Dense urban areas are often made up of a high fraction of impervious surfaces. Impervious surfaces cannot infiltrate precipitation and the excess water will flow over the surface and hence increase chances for flooding (Dingman, 2015). Although space is limited in dense urban areas, green roofs can be retrofitted to existing rooftops and can therefore offer an effective way to reduce number of impervious surfaces and hence improve the stormwater system in urban areas (Eckart et al., 2017).

Green roofs can improve stormwater management through retention of rainfall and detention of runoff. Vegetated roofs reduce the total runoff as well as reduce and delay the peak flow (Voyde et al., 2010). This mitigate the pressure on the municipal stormwater pipe system and can reduce the chances of overflow and flooding. The retained water gets removed through evapotranspiration (ET) (Sims et al., 2016, Voyde et al., 2010) and recovers the storage capacity (Locatelli et al., 2014, Sims et al., 2016, Voyde et al., 2010). The rate of ET is therefore important in order to determine green roofs capacity for the following storm event.

Evapotranspiration consists of two processes: evaporation and transpiration. Evaporation is vaporization directly from a surface and is influenced by the amount of energy available to induce the vaporization and the ability to remove the vapor from the surface. Solar radiation provides most of the available energy and the wind speed and the specific humidity in the air above the surface affects the capability to remove the vapor away from the surface. Transpiration occurs when water gets extracted through the roots of the plants and dispersed into the atmosphere through stomata in their leaves (Chow et al., 1988).

The local climate greatly affects the green roof performance. Wind speed, solar radiation, humidity and available moisture in the substrate are all climatic processes that affects the ET rate (Chow et al., 1988). This is supported by findings done by several previous researches among others Berretta et al. (2014), Poe et al. (2015) and Sims et al. (2016).

The mechanism behind the ET can be explained by the Penman-Monteith equation. The Penman-Monteith equation estimates the reference evapotranspiration (ET_0), which is the ET estimation for a surface covered with grass of a given height when water is unlimited (Chow et al., 1988). The FAO Penman-Monteith equation is found to have an overall good precision and is therefore suggested to be the standard calculation method for ET_0 (Allen et al., 1998):

$$ET_0 = \frac{0{,}408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273}\right)U_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0{,}34U_2)} \tag{1}$$

This method considers the effect the radiation from the sun, the wind, the humidity of the air and the temperature has on the evapotranspiration.

ET_0 is the reference ET (mm/day), R_n is the net radiation (MJ/m^{2}day), e_a is the actual water pressure (kPa), e_s is the saturated vapour pressure (kPa), T is the temperature of the air measured 2 m above the ground (°C), G is the heat flux density to the soil (MJ/m^{2}day), γ is the psychrometric constant (kPa/°C), Δ is the saturated vapour pressure curve slope (kPa/°C) and U_2 is the wind speed measured 2 m above the ground (m/s) (Allen et al., 1998).

The wind speed affects the evaporation by removing water vapor from the surface. As the water evaporates from a surface, the air around gradually gets a higher vapor pressure. As long as the saturated vapor pressure at the surface is bigger than the vapor pressure of the air above, evaporation will occur. When the air above the surface is fully saturated, evaporation will cease and additional vapor pressure will result in condensation. As the wind blows along the surface, it carries water vapour away (Dingman, 2015).

Davarzani et al. (2014) found that an increase in windspeed increased the evaporation rate up to a certain wind speed velocity. The influence of higher wind speed on the evaporation rate decreased after this level. Tabares-Velasco and Srebric (2011) found that the evapotranspiration would increase with 10-30% if the air speed was increased from 0,1 m/s to 1 m/s.

Many studies have identified a limited hydrological performance of green roofs in cooler climates, among others (Voyde et al., 2010), (Poe et al., 2015) and Johannessen et al. (2017). The evapotranspiration has been found to be higher during warmer conditions (Poe et al., 2015) and to be the limited factor for regeneration of storage capacity in cold and wet climates (Johannessen et al., 2017). Berretta et al. (2014) recorded a reduction in moisture loss from the green roof simultaneous as the relative humidity and wind speed increased and the temperature and solar radiation decreased. The moisture loss rate was also found to be higher with higher temperatures and initial moisture condition and vice versa. These results are supported by findings done by Poe et al. (2015), who found the initial ET rates to increase with higher temperature. Findings done by Voyde et al. (2010) indicated that the net radiation and relative humidity limited the ET, thus restricted available storage in the substrate.

Several studies have investigated the relationship between available moisture and evapotranspiration rate. Johannessen et al. (2017) found the retention capacity to be greatly affected by the evapotranspiration as well as the precipitation amount. These findings were supported by findings done by (Sims et al., 2016). The antecedent moist condition plays a direct impact on the retention capacity (Sims et al., 2016, Voyde et al., 2010), as the green roof will be able to retain less water if the substrate is saturated prior to a precipitation event. The moist condition in the substrate has been found to differ through the substrate depth. Vertal et al. (2018) found the lower part of the substrate to contain nine times the amount of water compared to the upper part of the substrate, even after a long dry period. Berretta et al. (2014) found the moisture content in the lower part of the configuration to be 10-20% higher compared with the upper part. Several studies (Davarzani et al., 2014, Poe et al., 2015, Tabares-Velasco and Srebric, 2011) have reported a reduction in the evapotranspiration rate with time as the available moisture in the substrate is reduced. This effect is well established in the hydrological sciences (Chow et al., 1988).

Pitched roofs with a ventilated air cavity is a broadly used construction method for buildings in northern and central Europe (Blom, 2001, Gullbrekken et al., 2018, Nusser and Teibinger, 2013). The air cavity is ventilated in order to remove moisture and thereby ensure dry conditions. The construction method also aims to prevent ice formation on the eaves (SINTEF Byggforsk, 2007). According to SINTEF Byggforsk (2007) a Norwegian technical specification series, good ventilation is most needed in areas experiencing large amount of snow and little wind or for buildings with low-pitched roofs.

There has been found a clear correlation between the air velocity in the ventilated air cavity and the external wind speed (Gullbrekken et al., 2017). It has also been found that the risk of condensation is lower during periods with high wind speeds and vice versa and that the risk of condensation is still present, even in air cavities with good ventilation (Bunkholt et al., 2020). The temperature in the ventilated air cavity has been found to be higher for lower cavity heights (Lee et al., 2009) and the air velocity in the ventilated air cavity has been found to increase with larger differences in the outdoor and cavity temperature (Nusser and Teibinger, 2013). Blom (2001) investigated ventilation of a roof construction in Norway. The roof was found to be better ventilated when the wind was allowed to blow through the whole roof. An increase in the air gap cavity area increased the moisture content in the roof, as the moisture in the outdoor air affects the climate in air cavities with good ventilation to a large extent. Gullbrekken et al. (2018) found that an increase in cavity height lead to increased ventilation. This is in contrast to the findings done by Nusser and Teibinger (2013), whose findings implies that an increase in the height of the air-gap cavity can reduce the air flow velocity. This does however depend on the design of the cavity inlet and outlet, the slope of the roof as well as the temperature difference between the outdoor temperature and the temperature in the cavity. Gullbrekken et al. (2018) also found the design of the eaves to affect the air velocity in the ventilated air cavity.

Based on the above findings this paper aims to investigate if introducing air-gap cavities for ventilating green roofs will increase evapotranspiration. The main objective of this research was to examine if a new building technique for green roofs would enhance the evapotranspiration in Nordic climate. The new green roof configurations were built with air-gap cavity that allowed the air to flow between the configuration and the roofing. The effect of different windspeeds on evapotranspiration was also investigated. It was expected that the green roof configuration tray with the ventilated air cavity would have an increased evapotranspiration rate compared to the tray without a ventilated air cavity. It was also expected that the evapotranspiration would increase with increased windspeed. There is a knowledge gap on how to enhance green roof performance in cold climate by changing the building techniques.

This paper aims to answer the following questions:

1. Evaluate the potential to use WUFI as a tool to simulate moisture movement in ventilated green roofs
2. Will a ventilated air cavity between the green roof and the roofing increase the evapotranspiration, and hence the capacity of the green roof?
3. Does evapotranspiration increase with increased wind speed?
4. Will a ventilated green roof increase the risk of drought?

2. Method

The method includes both a laboratory test model and hygrothermal simulations. A green roof laboratory setup was planned and built, but due to lockdown caused by the Covid-19 pandemic the laboratory tests were not possible to perform. A model of the green roof buildup was therefore created in the numerical simulation software WUFI. The simulations were performed in order to examine the effect of an air-gap cavity on the green roofs' hydrological capacity in Nordic climate.

2.1. Studied area

A green roof test field is situated at Høvringen and data from this test field was used to validate the simulation model. Høvringen is located in Trondheim, Norway. Trondheim experience relatively cold winters and cool summer and is classified as continental subarctic climate (Dfc), according to the Köppen-Geiger climate classification (Peel et al., 2007). Measurements from the last ten years from Voll weather stations shows that the average precipitation the city experience in August-September is 182 mm and the average temperature is 12,6 °C. The average wind during August-September is 2,2 m/s. Voll is situated

8 kilometer from Høvringen and is positioned at an elevation of 127 m.a.s.l, while Høvringen is at an elevation of 44 m.a.s.l. (Norwegian Meterological Institute, 2020).

