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Modeling the Hydrologic Performance of Green and Blue-grey Detention Based Roof Systems

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Abstract

In this thesis, a 2D version of Hydrus-2D/3D was used to model runoff from a green and blue-grey test roof at Høvringen. The van Genuchten-Mualem model was used to analytically describe the hydraulic properties of the substrates. The required input parameters were not available prior to this thesis, but found from literature. The parameters were then calibrated against both water content measurements and runoff measurements during the first two weeks of July, before they were validated against runoff measurements. The validation period showed that the most accurate results were obtained with the calibration against runoff measurements. NSE coefficients for the blue-grey roof was generally above 0.75. This indicates that the performance of the model is acceptable. The same coefficients were generally around 0.6 for the green roof, which is also acceptable. However, the green roof was more sensitive for dry periods, where the NSE was negative for a period in August.

Runoff from the blue-grey roof was also modeled with an NSE slightly above 0.2 for both January and February. The calibrated and optimized parameters from the summer calibration were used. The green roof was modeled with an NSE of -6.0 or less in January and February. The inaccuracies during winter time are likely due to limitations in Hydrus to only model unfrozen soils and a simplified snow accumulation module. The blue-grey roof was modeled significantly more accurate than the green roof during winter time. The main reason for this is that the blue-grey substrate is thicker and covered with pavers.

Overall, Hydrus was able to produce acceptable accuracy for both the leca material in the blue-grey roof and the green roof substrate during unfrozen conditions. Difficulties in modeling storage capacity and extremely dry or wet periods were found to be the disadvantages of the model. Laboratory results of the leca material were received late in the thesis, and could have provided better results for the blue-grey roof.

Sammendrag

I denne oppgaven ble en 2D-versjon av Hydrus-2D/3D brukt for å simulere avrenningen fra et grønt og blå-grått testtak på Høvringen. van Genuchten-Mualem-modellen ble brukt for å beskrive de hydrauliske egenskapene til substratene analytisk. Nødvendige input-parametere var ikke tilgjengelig i forkant av studien, men ble hentet fra annen litteratur. Parametrene ble så kalibrert mot både målinger av vanninnholdet i substratene og avrenning fra takene i løpet av en to ukers periode i juli. Valideringsperioden viste at kalibrering mot målinger av avrenning ga best resultat for begge takene. NSE-koeffisientene for det blå-grå taket var generelt over 0,75. Dette indikerer at modellen evne til å forutsi avrenning er aseptabel. For det grønne taket lå NSE-koeffisientene rundt 0.6. Simuleringene for det grønne taket var mer sensitive for tørre perioder. Modellen hadde blant annet en negativ NSE-koeffisient for det grønne taket i August.

Modellen ble også testet mot en vinterperiode i januar og februar. De kalibrerte verdiene fra sommerperioden ble brukt. For det blå-grå taket lå NSE på rundt 0.2 for begge månedene, mens den var -6,0 eller mindre for det grønne. De unøyaktige simuleringene skyldes i hovedsak Hydrus sin manglende evne til å modellere vann i frossen jord og en forenklet snømodell. Den simulerte avrenningen fra det blå-grå taket var likevel betydlig nærmere den observerte for det blå-grå, sammenlignet med det grønne. Temperaturmålingene tyder på at substratet i det blå-grå taket fryser skjeldnere, grunnet steindekke og et tykkere substrat. Hydrus var likevel i stand til å modellere avrenningen fra begge takene i et mildt klima.

Hydrus var generelt i stand til å forutsi avrenningen fra det blå-grå og grønne taket for en sommerperiode. Modellens evne til å modellere lagringskapasitet, og unøyaktigheter under veldig tørre eller våte perioder ble funnet til å være svakhetene med modellen. Laboratorieresultat fra lecamaterialet ble mottatt sent i prosessen, og kunne bidratt til mer nøyaktig resultat i modelleringen av det blå-grå taket.

Preface

The following report is a Master thesis, conducted at the Department of Civil and Environmental Engineering at NTNU. The work started during the Autumn of 2017, and completed in January of 2018. This Master thesis corresponds to a workload of 30 ECTS.

Acknowledgment

I would first of all thank my supervisor, Tone Merete Muthanna, for support, advice and instructions during the writing of this report.

A special thanks goes to my co-supervisor, Vladimir Hamouz, for helping me with literature suggestions, theory, and for taking me to the roofs at Høvringen.

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1 Introduction

1.1 Background

The overall goal of Klima 2050 is to reduce the risk associated with climate changes and increased precipitation. One of the pilots is a large scale roof system pilot, where the aim is to test the retention and detention performance of a green and blue-grey roof. This will be done by both modeling and observations.

1.2 Objectives

The aim of this master thesis was to answer the following research questions:

1. Evaluate the suitability of Hydrus to model detention performance of green roofs with different substrates?

2. Evaluate the suitability of Hydrus to model retention performance of green roofs with different substrates?

3. How well does Hydrus represent the seasonal variation in retention and detention performance?

The task included a literature review of the models that are currently available, followed by simulations of both the blue-grey and green roof at Høvringen. A 2D-version of Hydrus-2D/3D was used in this thesis.

1.3 Limitations

Hydrus-2D/3D requires knowledge of unsaturated water flow through the soil, which had to be gained through this thesis. The literature review was also time consuming, as this thesis was not a continuation of a project. There was also a limited amount of time and resources to prepare laboratory measurements that would have improved the input parameters that were used in the simulations. Learning Hydrus-2D/3D also presented a great challenge as it was quite difficult to learn a program by reading the manual.

2 Literature review on green roof modeling

Through this literature review, an assessment of the different modeling approaches has been conducted in order to gain a better understanding of green roof modeling. Both the methods and results from the different models have been in focus. Li, Y. et al. (2014) gave an overview of the most common models that had been applied up to date. The physical processes in the green roofs and how the detention and retention performance is quantified in literature is also reviewed in order to get a more general understanding of green roofs. Scientific papers and the Hydrus manual has been used to collect information about green and blue-grey roof modeling. The aim was to find models that have produced satisfactory predictions of the green or grey roofs performance.

2.1 What is a green roof?

A green roof is considered a BMP (best management practice). In terms of water quantity, the purpose of a green roof is to retain and detain runoff from precipitation. They are often also referred to as living roofs. A green roof consists of a plant cover, substrate layer, and a drainage layer on the bottom. Figure 2 illustrates how some of the precipitation will be intercepted, and then evaporate. The remaining water will then infiltrate through the substrate layer, where a portion of the water will leave through evapotranspiration. The water that does not leave through evapotranspiration will become surface runoff. (Li, Y. et al. (2014), She, N.et al. (2010), Stovin et al. (2012))

Modern green roofs often include a storage layer beneath the substrate. This increases the retention capacity and provides water for the plants. (Li, Y. et al. (2016).