2.2. Laboratory set-up

The method was developed to expose the green roof trays to different wind conditions. An experimental set-up was established to continuously monitor the moisture change in the trays over time, due to evapotranspiration from two green roof configurations.

The green roof configuration was built in a 1x0,8 m tray with a ventilated air cavity between the green roof and the roof membrane, allowing air to circulate. The analysis is based on comparison between green roofs with and without ventilated air cavity. An identical tray setup was therefore made without the ventilated air cavity and exposed to the same climatic conditions.

The roofs had a total thickness of 140 mm and was made up of four layers: a vegetation layer, a substrate layer, a filter membrane and a drainage layer. The vegetation layer consisted of a pre-cultivated sedum mat made up of a native selection of species. The sedum mat was delivered with a growing media and the total thickness was 30 mm with the vegetation and the substrate layer (Bergknapp). A 10 mm filter membrane was placed between the substrate and the drainage layer to prevent loss of fine particles from the substrate as well as to retain moisture and nutrients. The drainage layer consisted of a 100 mm layer of expanded clay aggregates with a particle size range between 0-6 mm. A wire mesh was placed along the bottom of the configuration in order to allow air to penetrate the substrate from beneath. In order to prevent loss from fine particles from the drainage layer, a protective geotextile was places between the wire mesh and the drainage layer.

SINTEF Byggforsk (2009) recommends a minimum of 73 mm air cavity for sloped turf roofs. Despite that the green roof modules were not sloped nor turf roofs, this was chosen as this regulation is the most comparable of the existing regulations.

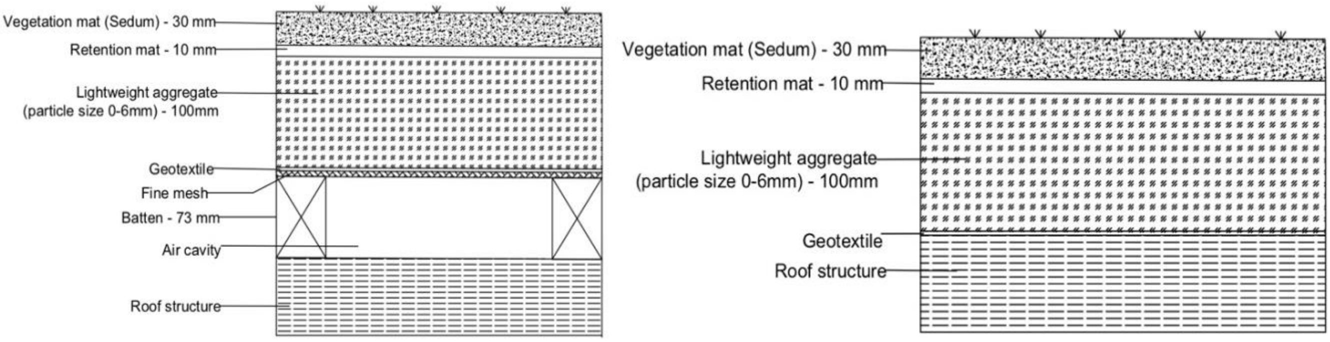


Figure 1 Cross sections of the module setups for ventilated green roof (to the left) and of the module setup for non-ventilated green roof (to the right).

The roof configuration with a ventilated cavity was therefore placed on a 73 mm batten allowing wind to circulate between the green roof configurations and the roof membrane. The reference roof was placed directly on the waterproof roofing membrane, without a wire mesh along the bottom. Both the ventilated and non-ventilated roof can be seen in Figure 1.

Figure 2. Load cell logging the weight loss of the trays due to moisture loss.

Both trays were installed with a 2-degree inclination and placed on to high-resolution load cells with one load cell in each corner of the trays, as seen in Figure 2. This allows for continuously track the moisture change through the change in weight, assuming the weight loss of the trays is exclusively due to evapotranspiration. The load cells had a manufacture reported linearity uncertainty of $\pm$ 0.1% (PT Ltd). Prior to testing the uncertainty was planned to be tested using pre-determined weights. Additionally, the placement sensitivity was supposed to be investigated also by using pre-determined weights.

To generate wind, two channel fans were planned to be used. The windspeed was supposed to be measured using an anemometer. The accuracy of the speed control of the fans would be found by measuring the windspeed three times for each setting, before calculating the variance.

The tests were planned to be performed in a climate room in the laboratory where the temperature was controlled. The air humidity cannot be controlled but would be logged. Before starting the test, the trays would be thoroughly soaked with water until fully saturated and the test would be started as soon as runoff no longer occurred from the trays. The load cells would be connected to a logging device that would continuously log the weight loss of the trays due to evapotranspiration.

2.2.1 Data collection method

Wind data from 2017-2019 measured at Høvringen in Trondheim, Norway was used as basis for the wind exposed to the green roof trays and the maximum, median and minimum windspeed was found. The maximum wind flow was 2,63 m/s, the minimum wind flow was 0,68 m/s and the median wind flow was 1,19 m/s. As the climate room allowed for temperature control, the green roof modules were also planned to be tested for different temperatures.

The tests were supposed to be replicated over 5 and 10-days periods. No test was planned to be performed over a longer time period than 10 days as Trondheim on average experience 2-3 precipitation events weekly (Norwegian Meterological Institute, 2019).

5 days would therefore be more representative, but one longer test period was planned to be performed in order to test if more ET would occur with a longer dry weather period.

The evapotranspiration should be measured by the weight difference between the onset and end of an event. The test would start immediately after runoff ceased, so that it could be assumed that no evapotranspiration occurred before the test started and that the weight loss from the trays during the monitored period therefore represents the amount of evapotranspirated water.

Evapotranspiration would be calculated using equation 2:

$$ET = \frac{Weight_2 - Weight_1}{Time_2 - Time_1} \tag{2}$$

where $Weight_{\ 2}$ and $Weight_{\ 1}$ are given in kg and $Time_{\ 2}$ and $Time_{\ 1}$ are given in hours. $\Delta time$ is the time length of the test. In a review concerning ET, Cascone et al. (2019) concluded that for any time-step, kg/m^2/day is the best unit to use when estimating ET. The evapotranspiration rate is therefore expressed in kg/m^2/day. In order to investigate the effect of the air cavity on the evapotranspiration, the calculated ET for the reference green roof and the new experimental set-up would be compared.

2.3 WUFI calculation model

WUFI (Wärme Und Feuchte Instationär) was used to perform the simulations. WUFI is a numerical software developed by Fraunhofer IBF and is used to calculate heat and moisture transport in building components exposed to local climatic conditions (Künzel, 1995). WUFI was chosen as the program has been validated for both green roofs as well as for roofing constructions (Mundt-Petersen and Harderup, 2015, Vertal et al., 2018, Zirkelbach et al., 2017). The calculations in WUFI is based on the European standard (2007) and satisfy all the requirements of standard EN 15026 (WUFI, 2020a).

2.3.1. Hygrothermal simulations/numerical simulations

The hygrothermal simulation model WUFI Pro 6.0 was used to simulate the coupled heat and moisture transfer for the whole green roof structure. The intention of the simulation was to analyse how a ventilated air cavity between the green roof configuration and the roofing membrane affected the moisture content in the expanded clay aggregate layer.

The calculations performed by WUFI is based on the non-steady heat transport (eq. 3) and moisture transport (eq. 4) process that are formulated as followed (Künzel, 1995, Zirkelbach et al., 2017):

$$\frac{dH}{d\vartheta}\frac{\partial\vartheta}{\partial t} = \nabla.((\lambda\nabla\vartheta) + h_v\nabla.\Big(\delta_p\nabla(\varphi P_{sat}\ )\Big) + S_h\ [\mathrm{J/m^3s}] \qquad (3)$$

$$\frac{dw}{d\varphi}\frac{\partial\varphi}{\partial t} = \nabla.\Big(D_\varphi\nabla\varphi + \delta_p\nabla.(\varphi p_{sat})\Big) + S_w\ [\mathrm{kg/m^2s}] \qquad (4)$$

Where:

$\frac{dH}{d\vartheta}$	[J/m^{3}K]	Heat storage capacity of the moist building material
$\frac{\partial\vartheta}{\partial t}$	[K/s]	The temporal temperature change
λ	[W/(mK)]	Thermal conductivity of the humid building material
ϑ	[°C]	Temperature
h_v	[J/kg]	Evaporation enthalpy of the water
δ_p	[kg/msPa]	Water vapor permeability of the building material
φ	[—]	Relative humidity
P_{sat}	[Pa]	Water vapor saturation pressure in the air
$\frac{dw}{d\varphi}$	[kg/m^3]	Moisture storage capacity of the building material
$\frac{\partial\varphi}{\partial t}$	[1/s]	Temporal relative humidity change
D_φ	[kgm/s]	Liquid conduction coefficient of the building material
S_h	[W/m^3]	Heat source strength
S_w	[kg/m^{3}s]	Moisture source strength

The left side of the equations describes the storage capacity of the heat and moisture in the building material. The heat storage consists of the heat capacity of the humid building material and the temporal change in temperature. The Moisture storage include the moisture storage capacity and the temporal change of the relative humidity. The right side of the equations describe the heat and moisture transport in the materials. The heat transport consists of the thermal conductivity of the moist material and the transport of heat due to phase change. The moisture transport makes up the transport of the vapor and liquid in the material (Künzel, 1995, Zirkelbach et al., 2017).

The heat and moisture source strength equations can be expressed like this (Thue et al., 2008):

$$S_h = \rho_{out} * \frac{ACH}{3600} * d_{cavity} * C_{p,air} * (T_{out} - T_{cavity}) \tag{5}$$

$$S_w = \frac{ACH}{3600} * d_{cavity} * (C_{out} - C_{cavity}) \tag{6}$$

Where:

S_h	[W/m^2]	The strength of the heat source
S_w	[kg/m^{2}S]	The strength of the moisture source
ρ_{out}	[kg/m^3]	The density of the external air
ACH	[1/h]	Air change rate of the ventilated air cavity
d_{cavity}	[m]	The height of the ventilated air cavity
$C_{p,\ air}$	[J/kgK]	The specific heat capacity in dry air at a constant pressure
T_{out}	[K]	External air temperature
T_{cavity}	[K]	Temperature in the ventilated air cavity
C_{out}	[kg/m^3]	The water vapor concentration of the external air
C_{cavity}	[kg/m^3]	The water vapor concentration of the air in the ventilated air cavity

The additional air change moisture source strength takes the difference in the water vapour in the ventilated layer and the outdoor air into consideration. The additional air change heat source strength takes the temperature difference between the outdoor air and the ventilated layer into consideration.

2.3.2 Hygrothermal green roof model

A green roof similar to the experimental test roof at Høvringen was designed as a reference roof in WUFI. The green roof consists of a 3 mm sedum layer, 10 mm retention mat and a 100 mm drainage layer. The roofing construction was taken from the WUFI example case database and fulfills the recommendations given by SINTEF Byggforsk (2018). It is constructed as a compact roof and consists of a 1 mm PVC roofing membrane, 300 mm mineral wool, 0,2 mm PE-membrane and a 200 mm concrete base. The green roof model was built as a flat roof with a 2° inclination. The material properties used for the drainage layer as well as the sedum layer are listed in Table 1.

The material data required by WUFI as input data are not commonly used parameters for stormwater solutions. This led to a lack of known input parameters for the drainage layer and sedum mat. Only the porosity and bulk density was known for the specific sedum mat and drainage layer used at the test roof at Høvringen. Little research has been executed for the material properties of crushed lightweight expanded clay aggregate with a particle size range between 0-6 mm as it is a new material. Some research has however been performed for other lightweight expanded clay aggregate materials (Wood, J.R., R&D Manager Leca, e-mail communication, 20. May 2020). Estimates from the limited available test results was therefore used for the reminding material parameters required in WUFI. The reminding required material properties for the sedum was retrieved from other types of sedum layers available in the WUFI material database. The modelled drainage and sedum layer have therefore not necessarily the exact same material properties as the green roof material layers at the test roof at Høvringen.

The model do not take the water transport due to gravity into account (Künzel, 1995). Some of the precipitated water will therefore end up as runoff during intense rainfall events before the expanded clay aggregate get time to absorb the water. A moisture source that transfer 40% of the rainwater directly into the expanded clay layer was therefore added to the lowest 20 mm of the layer to ensure that no runoff occur before the drainage layer is fully saturated (Zirkelbach et al., 2011, Zirkelbach et al., 2017). In the case of Zirkelbach et al. (2017) and (Zirkelbach et al., 2011) the moisture source was added directly into the soil and the growth medium, as the green roof build-up differs. Validations performed by Zirkelbach et al. (2017) showed a good fit between the model and the measured results. Even though there is an uncertainty connected to the choice of percentage precipitation directly added to the lower layer of the expanded clay aggregate, a 40% precipitation was chosen for the model investigated in this paper as it was found to be the best fit for the green roof system investigated by Zirkelbach et al. (2017). Zirkelbach et al. (2017) found no significant difference with small changes of percentage.

Table 1 Material properties for the sedum and drainage layer used in the WUFI simulation.

Material	Material property	Value	Reference
Crushed expanded clay aggregate (0-6)			
	Bulk density (kg/m^3)	430	(Hamouz, 2020)
	Porosity (%)	53,7	(Hamouz, 2020)
	Thermal conductivity (W/mK)	0,11	(Wood, J.R., R&D Manager Leca, e-mail communication, 20. May 2020)
	Specific heat capacity (J/kgK)	1000	(Wood, J.R., R&D Manager Leca, e-mail communication, 20. May 2020)
	Water vapor diffusion resistance factor (-)	2	(Wood, J.R., R&D Manager Leca, e-mail communication, 20. May 2020)
	Reference water content (kg/m^3)	30,1	(Wood, J.R., R&D Manager Leca, e-mail communication, 20. May 2020)
	Water absorption coefficient (kg/m$^2\sqrt{s}$)	0,22	(Busklein et al., 2014)
Sedum			
	Bulk density (kg/m^3)	833	(Bergknapp)
	Porosity (%)	30	(Tovslid, B., Markedssjef Bergknapp, e-mail communication, 11. May 2020)
	Thermal conductivity (W/mK)	0,2	Material properties data base built into the WUFI software
	Specific heat capacity (J/kgK)	1500	Material properties data base built into the WUFI software
	Water vapor diffusion resistance factor (-)	5	Material properties data base built into the WUFI software
	Reference water content (kg/m^3)	12	Material properties data base built into the WUFI software
	Water absorption coefficient (kg/m$^2\sqrt{s}$)	1	Material properties data base built into the WUFI software

A new green roof model was designed with the same build-up, but with an additional ventilated air cavity between the drainage layer and the roofing membrane. The effect of the changes in the moisture condition in the drainage layer, more specifically in the lower part of the layer was examined and compared to the reference roof.

A ventilated air layer without additional moisture capacity was added in order to model the ventilated air cavity. WUFI was initially not made to simulate air cavities and the possibility to add a ventilated layer to simulate an air cavity was added after the implementation of the simulation program (Straube and Finch, 2009). The free saturation for air layer without additional moisture capacity is 17 g/m^3, which corresponds well with air saturation at 20 °C. The saturation value is however fixed and will not change with temperature, as would be the case for real air (WUFI help built into the WUFI software). In order to simulate the air flow, an air change source was added to the layer.

Wind data measurements from the three-year period of 2017-2019 at Høvringen was used. The monthly maximum, median and minimum wind was used to generate average monthly maximum, median and minimum values. The models were also simulated for a wind speed of 0,33 m/s. This was done in order to investigate the effect of a particularly low windspeed. The wind speed was converted to air velocity by the use of the connection found by Gullbrekken et al. (2017). The air velocity needs to be simulated as air change rate per hours in WUFI. The air change rate per hour was therefore calculated based on the air velocity. The wind speed, air velocities and air change used for the simulations are listed in Table 2.

Table 2 Wind speed, air velocities and air change rate used in the simulations.

	Minimum	Median	Maximum	Particularly low
Wind speed (m/s)	0,68	1,19	2,63	0,33
Air velocity inside air cavity (m/s)	0,1	0,2	0,5	0,06
Air change rate (h^{-1})	42	73	162	20

To investigate the influence of the cavity height on evapotranspiration of the green roof, the roofs was also modelled for different batten heights. The investigated cavity heights are based on recommendations given by the Norwegian technical specification series. SINTEF Byggforsk (2009) recommends a minimum of 73 mm batten height for turf roofs and SINTEF Byggforsk (2007) recommends a minimum cavity height of 48 mm for insulated sloped wooden roofs. As the recommendations are minimum recommendations, a 100 mm cavity was also investigated for. Air layers with the thickness closest to the recommendation were therefore retrieved from the WUFI material database as listed in Table 3.

Table 3 Investigated cavity heights.

Cavity heights	50 mm	70 mm	100 mm

2.3.3 Climate data

Outdoor climate data required as input in the model is the air temperature, relative humidity of the outdoor air, windspeed, wind direction, short-wave radiation, long-wave radiation and the precipitation (WUFI, 2020b). The climatic data used in the simulation was mainly measurements measured at the field site at Høvringen, except from data for long-wave radiation. The long-wave radiation climate data was retrieved from the Norwegian Meterological Institute (2020) climate database from a nearby measurement station, as Høvringen did not measure long-wave radiation. The short wave radiation adsorption was set to 0,6 and the long wave radiation emission was set to 0,9, as these values were found to represent the real conditions for green roofs well according to Zirkelbach et al. (2017). WUFI requires climate data from 1. January until 31. December. The simulations were carried out from September 2018 until August 2019 as the moisture content in the test roof at Høvringen was logged for this period. The climate data for 1. January-31. August 2019 was therefore simulated before the period of 1. September-31. December 2018. The one-year simulation was repeated ten times in order for the moisture content in the material layers to stabilize and the result from the tenth time was used. Extreme tests with artificial precipitation were executed on the test roof from May to August 2019. An extreme test was also performed 30. August 2019, so this event was excluded for in the investigation as the precipitation do not correspond with the other climate data. The rest of August 2018 and September 2019 were investigated more thorough as this period was expected to experience evapotranspiration. An hourly timestep was used for the calculations for the whole calculation period.

2.3.4 Model validation

In order to validate the WUFI model, the moisture results from the tenth simulation of the lightweight aggregated layer in the reference model was compared with the measured moisture content at Høvringen. During the extreme tests the drainage layer at the test field got supersaturated. WUFI was not able to capture this effect, as the program is only able to simulate material that has reached its maximum water capacity. The measured moisture content results were therefore manipulated, so that the pores could not be filled with more than 100% water. The porosity of the lightweight expanded clay aggregate 0-6 is 53,7%, meaning that the drainage layer has 53,7% pore space available for water when it is dry. The period investigated was from August 2019 and September 2018. An extreme test was also performed 30. August 2019. It was therefore not expected that the measured and simulated moisture content in the transition between the months would correlate very well.