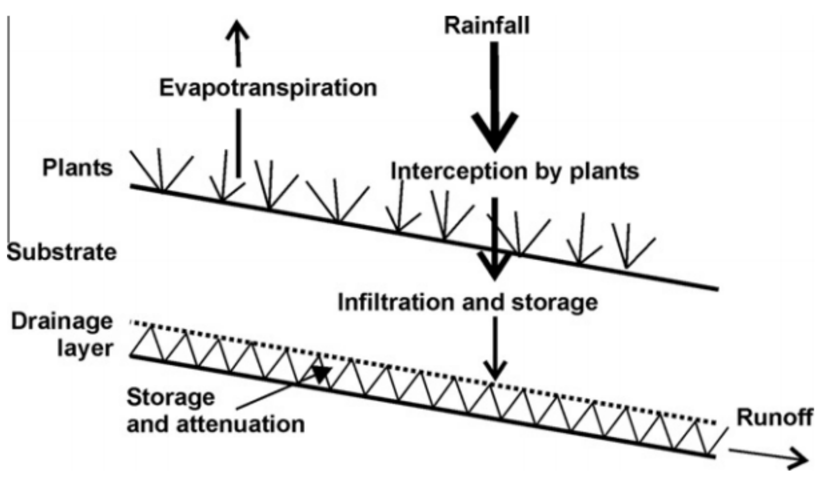

Figure 1: Hydrological processes (Stovin, V., et al. 2012)

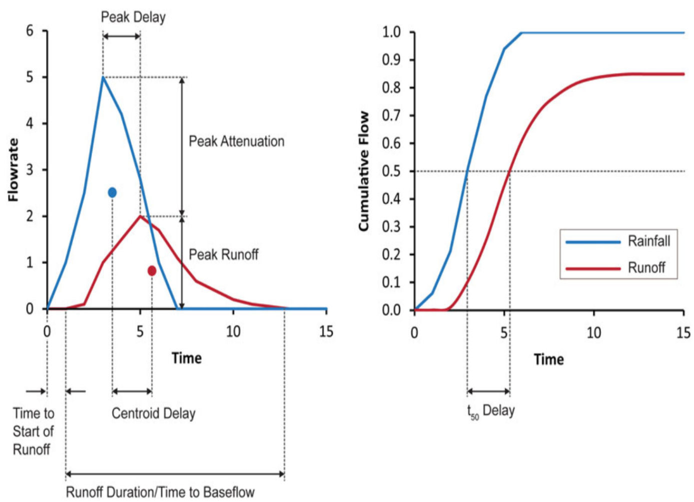

Figure 2: Graphical illustration of detention metrics (Stovin, V., et al. (2017))

The purpose of a green roof is to retain and detain water. Li, Y. et al (2016) investigated the most important factors influencing the total volume reduction, peak reduction and peak delay for single precipitation event. A physically based model (Hydrus-2D) was used in this study. Results from the model suggested that effective and transient capacity were the two most important factors influencing the total volume reduction of a single precipitation event. Drainage opening size and growth media depth were found to be the most influencing factors for peak delay and peak reduction. Infiltration speed of the media was also found to be an important effect on the peak delay and peak reduction.

2.2 Metrics to determine the performance of green roofs

The metrics for analyzing the retention performance of a green roof are quite simple, and often include parameters that describe the retention performance on annual or per event basis. The detention performance on the other hand, does not have a common metric for quantifying the performance of a green roof. Typical detention parameters that are often used by researchers include peak attenuation, time to start runoff, peak delay, centroid delay and t50 delay. Though these are common parameters, the definition and understanding of some of these parameters is open to interpretation. Peak attenuation will for instance be much greater for a rain event with a short duration rather than a long duration. According to Stovin, V. et al. (2017), peak attenuation should be quantified by time though this is very uncommon.

Figure 2 illustrates the definition of different detention metrics according to Stovin, V., (2017). Peak attenuation is the reduction in peak flow rate, often given in percentage. Peak delay is the lag time for the peak runoff. Through this literature review, peak attenuation, volume reduction and peak delay were the most commonly used metrics for analyzing the hydrological performance of a green roof. The various studies that have been reviewed in this thesis have mainly used peak attenuation, peak delay and volumetric reduction as metrics to assess the performance of a green roof. The governing equations for these metrics are given by Li, Y. et al. (2016) as:

$$R_v = \frac{D-d}{D} * 100\% \tag{1}$$

R_v is the volume reduction, D is the precipitation depth, and d is the runoff depth.

$$R_p = \frac{P-p}{P} * 100\% \tag{2}$$

R_p is the peak reduction, P is the precipitation peak, and p is the runoff peak

$$R_t = \frac{t-T}{L-T} * 100\% \tag{3}$$

R_t is the peak delay, T is the precipitation peak time, t the runoff peak time, and L is the precipitation duration.

2.3 Evaluation of model accuracy

In order to evaluate the accuracy of the model simulations, simulated data is normally compared with observed data. This is done for both calibration and validation of data. Moriasi et al., (2007) recommended three quantitative statistics to evaluate the models for hydrologic data. The Nash-Sutcliffe efficiency (NSE) evaluates how the observed versus simulated data fits. It is less sensitive to high extreme values because of the squared differences.

$$NSE = \left[1 - \frac{\sum(Y_i^{obs} - Y_i^{sim})^2}{\sum(Y_i^{obs} - Y^{mean})^2}\right] \tag{4}$$

The values of NSE ranges up to 1 and has no negative limit. In general a simulation is considered satisfactory with a NSE above 0.5. (Moriasi et al., (2007))

Percent bias (PBIAS) is a method that evaluates if the simulation data tends to either overpredict or underpredict values, compared to observed data.

$$PBIAS = \left[\frac{\sum(Y_i^{obs} - Y_i^{sim}) * 100}{\sum(Y_i^{obs})}\right] \tag{5}$$

The optimal value of PBIAS is 0.0, while values within +/- 25% is considered satisfactory for streamflow.

Standard deviation ratio (RSR) is the ratio between the root mean square error (RSME) and standard deviation data. Values below 0.7 is considered acceptable while 0.0 is optimal.

$$RSR = \frac{RSME}{STDEV_{obs}} = \frac{\left[\sqrt{\sum (Y_i^{obs} - Y_i^{sim})^2}\right]}{\left[\sqrt{\sum (Y_i^{obs} - Y^{mean})^2}\right]} \tag{6}$$

Pearson‘s correlation coefficient of determination is not among the recommended methods due to its sensitivity for high extreme values. Some studies mentioned in the literature study have though applied Pearson‘s coefficient to evaluate the simulated data (Stovin, V., et al. (2012)). R^2ranges from 0 to 1, where values above 0.5 are considered acceptable.