As little to none research has been performed on the effect of air-gap cavity in green roofs there was no experimental field study results or laboratory results to calibrate and validate final model with. The ventilated model is therefore not validated. As the reference modelled roof showed the same tendencies as the observed field roof, it is assumed that the ventilated roof also shows the correct tendencies.

3. Results and discussion

Temperature, solar radiation, air humidity as well as precipitation for the investigated period is presented in Figure 3. An extreme test was performed 30. August, causing the amount of precipitation during this period to be artificially high. The temperature, solar radiation and relative humidity does therefore not correspond the precipitation at that time.

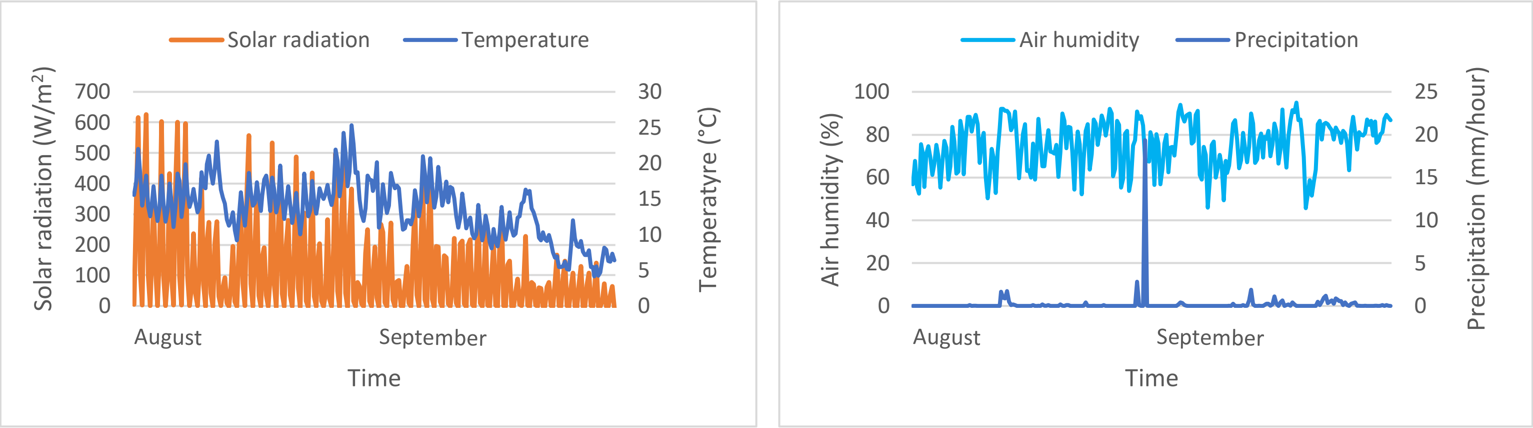


Figure 3 Solar radiation, temperature, air humidity and precipitation measured at Høvringen for the investigated period.

3.1. Model validation

The modelled moisture content for the reference roof was compared with the measured moisture content at Høvringen in order to validate the model. The water content in the test roof at Høvringen was measured in the middle of the roof, at the bottom of the drainage layer. The simulated water content values were therefore retrieved from the bottom of the drainage layer. During an extreme test performed 30. August, 2019, it was observed that the drainage layer at Høvringen was getting supersaturated. Due to the boundary conditions in WUFI, the program is not able to simulate this effect. The measured values were therefore manipulated so that they had the same boundary conditions as the modelled results.

The measured and simulated moisture content results for the simulated period can be seen in Figure 4. The water content is given as the percentage of total volume in the drainage layer. The measured moisture values are from August 2019 and September 2018, as the climate data used for the time period is from 1. September 2018 until 31. August 2019. The moisture content in the transition between the months are therefore not expected to correlate. The measured moisture values and the simulated moisture values do in general not correlation very well over the investigated period. One of the main problems is that the measured and the modelled results do not have the same base. There is however a clear trend between the measured and simulated moisture content, particularly during the month of August. There are several possible explanations for the deviation between measured and simulated moisture content.

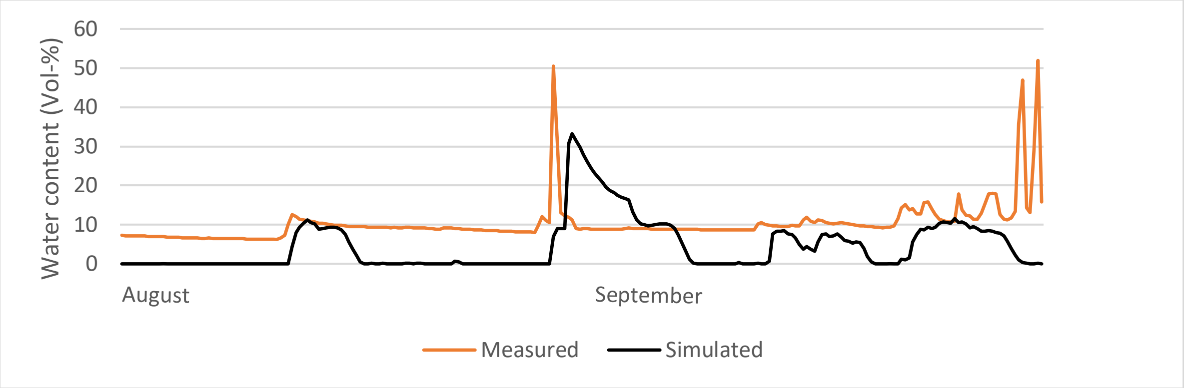


Figure 4 Comparison of the observed and simulated moisture content in the lower part of the expanded clay aggregate.

The discrepancy between the observed and simulated base may be due to incorrect input material data or boundary conditions in the model. According to WUFI (2018) all necessary material parameters must be available and the initial conditions as well as the boundary conditions must be known in order to validate the model. These requirements were not met in this research, which can clearly affect the results. A material testing for the needed parameters could had been performed, but this is both costly and time consuming. The lack of available input material parameter shows that it can be challenging to combine two different disciplines. In this research WUFI, which is initially a simulation program used for building physics, required different input parameters than what is normally tested for materials used in stormwater management.

There may also be some qualitative uncertainties in the measured moisture values. The model used to convert the moisture data measured at the field site to water content has been found to be inaccurate for cold temperatures. There may also not be complete contact between the moisture sensors and the expanded clay aggregate, which can affect the moisture results (Pons, Vincent, PhD candidate, e-mail communication, 15. April 2020). Another source of error is the lack of user experience.

The intension of this study was however not to make a perfect fit between simulated and measured moisture results, but to investigate the potential of the concept of a ventilated air gap cavity in green roof construction.

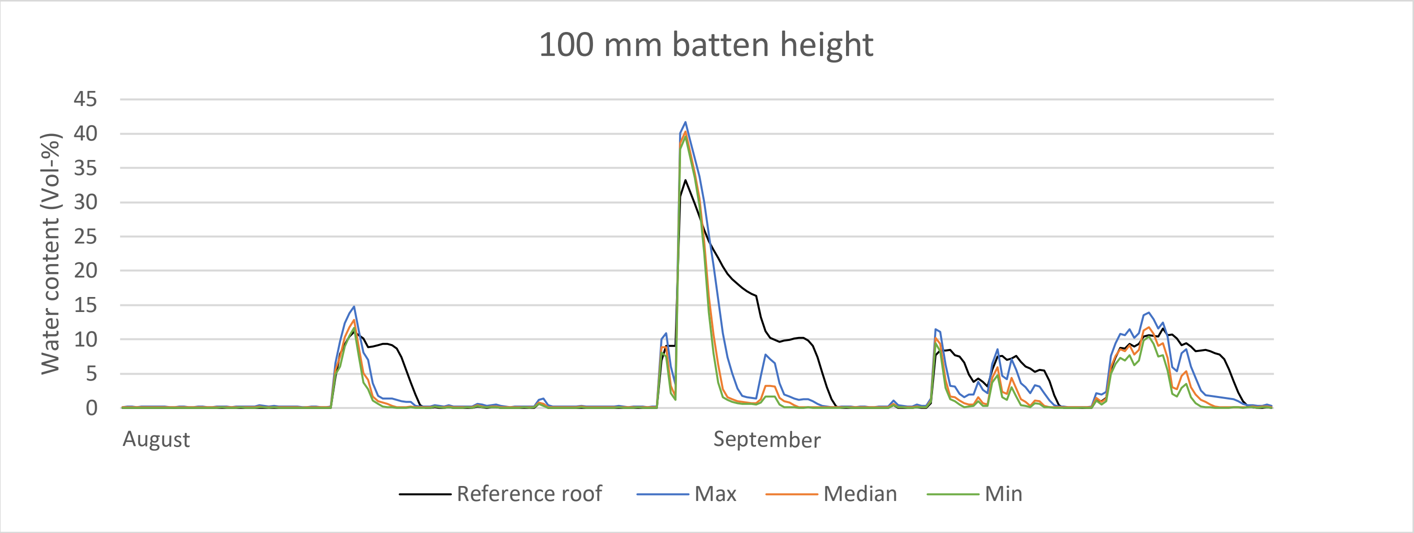
3.2. Moisture content with ventilated air cavity

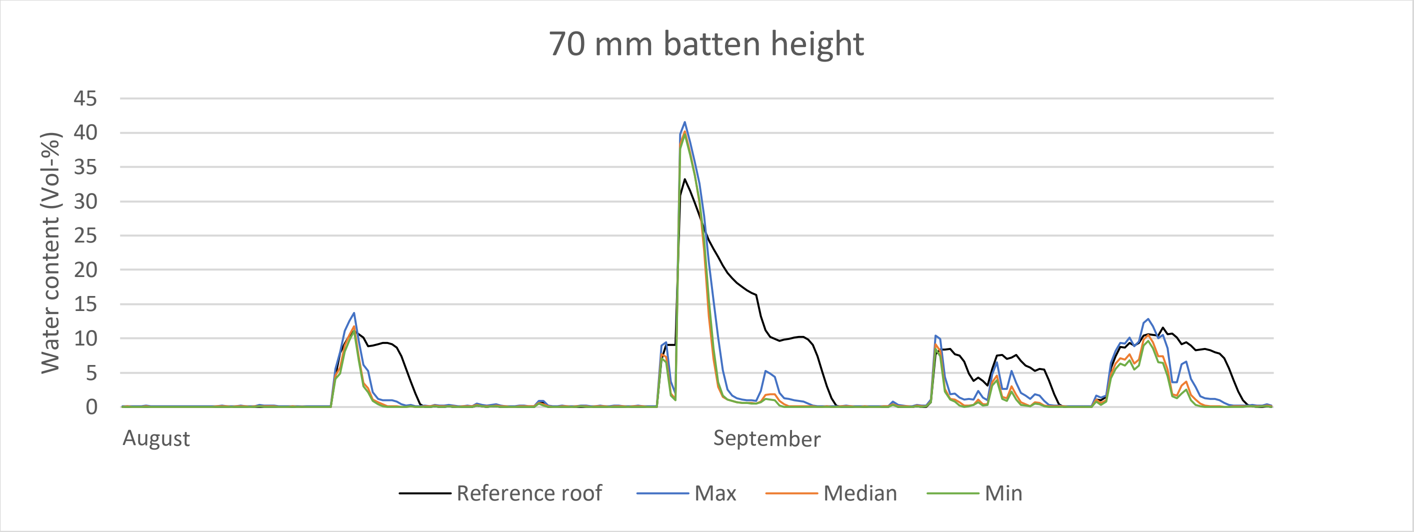
3.2.1. Ventilated air cavity

The models were simulated for the average maximum, median and minimum wind speed over the last three years at Høvringen. The moisture content results from the different ventilated air cavity models exposed to the various wind speed is plotted in Figure 5. The simulations are performed for the same green roof build-up where the only difference between the simulations are the air cavity height and wind speed. It is therefore assumed that the change in moisture content in the drainage layer is solely due to change in evapotranspiration.

The results show tendencies of higher ventilated air cavity leading to higher maximum moisture after a precipitation event. The maximum moisture content was higher for all ventilated roof simulations compared with the reference roof. It can also look like a higher wind speed induce a higher maximum moisture content. This result was somewhat unexpected, as it was anticipated that the drainage layer would reach its maximum water content for all simulations and that the difference between the simulations would mainly be the regeneration rate. The percentage difference in moisture between the baseline for the varied wind speeds for the models was therefore calculated for four moisture peaks. The results were then compared with the difference in maximum moisture content. The results can be found in Appendix B. Even though the simulations were found to hold different start moistures before an upcoming precipitation event, the difference was not large enough to solely explain the variation in maximum moisture content. It is however clear that the drainage layer does no reach maximum available moisture content during the simulations, as that would be 53,7 vol-%. The maximum moisture content was nor reached during the extreme test 30. August as seen in Figure 4.

It may also look like the change in windspeed affects the moisture content to a bigger extent for a roof with a 100 mm air cavity than for a roof with a 50 mm air cavity height. As described above, it is assumed that change in moisture content is purely due to evapotranspiration. If the ventilated models experience a decrease in moisture content compared to the reference model, it is therefore assumed that this moisture decrease is due to an increase in evapotranspiration. In Figure 5 it can be seen that a lower windspeed lead to a lower moisture content for all cavity heights compared to the reference model. It may also look like there is an increase in ET with decreased air cavity height. This may imply that ventilated roofs increase ET for all cavity heights, but to a greater extent for lower cavity heights and that a lower wind speed lead to higher evapotranspiration. The results may also indicate that the windspeed is less important with lower batten heights.





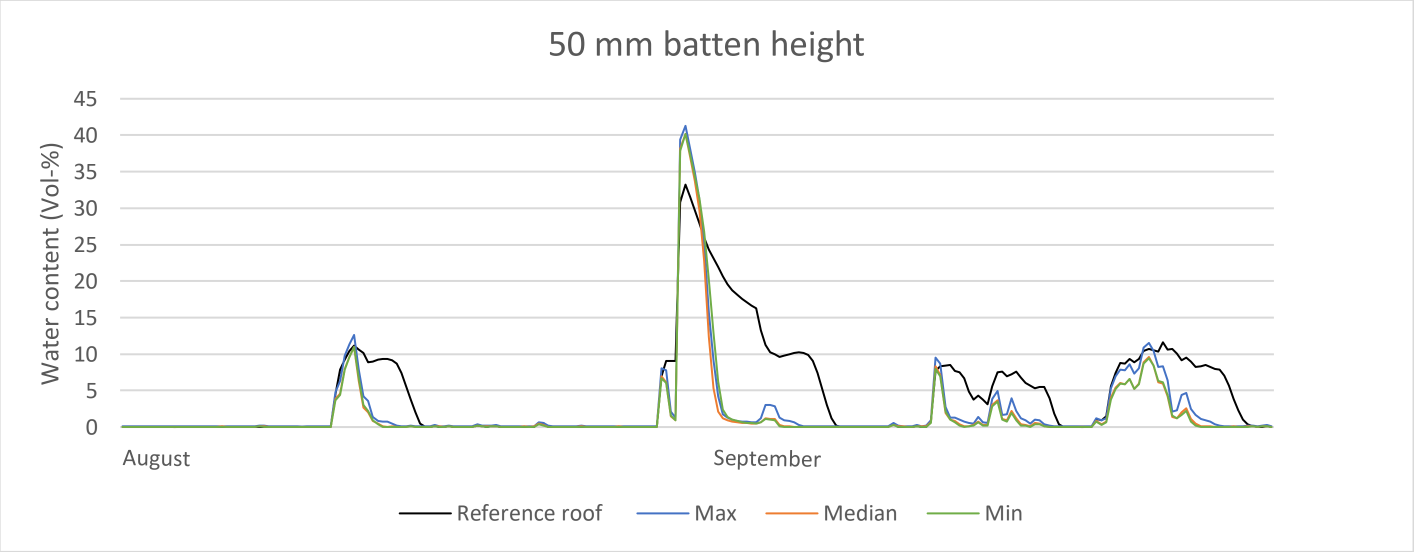
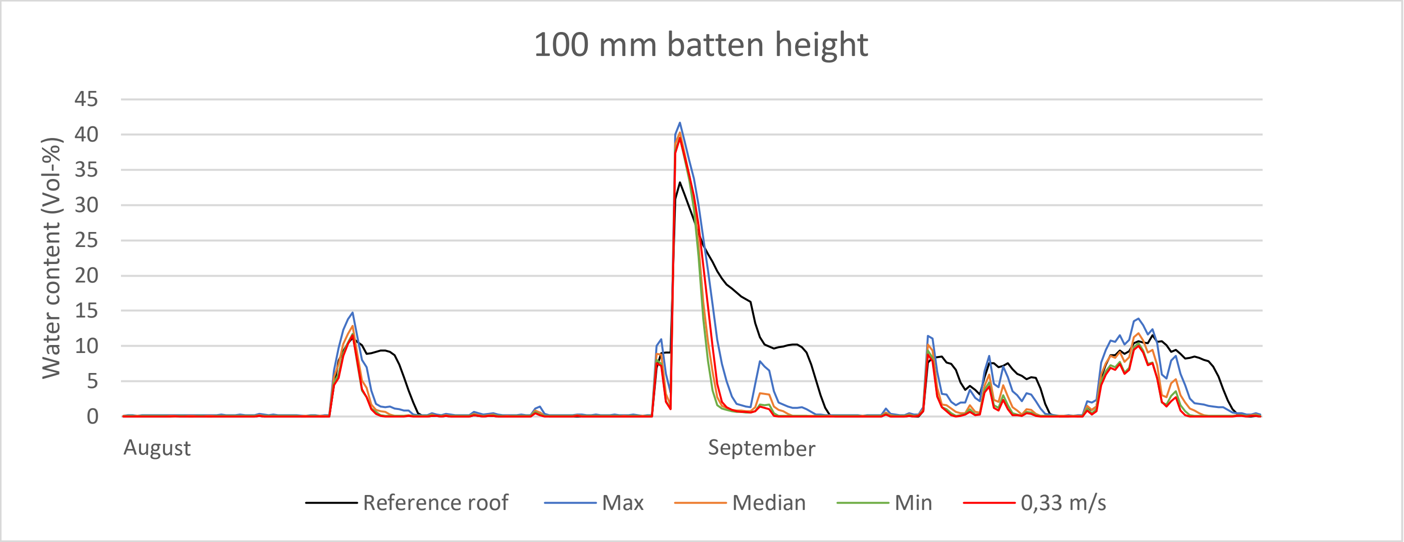