In addition to the above mentioned methods, graphical techniques are considered essential for appropriate evaluation. Moriasi et al., (2007) mentions hydrograph and percent exceedance probability as the two most important coefficients. In a hydrograph, the values of measured and simulated flow is presented as a graph.

2.4 An overview of the existing models and methods for runoff predictions

2.4.1 Probabilistic models

Probabilistic models aim to predict the responses from a green roof based on observation data from previous storm events.

Several researchers have tried to predict the performance of a green roof for a given storm event. Usually these studies have been statistical analysis of field observations or predictive tools based physical models (Li et al. (2014)). Stovin, V., et al. (2012) used regression analysis to investigate the possibility of predicting the hydrological performance of a green roof. Equations for; TR (runoff depth), TS (retention depth) and VR (retention percentage) were established based on the parameters; TP (rain depth), ADWP (antecedent dry weather period), i (mean storm intensity), Rp (peak 5-min storm intensity). Low R^2-values in figure 2 show poor correlation between both retention depth and percentage retention with ADWP. Multiple regression analysis was also performed in this study. The results from this analysis show slightly improved, but yet low, correlation between storm parameters and hydrological performance. Based on these results Stovin, V., et al. (2012) conclude this method lacks a predictive capability for a green roof, due to complex inter-event processes in the substrate.

2.4.2 Conceptual models

Conceptual models often include a cascade of reservoirs. Carbone, M., et al. (2014) for instance divided the green roof system into superficial layer, sub-

Equation	R^2	t-statistics
$TR^{1/3} = -2.410 + 1.514 \ln TP$	0.7239	-3.60^{**}, 7.06^{**}
$VR^{0.43} = 11.05 - 2.173 \ln TP$	0.3290	4.97^{**}, -3.05^{**}
$TS^{0.55} = 3.130 + 0.882 \ln ADWP$	0.2481	9.88^{**}, 2.50^{*}
$VR^{0.43} = 4.832 + 1.136 \ln ADWP$	0.1746	9.48^{**}, 2.01^{NS}
$VR^{0.43} = 3.916 + \ln i$	0.0253	4.68^{**}, 0.70^{NS}
$VR^{0.43} = -1.858 + 3.421 R_p{}^{1/5}$	0.0881	-0.40^{NS}, 1.35^{NS}

NS – not significant.

* Significant at $p = 0.05$.

** Significant at $p = 0.01$.

Figure 3: Retention as a function of TP, ADWP, i and Rp (Stovin, V., et al. (2012))

strate layer and a storage layer. The physical processes of each layer then need to be determined. The physical process of the top layer typically include evapotranspiration, infiltration and possibly runoff generation. Storage and water movement in the soil will occur in the substrate layer. Carbone, M., et al. (2014) used Green-Ampt to describe this process. However, there are several other models that also describe water movement in a soil. The storage layer can be modeled using mass balance equations. The model was calibrated and validated against measured values from a small-scale model roof. R^2 values close to 1 indicate that the model was accurate. Other conceptual models also use the same principle of dividing the green roof into a cascade of reservoirs.

A recent study (Stovin, V. et al. 2017) used a hydrological retention and detention model to describe the hydrological performance of a green roof. The retention model is validated and described in Stovin, V., et al. (2013), and the hourly runoff was modeled with a NSE of 0.770 and a runoff depth simulation with an NSE of 0.956. In this model, soil water balance is estimated based on water loss due to evapotranspiration and inflow due to rainfall. The detention model in Stovin, V., et al. (2017) used reservoir routing concepts for modeling the green roof performance. From findings in literature and results, the paper concludes that this approach can be effective in both long-term statistical evaluation and design storm based evaluation of detention performance.

2.4.3 SWMM

Storm Water Management Model (SWMM) is a software that simulates the runoff and pollutant movement after a continuous or single rain event. The purpose of the model is to simulate the runoff and drainage in an urban catchment given a rain event. It is commonly used because of its simplicity and minimal requirements of programming skills. The typical inputs to the model are precipitation and the retention characteristics of the BMP. Detailed physical properties are not directly required to run SWMM as the hydrological performance of a green roof determined prior to the simulation of a rainfall event. (Li, Y. et al. (2014))

The infiltration process in SWMM can be described by several methods. Among them are the Horton, Green Ampt and CN methods. The CN (curve number) represent the relationship between precipitation and runoff depth, and will range from 0 to 100. The storage capacity is described by this number. There is no other required input in terms of soil properties, except for initial water content. The hydrological processes in the roof are described in more detail when the Horton or Green ampt methods are applied. Typical applications of SWMM include; varying the CN number, adding a storage node or using a cascade of reservoirs.(Li, Y. et al. (2014))

Burszta-Adamiak, E. et al (2013) investigated the possibility of using SWMM along with LID (Low Impact Development) Controls module for evaluating the retention performance of green roofs. Actual measurements of runoff were compared to the simulated runoff in order to evaluate the runoff predictions by using SWMM. Three extensive green roofs were used in the model. Results from the comparisons between measured and simulated data showed that the results from the model were inaccurate. By trying to minimize the difference between actual and measured total runoff volume, the maximum flow rate was greatly overestimated. In addition, by calibrating the maximum flow rates, the simulated total runoff was underestimated in the model. The paper points to simplifications in the model, such as ignoring evapotranspiration, roof slope and cover type, as the main factors for the inaccuracies. Li, Y. et al (2014) concluded that the results obtained from SWMM should be considered an estimate of an already known green roof performance given a rainfall event. Alfredo, K. et al. (2010) also concluded that SWMM underestimate runoff with the CN method. In that case, better accuracy was obtained by adding a storage node instead of the CN-module.

In more recent time, Carson, T., et al. (2017), compared the different models. Among them were the CN method and the SWMM (V5.1) model. It was found that the CN method predicts cumulative runoff per event more accurately than the SWMM (V5.1) model. The SWMM (V5.1) model also tended to overestimate the total cumulative runoff depth per event. The main difference between the CN and the SWMM (V5.1) module is that the SWMM (V5.1) takes the hydraulic properties of the soil into account. The SWMM (V5.1) module is described by Carson, T., et al. (2017), among others. One of the main weaknesses of the SWMM module seems to be the calculation of actual evapotranspiration. The model does not take into count available soil water. This will likely lead to an overestimation in the retention performance of the green roof.