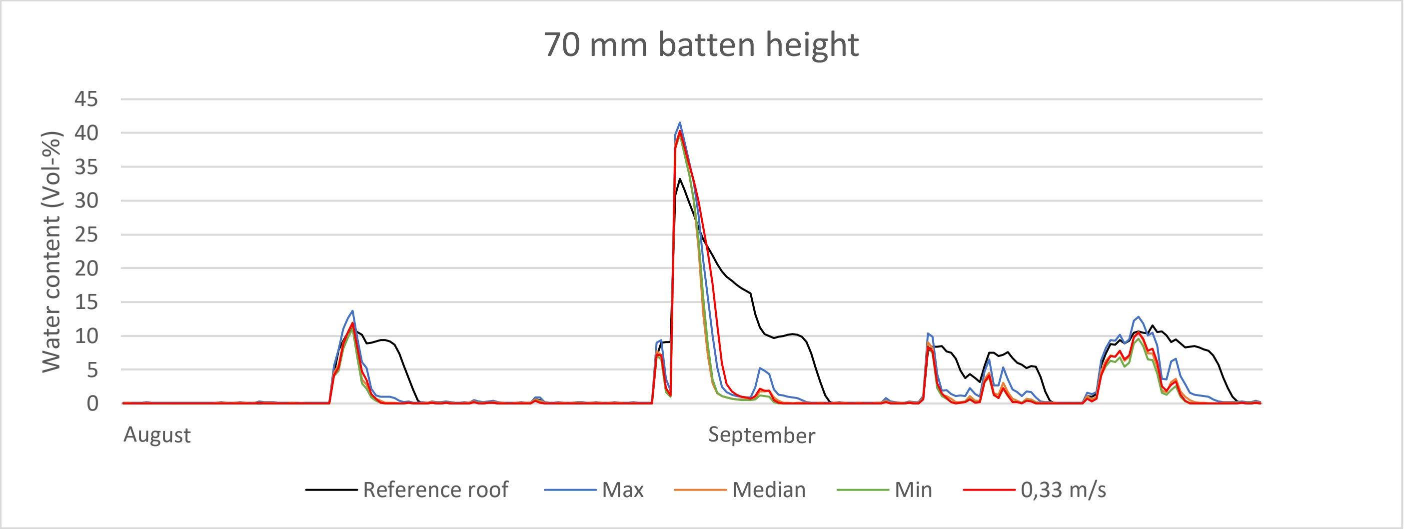
Figure 5 Comparison of the moisture content in the bottom part of the drainage layer for the measured roof and the simulated roofs for different cavity heights exposed to minimum, median and maximum wind speed.

In order to investigate how a very low windspeed impact the moisture content for the different cavity heights a simulation with wind speed of 0,33 m/s was performed. The results were plotted together with the minimum, maximum and median wind speeds in Figure 6. For the 50 mm air cavity height, it can look like a wind speed of 0,33 m/s induce a higher moisture content in the drainage layer than both the minimum and median air velocity do. It looks like the water content in the drainage layer lead to about the same moisture content as the maximum wind speed does. For the 100 mm cavity height, a 0,33 m/s wind speed seems to actually give the greatest ET of all the wind speeds exposed to the model.

The moisture results may indicate that reduced air velocity through the ventilated cavity will to a certain extent increase the evapotranspiration, but when the air velocity becomes low enough it may not be high enough to remove the moisture. A research done by Lee et al. (2009) found the air velocity to be higher for a high cavity height. In addition, the temperature was found to be lower for a high cavity height. The low temperature was partly explained by the low air velocity through the cavity. A possible explanation for the findings in this paper may therefore be that a high temperature gets retained in the cavity with lower air velocity, leading to a higher evapotranspiration.

A weakness by adding a ventilated air cavity in WUFI is that WUFI treats the air flow as a constant. This is not the case in reality, as the air flow is affected by the friction in the air cavity (Lee et al., 2009), the inlet and outlet cavity design, the slope of the roof, the cavity height and the outdoor and cavity temperature (Nusser and Teibinger, 2013). Some air will also most likely go *up* in the expanded clay aggregate and contribute to additional dry-out potential. As the air flow in the cavity is modelled as air change per hour, the WUFI models are not able to capture this effect. The increase in evapotranspiration by adding a ventilated air cavity is therefore likely to be underestimated.





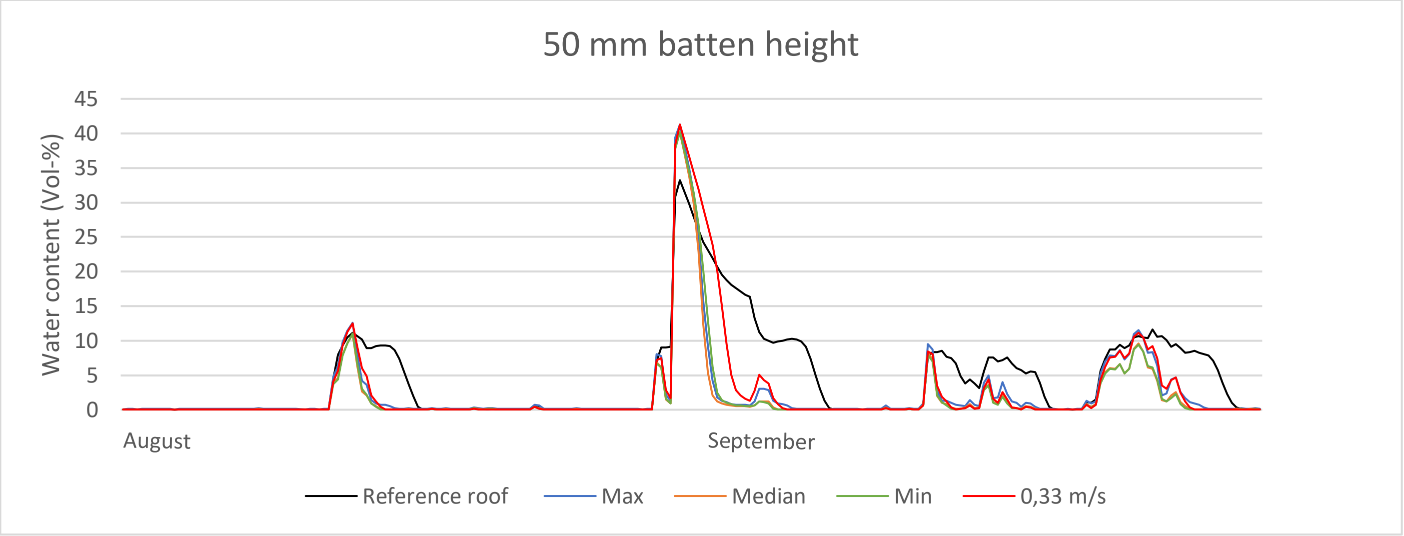


Figure 6 Comparison of the moisture content in the bottom part of the drainage layer for the measured roof and the simulated roofs for different cavity heights exposed to minimum, median, maximum and 0,33 m/s wind speed.

3.2.2. Change in ET potential

From Figure 5 it could look like a lower windspeed would lead to an increase in evapotranspiration and that ET would increase for lower cavity heights. The effect of the ventilated cavity on green roofs was therefore investigated further by examine the moisture content for models exposed to median wind more thoroughly. The median wind was chosen to be investigated further as the green roof is most likely to be exposed to a wind in this range. Figure 7 shows the moisture content in the lower part of the drainage layer for both the reference model and ventilated models. In order to investigate how the ventilated air cavity affect the retention capacity, the water content captured by the roof for the four moisture peaks for the different cavity heights were calculated by area under the curve. The four moisture peaks are marked in Figure 7. The moisture peak at the end of August is a result of the extreme test, hence it was not investigated further. As discussed in chapter 3.2.1. it can in general look like a lower air cavity height lead to a higher evapotranspiration thus reducing the regeneration time of the drainage layer between the precipitation events.

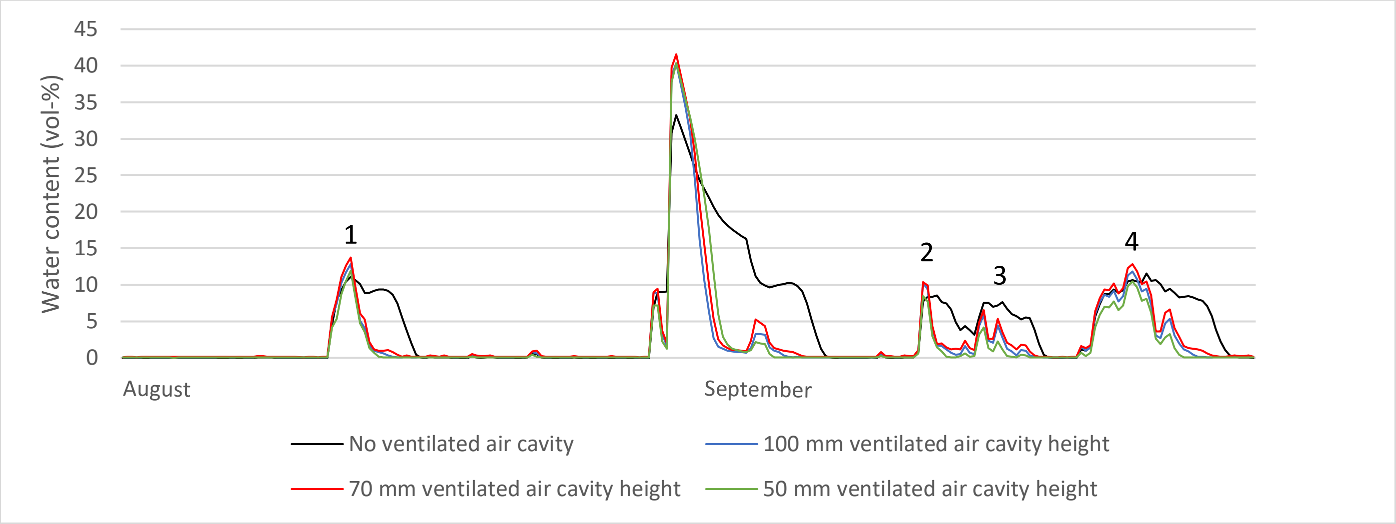


Figure 7 Comparison of the green roof model without ventilated air cavity and the green roof models with ventilated air cavity of different heights. The median windspeed has been used for the ventilated roofs.

In order to investigate the retention regeneration rate, the slopes of the investigated moisture peaks were calculated and are listed in Table 4. The slopes indicated how fast the drainage layer manage to release the retained water, i.e. the retention regeneration rate. It can be seen that a decrease in air cavity height lead to an increased slope, except from for the third moisture peak. This may indicate that the roofs with a ventilated air cavity in general can regenerate the available moisture capacity faster than the unventilated roof. The ventilated roof will thus be faster ready for the next precipitation event. The deviation in moisture peak three may be due to the fact that it actually consists of several moisture peaks. The slope was calculated for the first peak in this event and the slope may therefore not reflect the event correctly.

Table 4 Total water content for the different cavity heights and the associated slope for the four different models for four moisture peaks in August and September.

		Roof without ventilated air cavity	Roof with 100 mm air cavity height	Roof with 70 mm air cavity height	Roof with 50 mm air cavity height
Total water content (vol-%)		550	275	215	179
Slope (%)	Peak 1	-0,70	-1,28	-1,46	-1,56
	Peak 2	-0,52	-1,22	-1,27	-1,37
	Peak 3	-0,56	-1,94	-1,61	-1,36
	Peak 4	-0,50	-0,73	-0,75	-0,79

The total water content listed in Table 4 indicates that the moisture content decrease with decreased cavity height. In order to investigate how much a ventilated air cavity can potential increase ET, the percentage difference between moisture captured by the non-ventilated green roof and ventilated green roof was found and presented in Table 5. The results show that the evapotranspiration can possibly be increased with 50-67% by adding an air cavity to the roof. It can also be seen that a lower air cavity height induces a higher evapotranspiration.

Table 5 Percentage increase in evapotranspiration with ventilated air cavity compared to green roof without ventilated air cavity.

	Roof with 100 mm air cavity height	Roof with 70 mm air cavity height	Roof with 50 mm air cavity height
Percentage increase in moisture loss (%)	50	61	67

The 50 mm cavity height experienced the largest increase in evapotranspiration compared to the other cavity heights. Findings done by Lee et al. (2009) showed that a lower cavity height gave a lower air velocity and higher temperature in the ventilated air cavity. It was also found that a higher cavity height induced a higher air velocity and lower temperature in the ventilated cavity. The lower air velocity was explained by a lower friction for a larger area and the low temperature was explained by the high air velocity. A possible explanation why the 50 mm cavity height experiences the highest potential increase in ET can therefore be due to higher temperatures in the ventilated air cavity for lower cavity heights compared to higher cavity heights. A previous study have detected a connection between low windspeeds and higher risk of condensation (Bunkholt et al., 2020). Findings done by (Blom, 2001) showed that a higher ventilated air cavity gave a higher moisture content. This was explained by a higher influence of the outdoor air, which may be cold and humid, for higher ventilated air cavity heights.

It should therefore be strived to have a cavity size that gives an as low ventilation rate as possible in order to keep the temperature high and at the same time a high enough air flow velocity to remove the moisture. In the simulation, the air velocity was an input parameter and thereby fixed. In reality, the air flow velocity will however be dependent on how much friction that occurs in the ventilated air cavity (Lee et al., 2009), the slope of the roof, the design of the cavity inlet and outlet, the cavity height and the outdoor and cavity temperature difference (Nusser and Teibinger, 2013).

3.3. Moisture content during dry periods in the future

If longer dry periods occur, there may be a risk of water deficit exposing the sedum to drought conditions. As ventilated air cavities increase the regeneration rate of the drainage layer it may also lead to longer and more frequent dry periods. Norway is a country that experience large geographical differences in climate, with a wet coastline and a dry inland. This is causing the drought exposure to vary significantly throughout the country (Johannessen et al., 2017).

A implementation of a tax on stormwater has been proposed in Norway, which should be partly based on the expected runoff from the property (NOU 2015:16, 2015). It can therefore be useful to investigate the expected reduction in runoff volume from a specific property a ventilated green roof may induce. Kristvik et al. (2019) investigated the risk of green roof drought in the future for three cities in Norway experiencing different climates. It was found that there most likely will be more drought events in the future as the ET rate increases. It was also found that Trondheim is expected to experience up to five drought incidences in 30 years, from zero at present time. Oslo was the area found to expect the highest number of drought incidences, with up to 19 events, from four today. Bergen can expect up to six green roof drought events in 30 years in the future. Table 5 shows the expected increase in evapotranspiration by adding ventilated air cavities of the different heights to the green roof. An increase in ET may imply an increase in drought incidences for areas that are already exposed to drought. The results from the simulation showed that it can be expected an increase in evapotranspiration from 50-67% by adding a ventilated air cavity to the green roof. By designing green roofs with ventilated air cavities in Oslo and areas experiencing similar climate, there could be a risk for up to 28-32 drought incidences in the future. Implementation of ventilated air cavities in the green roofs in Trondheim can possibly increase the drought incidences in 30 years to 7-8, depending on the cavity. Bergen may be at risk to experience up to 9-10 drought incidences in 30 years. The temperature and precipitation is also expected to increase for all cities in the future (Kristvik et al., 2019). The highest increase in precipitation is expected to occur in Bergen, with an increase of up to 2 mm daily rainfall. Oslo is expected to experience the lowest precipitation increase, closely followed by Trondheim with respectively 0,3 mm and 0,6 mm daily increase. The temperature increase is not expected to differ that much between the cities.

As Oslo was found to be more exposed to increased drought incidences (Kristvik et al., 2019) it is reasonable to believe that a ventilated green roof will increase the risk of drought additionally in this area. Even though Bergen is expected to have some increase in number of drought incidences in the future, the city is also expected to have a great increase in precipitation amount. The temperature is expected to increase as well, but the effect of the increase precipitation may be higher than the effect increased temperature will have on ET. As property owners most likely will have to pay for stormwater in the future, it may still be beneficial to implement the solution even if it increases the risk of drought a bit. The benefit of increased stormwater retention and detention capacity may still be greater than the risk of a few extra drought incidences in certain areas. For areas experiencing in general a wet and cold climate but are subjected to a relatively low number of drought incidences during a certain time of year, a solution may be to collect stormwater runoff from the roof that can be used for irrigation through dry periods. It may therefore be a beneficial solution in particularly wet and cold areas.

4. Conclusion and future work

4.1. Conclusion

The aim of this study was to investigate the effect ventilated green roofs would have on evapotranspiration in cold climates. Three different cavity heights exposed to four different wind speeds were investigated. The investigated windspeeds was the minimum, median and maximum windspeed measured at Høvringen, Trondheim as well as a very low windspeed of 0,33 m/s. Further was the effect of the median windspeed investigated more thoroughly for the three cavity heights and the potential increase in ET by adding a ventilating layer to the roof was calculated.

The observed and simulated moisture content in the drainage layer did not give a perfect correlation, but the simulated moisture content followed the same tendencies as the observed moisture content. WUFI required other input material parameters than stormwater materials are normally tested for. Most of the material parameters therefore had to be estimated. WUFI is also initially not developed to simulate ventilated air cavities. This demonstrate some of the challenges by combining two different disciplines. It is not possible to give a definite conclusion based on the results from this research, but the results show tendencies and may indicate the effects ventilated green roofs can have on evapotranspiration. The results can also be used to determine how the laboratory tests should be performed and what to investigate closer.

The results from this study shows that the evapotranspiration may increase by decreased cavity height. It also seems like lower windspeed increase ET to a certain extent. The results showed that a 50 mm cavity height potentially can increase ET more than a 70 mm and 100 mm cavity height. The retention regeneration rate was also found to be highest for a

50 mm cavity height for most of the cases. This may indicate that a green roof with a 50 mm ventilated cavity height will be able to hold more water from the next precipitation event compared to the other models investigated.

The increase risk of drought was investigated, and it may look like a ventilated green roof will increase the risk of drought and hence wilting of the vegetation quite drastically in areas that are already prone to drought events. The construction method may nevertheless be beneficial in wet and cold areas that are expected to experience a limited amount of drought incidences, where precipitation and flooding is a greater threat. This may for example be the case in the area of Bergen. In these areas, a solution may be to collect stormwater from the roof, which will later be used for irrigation during dry periods.