Direct comparisons of measured and simulated hydrographs from SWMM have also been conducted by Cipolla, S. S., et al. (2016) and Peng, Z. et al. (2017). The NSE generally varied from 0.4 to 0.9 for precipitation events where calibrated parameters were used.

2.4.4 Hydrus-2D/3D

Hydrus is a program for simulating water, heat and solute transport in both saturated and unsaturated media. For water transport and water uptake in the plant roots, the input data includes meteorological data and soil properties. Precipitation and evapotranspiration are among the meteorological data, while the soil properties include hydraulic conductivity, water retention curve parameters, plant root distribution parameters, wilting point and soil texture. The outputs of the simulation are spatial and temporal distribution of water content, suction, surface runoff, root water uptake and drainage. In order to simulate the runoff from a green roof during a rainfall event, input on meteorological data, soil properties and evapotranspiration need to be accurate.

Li, Y.et al. (2015) proposed a procedure for simulating with Hydrus 2D. This is the first time a green roof has been modeled with Hydrus 2D, and was mainly done in four steps. The first step was to acquire growth media retention curve parameters, such as ϑs, ϑr, α and n. These were acquired through laboratory tests. Then the green roof geometry was set up. After the input of the model was included, the third step was to calibrate the model using precipitation/irrigation data and calculation of evapotranspiration. By determining regression equations, the hydrological performance of the green roof for a given event can be predicted. The soil hydraulic parameters were calibrated against water content measurements in this study. Water content profiles were used to assess the hydrological performance during precipitation events. The outflow of the model was not verified against measurements.

As a continuation of the paper mentioned above, Li, Y. et al. (2016) also modeled the hydrological performance of a green roof, using Hydrus-2D. It was here stated that Hydrus 2D has difficulties modeling open water storage, as one of the main disadvantages with this model. Convergence problems during extremely wet or dry periods also occurred. It is stated that it requires advanced skills to simulate precipitation events with variable recurrence intervals, duration and depths, and is also mentioned as one of the main challenges with Hydrus-2D/3D-modelling. In this study, the model was calibrated by fitting the simulated water content against observed water content measurements at different substrate depths. The simulations were able to simulate the water content trends, as figure 4 illustrates. The water would leave the substrate through drainage holes, as a function of the drainage openings and the hydraulic conductivity. A water storage was also added in the simulations. The results from this study show that the hydrologic response from a green roof is mainly affected by the effective capacity, transient capacity, infiltration speed, draining speed and precipitation duration. An important discovery was also that it is more effective to add a water storage, rather than increasing the media depth of the roof.

Brunetti et al., (2016) modeled an extensive green roof in Mediterranean climate by the use of Hydrus 3D. The aim of the study was an accurate and comprehensive analysis of the hydrological behavior of the green roof. The water

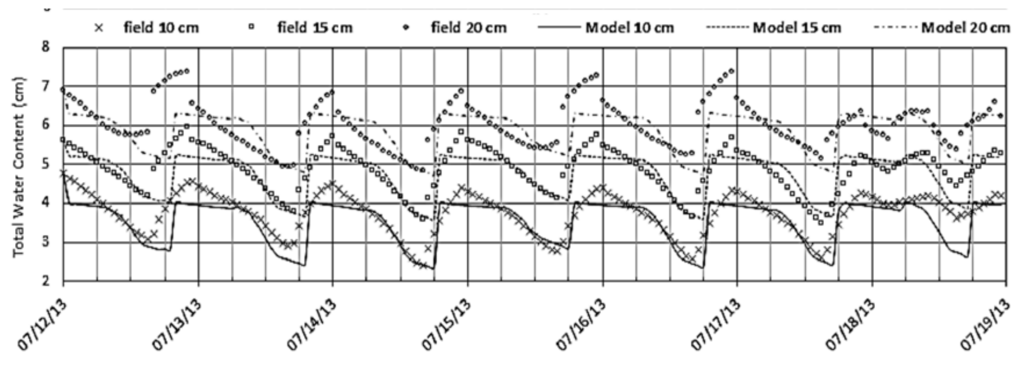

Figure 4: Simulated and observed water content (Li, Y. et al. (2016))

retention curve and unsaturated hydraulic conductivity were first found through a simplified evaporation method. Both van Genuchten and Durners model were used. The bimodal model of Durner would require additional two parameters to be determined and optimized. Geometry, substrate characteristics, and input data were then implemented in Hydrus 3D. The water would leave the green roof through drainage holes during saturation of the substrate. This would require a seepage face as a lower boundary condition. The drainage layer of the roof was then neglected after an assumption that the water would drain quickly after leaving the substrate. Evapotranspiration was modeled with the Penman-Monteith method, and an implemented model in Hydrus calculates actual evapotranspiration in terms of soil moisture in the roof. The results from the simulations show that the outflow was simulated with an NSE of 0.74 and 0.8 for the van Genuchten and Durner model, respectively. This was a period of selected dates in October and September, and not single precipitation events. This indicates that the Hydrus was able to simulate outflow from the roof accurately. The model also showed good accuracy in simulating single precipitation events, especially for the events with an early peak. Although the model produced fairly accurate results, the modeled peak flow seemed to be somewhat overestimated. The accuracy of total volume reduction for the month of October was also considered poor.

SWAP and SWMS-2D model the same physical processes as Hydrus-2D/3D. The main difference is that they were meant for agricultural purposes. (Li, Y. et al. (2014)

2.4.5 Hydrus-1D

Hydrus-1D contain most of the features of as Hydrus-2D/3D, except for that storage structures are not accounted for in 1D. Therefore, Hydrus-2D/3D is a more suitable tool for modeling complex green roof (Li, Y. et al. (2014), Li, Y. et al. (2015)). Hydrus-1D is the oldest version of Hydrus, and is free to download

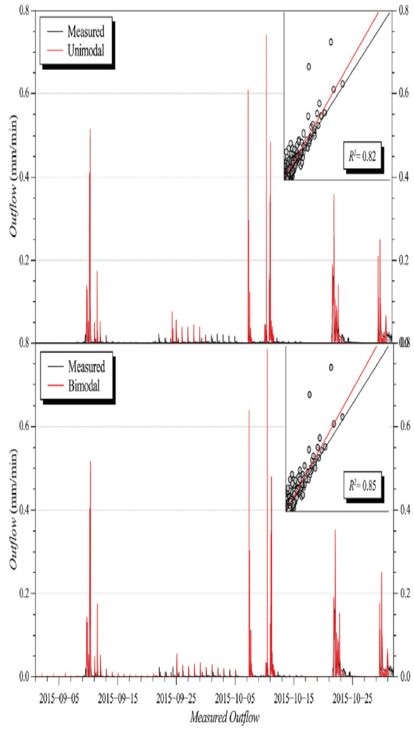

Figure 5: Simulated and measured outflow for September/October Brunetti et al. (2016)