4.2. Future work

Further investigation on ventilated green roof is needed to present more accurate results. Laboratory tests should be performed and investigated further. The risk of drought should also be investigated closer by performing laboratory tests. The winter period was not taken into account and investigated in this paper. It would however be interesting to investigate if the ventilated air cavity can prevent ice formation at wintertime, thus contribute to stormwater management during the winter period as well.

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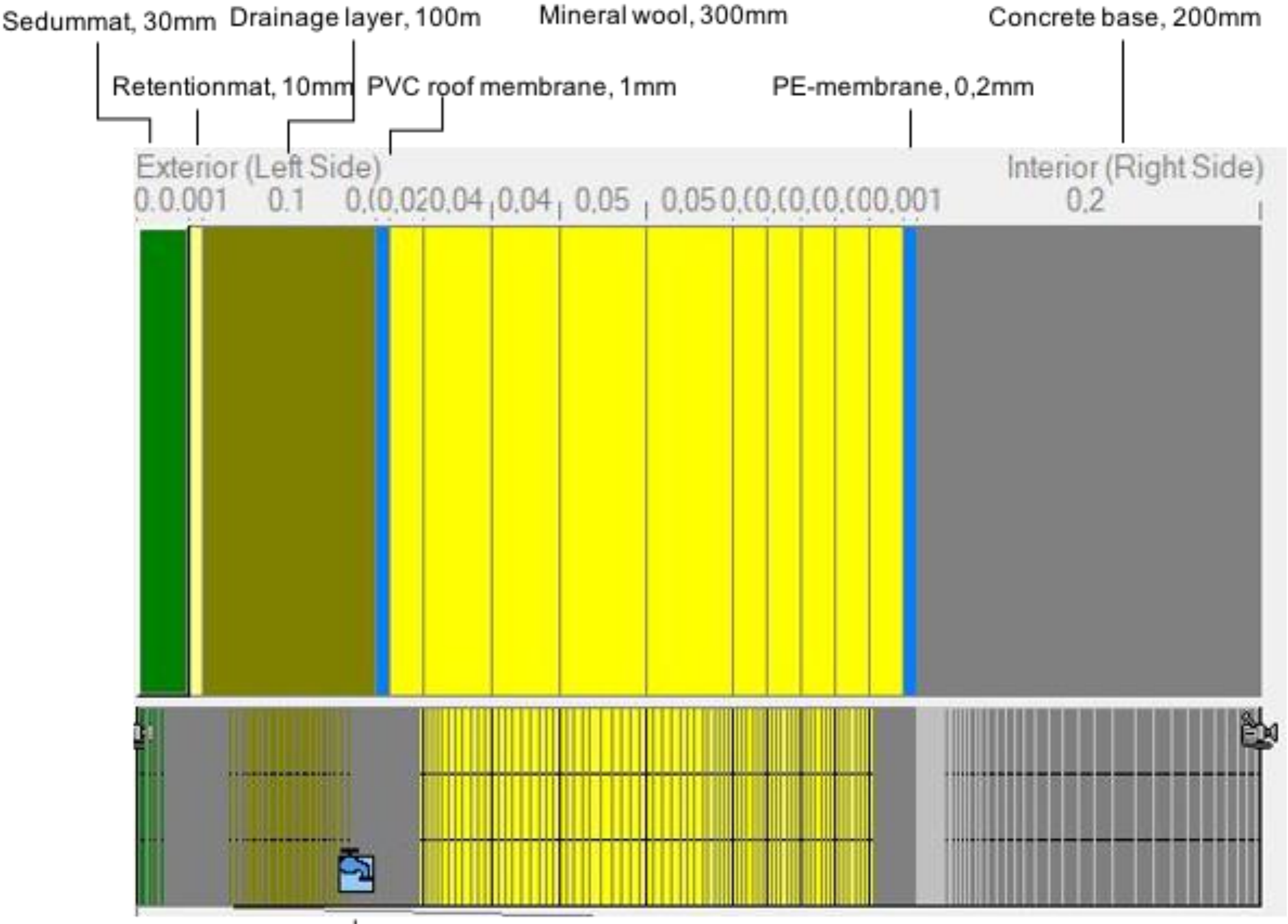
Appendix A – Construction simulated in WUFI



Moisture source used to add 40% of the precipitation directly into the drainage layer to avoid runoff before the drainagelayer is fully saturated

Figure 8 The construction without a ventilated air cavity simulated in WUFI.

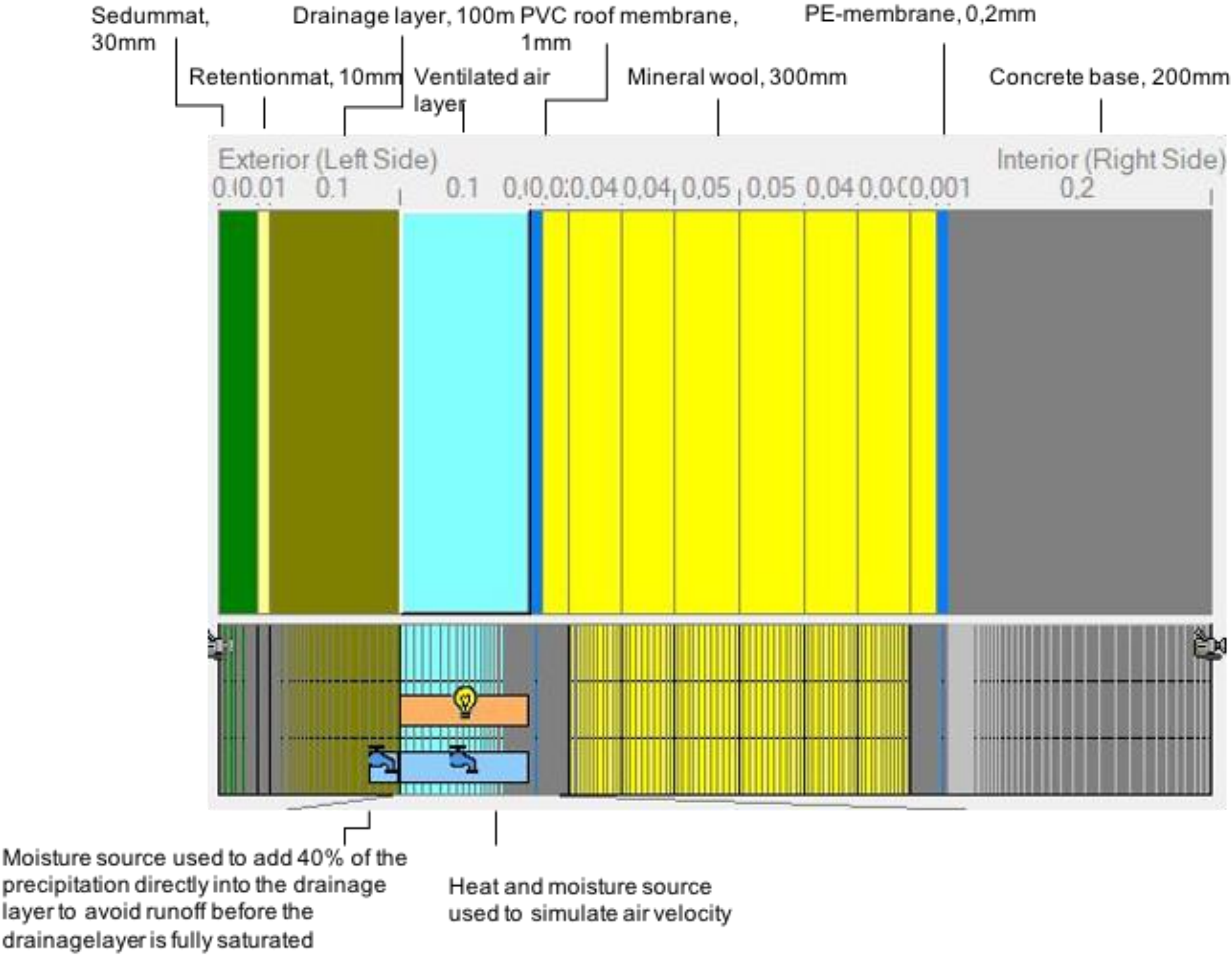


Figure 9 The construction with a ventilated air cavity simulated in WUFI. The thickness of the ventilated layer was changed to simulate the different air cavity heights.

Appendix B – Percentage difference in baseline and max water content

Table 4 Comparison of the percentage difference in baseline- and max water content for the different air change rates for the three air cavity heights investigated.

	Topp 1	Topp 2	Topp 3	Topp 4
100 mm				
162h compared with 73h				
Baseline	-34%	-52%	-88%	-36%
Max	-13%	-11%	77%	-15%
73h compared with 42h				
Baseline	-55%	-43%	-40%	-57%
Max	-9%	-8%	-49%	-12%
70 mm				
162h compared with 73h				
Baseline	-41%	-59%	-80%	-41%
Max	-14%	-12%	-14%	-18%
73h compared with 42h				
Baseline	-54%	-45%	28%	-56%
Max	-6%	-7%	-51%	-9%
50 mm				
162h compared with 73h				
Baseline	-46%	-17%	-83%	-43%
Max	-13%	-12%	-26%	-17%
73h compared with 42h				
Baseline	-51%	-54%	92%	-56%
Max	1%	-4%	-48%	-1%