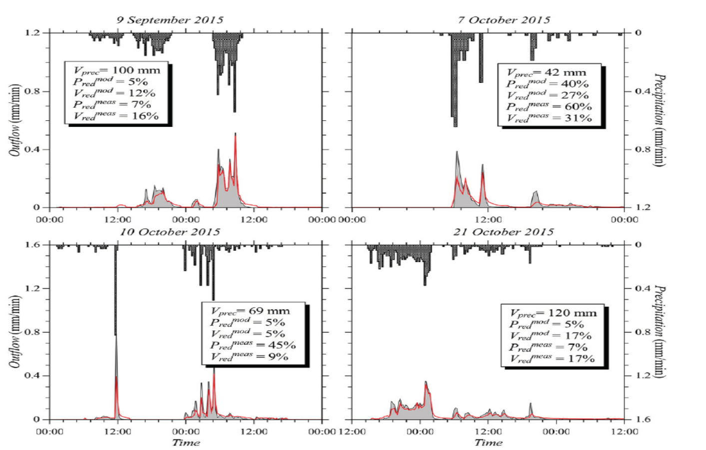

Figure 6: Simulated and measured outflow for precipitation events Brunetti et al. (2016)

at pc-progress.com. That is probably also why the 1D-version has been the most frequently used version in previous studies, found in the literature review. Among them are Palla, A., et al. (2012), Soulis, K. X et al (2017), Castiglia Feitosa, R. et al. (2016) and Hilten, R. N., et al. (2008), who have all simulated the runoff from precipitation events with Hydrus-1D.

Palla et al. (2012) compared a mechanistic model against a conceptual model. The conceptual model included three reservoirs to describe the infiltration process, and the lateral flow for water far from and close to the outlet. A linear two stage reservoir was also adopted in the mechanistic model, while Hydrus-1D was used to simulate the infiltration process. The models were calibrated and validated based on ten precipitation events. Results from the validation events revealed that the mechanistic model predicted the runoff more accurate. However, it is concluded that the conceptual model can be suitable when there is limited information about the hydraulic characteristics of the growing media and drainage layer. In contrast, Soulis, K. X et al (2017) compared a conceptual model to a physically based model (Hydrus-1D). The NSE was generally greater than 0.7 for the conceptual model, and 0.6 for the physical model.

Generally, Hydrus-1D was able to predict runoff response from a green roof. Limitations in Hydrus made it difficult to model the storage layer of the green roof. Hilten, R. N., et al. (2008) also concluded that Hydrus generally seems to overpredict runoff, and is more accurate for smaller precipitation events.

2.5 Blue-grey roof

The models that are mentioned in chapter 2.4 have all been used to model green roofs, and not blue-grey roofs. The literature search gave no results by searching for “blue-grey roofs”. Eriksson, A.O. (2013) however, modeled runoff roof of leca material, which is the same material as the blue-grey roof at Høvringen. A back calculation of a water runoff experiment was performed, showing good correlation between measured and modeled water runoff. SEEP/W was used to model the green roof. Based on the readings from this thesis, SEEP/W shares many similarities with Hydrus-2D/3D. As Hydrus, SEEP/W generates a mesh, where the galerkin finite element method is used for the calculations. Geometry and boundary conditions are also set up in a similar way. The unsaturated hydraulic conductivity also depends on the volumetric water content curve in both models. This function is further described in chapter 4.4. Inspiration for input parameters can therefore be taken from this thesis, as the soil texture for the blue-grey roof at Høvringen is quite similar, except for different particle size distribution.

No literature was found where a blue-grey roof or Leca material was used in the same way as the test roof at Høvringen. However, since there is no plant transpiration, plant interception or storage layer in the roof, it can not be expected that the roof will not. Runoff from single precipitation events will most likely only be detained, and not retained. The detention performance will mainly be a function of infiltration speed and storage capacity of the substrate.

3 Hydrus-2D/3D

3.1 Introduction

Hydrus-2D/3D is introduced and described in chapter 2.3.4 and 2.3.5. This section is a review of the inputs to model, and how the model solves the numerical equations for water flow in an unsaturated soil. While there are several options for methods to analytically describe the physical processes in the roof, only the applied van Genuchten-Mualem model will be described in this thesis. This is the most widely used model, though Brunetti, G., et al. (2016) achieved better results with Durners model. The van Genuchten-Mualem model has fewer parameters however. It is also easier to adopt the model parameters from literature when this model is used.

3.2 Richards equation

Richards equation represents the movement of water in unsaturated soil. It is derived by conservation of mass and Darcys law for water flow through a porous medium.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}\frac{\partial h}{\partial x_j} + K_{iz}\right)\right] - S \tag{7}$$

Equation 9 is the modified Richards equation for Hydrus 2D/3D. $\frac{\partial\theta}{\partial t}$ is the change in soil water content per time unit, K is the hydraulic conductivity, K_{ij} and K_{iz} is used to account for anisotropic medium, and h is the pressure head. S is the sink term and represents the root water uptake.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + cos\alpha\right)\right] - S \tag{8}$$

For Hydrus 1D, the equation looks similar as for the 2D/3D, except $K_{ij,iz}$ is not accounted for and cosα is added. cosα is the angle between the flow direction and the vertical axis.

Richards equation is then solved numerically using Galerkin-type linear finite element schemes. The solution is described in chapter 5 of the Hydrus 2D/3D manual (Šimůnek et al. (2011) chapter 2.1).

Richards equation will only apply as long as the soil is unfrozen. The water transport through a frozen soil will be significantly different compared to unfrozen conditions. A special freezing module must be downloaded and implemented in Hydrus to model a cold period. This module implements a modified Richards equation that accounts a frozen soil. However, this module was not meant for public use. There are several weaknesses in this module as it is not fully developed. The module is likely prone to instabilities.

3.3 Soil hydraulic properties

The hydraulic properties of the soil need to be determined prior to the simulations. This means determining the volumetric water content and the hydraulic conductivity as a function of the pressure head (ϑ(h) and k(h)). It's distinguished between direct and indirect methods for estimating the hydraulic properties of an unsaturated soil. The direct measurements are time consuming and expensive, and will not be described in this thesis. In Hydrus, the soil hydraulic properties are described by indirect models. An overview of the different methods of describing the soil hydraulic properties can be found in the publication paper from "International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils Riverside, C. (1992)".

There are five different analytical methods that can be used for finding ϑ(h) and K(h) in Hydrus. [Brooks and Corey, 1964; van Genuchten, 1980; and Vogel and Císlerová, 1988; Kosugi, 1995, Durner, 1994]. ϑ(h) is the water retention curve, and K(h) is the hydraulic conductivity. These are non-linear functions of the pressure head, and need to be determined in order to solve Richards equation. Through literature review, van Genuchten, M. T. (1980) was found to be the most frequently used model. Based on Mualem et al. (1976), the relative hydraulic conductivity is predicted from a known soil water retention curve. The following equations are derived:

For h < 0

$$\theta(h) = \theta r + \frac{(\theta s - \theta r)}{[(1 + |\alpha h|^n)]^{\,m}} \tag{9}$$

For h >= 0

$$\theta(h) = \theta_s \tag{10}$$

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{\frac{1}{m}})^m)\right]^{\,2} \tag{11}$$

For n > 1

$$m = 1 - \frac{1}{n} \tag{12}$$

$$S_e = \frac{(\theta - \theta_r)}{(\theta_S - \theta_r)} \tag{13}$$

In the equations above, ϑs is the saturated water content, ϑr is the residual water content, α is the inverse of the air entry value, n is the pore size distribution index, and l is a pore conductivity index assumed to be 0.5 in Hydrus. Residual water content is defined as the maximum water content in the soil that will not contribute to runoff. Ks is the saturated hydraulic conductivity and can be found from literature or laboratory measurements. S_e is the effective water content. The other methods are briefly described in the manual along with van Genuchtens model. (Šimůnek, J. et al. (2011), chapter 2.3)

3.4 Estimation of the soil hydraulic parameters

There are six parameters that need to be determined as inputs in order to run the Hydrus simulations when using the van Genuchuchten-Mualem method to describe the unsaturated hydrological soil properties. l, ϑr, ϑs, Ks, α and n are described in the chapter above.

According to Li, Y. et al. (2015), simulations without parameters that are calibrated against observed data or measured properly, can be highly inaccurate. Chapter 7.3 in the Hydrus-2D/3D also points out that it is the users responsibility to give initial parameter values that make sense. It is also recommended to run the simulations with different parameters to make sure that the optimization procedure converges towards the same global minimum in the objective function. The global minimum function is described in section 2.5.1.

3.4.1 Estimation of the soil hydraulic parameters based on water retention data

van Genuchten, M. T. (1980) proposed a method for estimating the parameters θ_r,θ_s,α and n, in addition of providing the equations for $K_r(h)$ and $\theta(h)$. The saturated water content should be easy to find through laboratory tests. The residual water content can also be found by measuring the water content in a very dry soil. van Genuchten also suggested that θ_r can be assumed as the water content at the wilting point, for practical reasons. To find the curve fitting parameters α, n and m, one has to look at the water retention curve. These points are ideally measured in a laboratory. van Genuchten states that the best point to evaluate the slope S is halfway between θ_r and θ_s, noted P in the figure below.

The first step is to graphically determine the slope of the curve at point P. From the following equation one can calculate the dimensionless slope

$$S_P = \frac{1}{\theta_s - \theta_r} \left| \frac{\partial \theta}{\partial(\log h)} \right| \tag{14}$$

From here, it is possible to calculate m;

$$m = \begin{cases} 1 - exp(-0.8 S_P) & 0 < S_P \leqq 1 \end{cases} \tag{15}$$

$$m = \begin{cases} 1 - \frac{0.5755}{S_P} + \frac{0.1}{S_P^2} + \frac{0.025}{S_P^3} & S > 1 \end{cases} \tag{16}$$

When a value for m is found, n is also available from equation 12 in chapter 4.4.1. Finally, α is found from the final equation;

$$\alpha = \frac{1}{h_P}(2^{\frac{1}{m}} - 1)^{1-m} \tag{17}$$

h_P can be read of figure 4 on the y-axis, and will in that case equal $10^{2.55}$.

Li, Y.et al. (2015) measured Ks, ϑs, and ϑr, while the curve parameters α and n, were determined through laboratory tests. Matric potential and soil

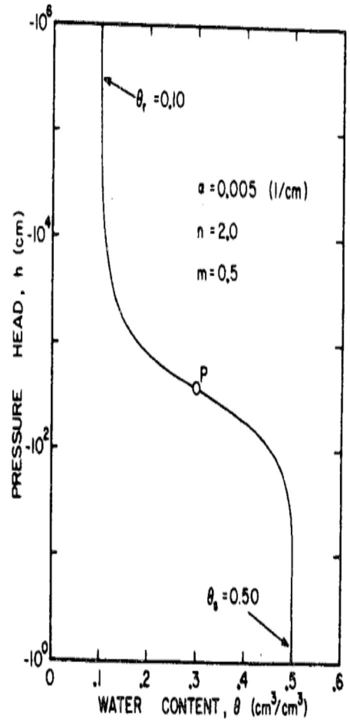

Figure 7: A typical pressure head vs water content function (van Genuchten, M. T. (1980))

water content was measured and regressed to fit the van Genuchten, M. T. (1980) hydraulic functions. Brunetti et al. (2016) also measured several points on the water retention curve. An acceptable accuracy in both of the studies indicate that this approach is a safe way of estimating the soil hydraulic input parameters. However, this method requires resources, time and knowledge to do the laboratory tests.

3.4.2 Other indirect approaches

As laboratory tests can be both expensive and time consuming, several researchers have explored the opportunity to predict the soil hydraulic properties based on soil texture, particle size distribution and bulk density of the soil. The in-built neutral network prediction in Hydrus-2D/3D predicts the parameters from soil texture and bulk density of the soil, and offers a convenient tool for predicting the soil hydraulic parameters. A program called Rosetta Lite 1.1 is used, which is based on Schaap et al. (2001). The program can predict the parameters for entire soil textures, but can also include the bulk density and a couple of points in the water content function if the information is available. Hilten, R. N., et al. (2008) used the in-built neutral network prediction to estimate the van Genuchten model parameters, assuming the green roof texture was 100% sand. The volumetric water contents at pressure heads 33 kPa and 1500 kPa were measured in a laboratory.

Feitosa et al. (2016) also used the internal Hydrus database to determine the soil hydraulic parameters of a green roof substrate. Instead of sand, sandy loam was chosen due to its drainage capacity. The choice of both the soil hydraulic parameters and soil hydraulic function was based on a literature review, without any previous knowledge of any specific soil data.

In recent years, Meskini-Vishkaee, F., et al. (2014) proposed a method of deciding the soil hydraulic parameters based on particle size distribution and bulk density by using a packing density scaling factor.

3.4.3 Parameter optimization

Hydrus-2D/3D incorporates an optimization process that iteratively improves the initial unsaturated hydraulic parameters. The output of the model is represented by a numerical solution of the flow equation, parameterized hydraulic functions, initial parameters, and initial and boundary conditions. The procedure of the calibration is to minimize an objective function of deviation between observed data and the predicted response from the simulations. This is done by iteratively improving the parameters until an acceptable deviation is obtained. An example of an objective function is given in chapter 7.1 of the Hydrus-2D/3D manual.

The Marquardt-Levenberg nonlinear minimization method is used to minimize the objective function. This means in practice to minimize the error between measured and simulated observations in the model. Confidence intervals for the optimized parameters are then provided. The method has been found to be highly effective and is now a standard method for soil scientists and hydrologists.

Soulis, K. X et al (2017) calibrated the parameters in Hydrus-1D in the following step:

1. Compare the resulted parameter values for each event
2. A new set of initial values and ranges were defined manually
3. The model was calibrated again, using the new initial values and ranges
4. The procedure was repeated until a common set of parameters with acceptable performance for all events were reached

3.5 Root uptake

Precipitation will leave the green roof as either transpiration, evaporation or runoff. In Richards equation, S represents the root water uptake which is the transpiration. Potential root water uptake is a function of the potential transpiration and area of the root zone. The potential transpiration is assigned in the atmospheric input file. Hydrus incorporates a setting that reduces the actual root uptake as a function of available soil moisture. The actual root water uptake is for example reduced at very high or low soil moistures. The root water uptake will also cease when the soil volumetric water content drops to a certain level. This should be set close to the wilting point of the substrate. Parameters that determine the actual root water uptake can be edited by the user. Pressure heads that correspond to a certain volumetric water content are assigned, and determine the actual root water uptake. Reduction in actual root water uptake due to osmotic stress can also be assigned. This requires that solute transport is also modeled. Potential and actual root water uptake is completely described in chapter 2.2 of the Hydrus-2D/3D technical manual. (Šimůnek, J. et al. 2011)

3.6 Boundary conditions

The boundary conditions are assigned to geometric objects in the graphical user interface. A water flux is either added or extracted to the system depending on the boundary condition. A variable flux can extract or add a predetermined amount of flux. When the water flux is unknown prior to the simulations, a free drainage, seepage face or atmospheric boundary conditions are usually assigned. The free drainage or seepage face is usually assigned as a lower boundary condition when water is leaving a substrate. For a free drainage condition, water flux will be a function of the hydraulic conductivity and the width of the surface.

$$Q(n) = -width(n) * K(h) \tag{18}$$

Width(n) is the width of the node, while K(h) is the hydraulic conductivity as a function of the pressure head. (Šimůnek, J., et al. 2011, chapter 8.3)

A seepage face works as a zero head boundary condition. This means that runoff will start once the substrate is fully saturated. In the later versions of Hydrus, it has been added a setting which activates runoff once a certain pressure head is reached. The seepage face flux will function the same way as the free drainage once the required pressure head is reached. Boundary conditions are described in chapter 2.7 of the Hydrus manual (Šimůnek, J. et al. (2011)).

3.7 Atmospheric boundary conditions

This is a boundary condition that can be assigned as an upper boundary condition, to a geometric object in in Hydrus. Precipitation, potential evapotranspiration and temperature is edited in an input file. Potential evapotranspiration must be divided into potential evaporation and transpiration by the user. Actual transpiration is equal to the actual root water uptake (see chapter 3.5). Actual evaporation is calculated by Hydrus, based on the amount of water available in the soil.

When evapotranspiration is calculated in Hydrus, a hCrit must be assigned in the atmospheric input file. hCrita is the pressure head that divides the evaporation into two stages; one stage where the actual evapotranspiration equals the potential evapotranspiration, and a second where the actual evapotranspiration is limited by the soil water available. When the hCrita value is reached, the actual evapotranspiration decreases since the earth is too dry to contribute to the evapotranspiration. The hCrita value is usually set between -150 and -1000m, and may lower for course-textured soils. hCrita should always be chosen so that the corresponding water content to this pressure head is at least above 0.005 higher than the residual water content. Through literature review a hCrita has usually been set without any further explanation. Another way to set this value is by the following equation;

$$Hr = exp(\frac{hMG}{RT}) \tag{19}$$

where Hr is the relative humidity (%), h is the pressure head (m), M the molecular weight of water (0.018015 kg/mol), G is the gravitational acceleration (m/s^2), R the gas constant (8.314 J/(mol K)) and T the absolute temperature. (Hydrus graphical user interface manual, Brunetti et al., 2016)

3.8 Simulation of snow accumulation

Hydrus-2D/3D incorporates a code that assumes all of the precipitation is in form of snow when the temperature is below -2 degrees Celsius. Similarly, all of the precipitation is in liquid form when temperature is above 2 degrees Celsius. A linear distribution is used to describe the snow accumulation between these surface temperatures. For an already existing snow layer, melting will occur proportionally to the air temperature, when the temperature is above 0 degrees Celsius. A condition for simulating snow is that heat transport is simulated simultaneously as water flow and atmospheric boundary conditions. Simulation of snow accumulation is fully described in section 2.7.2.5 in the Hydrus-2D/3D manual. (Šimůnek, J., M. et al. 2006)

3.9 Initial conditions

Initial soil conditions can be specified in terms of both pressure head and initial soil water content. The simulations are though expected to be sensitive to the initial conditions only during the first few simulation days (Brunetti, G., et al. (2016)). Initial conditions are also described in the Hydrus manual (Šimůnek, J. et al. (2011)), chapter 2.7.

3.10 Geometry

For Hydrus-1D, the geometry is confined to one dimension (Li, Y. et al. 2014). Length and width of the substrate can be edited in the graphical user interface in the 2D version. For simulating complex green roofs with various drainage and water storage structures Hydrus-2D/3D must be applied, as those features will not be included in Hydrus-1D. Li, Y. et al. (2015) divided the volume of the pockets in the bottom by the length and proportionally distributed the volume over the width to represent the storage per linear length. This was done to adjust the green roof to a 2D-model. However, the aim of that study was to calibrate and validate the model against water content measurements. The hydrologic responses and cumulative runoff reduction were also based on water content measurements. Outflow measurements were not conducted in this study. This way of accounting for water storage is therefore not validated for outflow measurements. Soulis, K. X., et al. (2017) accounted for storage by adjusting seepage face boundary condition. This was done by increasing the pressure head that activates runoff. The pressure head was changed from a zero boundary condition 1.5 cm. Brunetti, G., et al. (2016) among others, neglected the storage layer.

3.11 Heat transport simulation

Heat transport simulation has not been conducted in either of the previous green roof simulations that have been assessed in the literature study. Accurate results of runoff were obtained without considering heat flow for Hydrus-1D, 2D and 3D. However, simulating heat transport is a condition for simulating snow accumulation. Hence, heat transport must be included when the precipitation is in form of snow. A suggestion for the heat transport parameters is given in the graphical user interface of the model. The model assigns the values based on soil texture in the model. Sand, loam and clay are the three textures that are included. The parameters can also be set manually. Heat transport is fully described in chapter 4 of the Hydrus technical manual. (Šimůnek, J., M. et al. 2006)

Figure 8: Test site at Høvringen

4 Method

4.1 Site description and materials

The test roofs that have been modeled in this thesis are all located at Høvringen in Trondheim. The roof consists of a blue-grey roof, an extensive green roof, and a black reference roof between them. Runoff from the roofs is collected and measured by a tipping bucket, located at the end of each roof. Runoff water will first filtrate through the substrate before it reaches the impervious layer. The green roof also includes a storage layer below the substrate. All of the roofs have the same geometry, with an area of 8x11 meters and a slope of 2 %. Above the blue-grey leca substrate, there is a walkable pavement layer that covers the entire roof. Water will quickly infiltrate between the cracks, and it can be assumed that most of the precipitation water will flow through the substrate before it ends up in the tipping bucket. Pictures from the site area are presented in figure 8. A tipping bucket is located below the outlet of roofs. In addition to the runoff measurements, two sensors are horizontally placed in the middle of each roof. Data of both volumetric water content and temperature measurements is therefore available. Meteorological data such as air temperature, wind speed, air humidity, radiation and precipitation is also available.

4.2 Modeling with Hydrus-2D/3D

A 2D version of Hydrus-2D/3D is used to model the substrate of the blue-grey and green roofs. The runoff is calibrated and validated against runoff measurements at the end of the roof. This means that the time the water uses from the substrate to the measuring device is neglected, and that no water will flow over the edge of the roof. The storage layer of the green roof, is as mentioned in the literature study, very difficult to model with Hydrus-2D/3D. Brunetti et al. (2016) solved a similar problem by neglecting the water storage, since the storage layer usually would be full. Water can leave through both evaporation and root water uptake, but will be limited by lack of air turbulence and solar radiation. This assumption is likely valid as long as the climate is wet. In practice this also means that the water storage is assumed constantly full, and has no capacity. Water that enters the storage through the substrate will then very quickly be drained through the drainage holes. During a long ADWP, the storage layer will still dry in spite of limited evapotranspiration. An overestimation of the simulated runoff after a long ADWP can therefore be expected.

The FE-mesh was created after the geometry layout of the model was determined. The mesh should be created fine enough, so that the simulations are accurate. If the mesh is too fine, numerical problems may occur. A mesh refinement of 6 cm for the blue-grey, and 3 cm for the green roof was inserted in the model. The same principle should be applied when determining time steps in the model. Large enough so that numerical problems don‘t occur, and short enough to produce accurate results. The geometry, boundary conditions and FE-mesh is illustrated in figure 9 and 10. The boundary conditions are assigned to geometric surfaces and assigned a specified color. The red dot in the middle of the substrate is an observation node, where water content measurements can be assigned for calibration runs.

Initial water content conditions can be assigned as either pressure head or volumetric water content. In this model, the volumetric water content is used and considered constant throughout the substrate. The values for the initial water content is read from the sensors in the substrate.

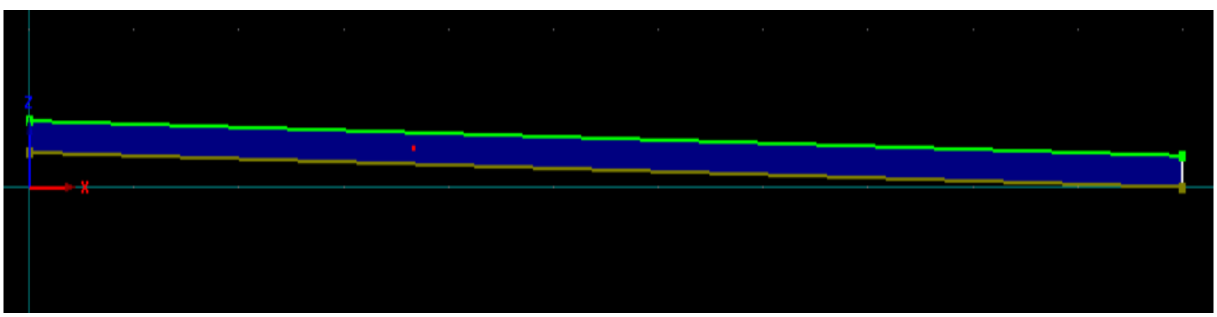

Figure 9: Geometry and boundary conditions of the blue-grey roof

4.3 Evapotranspiration

The Penman-Monteith equation for short time steps was used to calculate the potential evapotranspiration. The atmospheric input file in Hydrus requires potential evapotranspiration to be divided into potential evaporation and transpiration manually. This is done by assigning a crop coefficient to the roof. The method was first introduced by Allen et al. (1998):

$$ET_c = ET_0(K_e + K_{cb}) \tag{20}$$

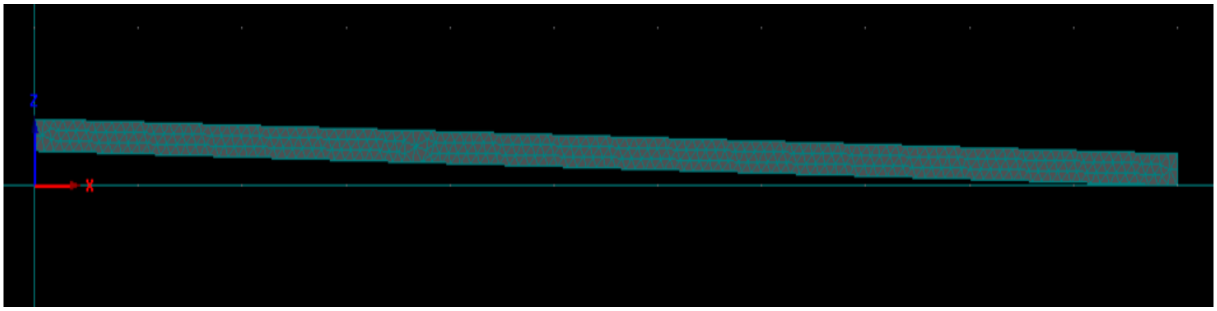

Figure 10: Geometry and FE-mesh of the blue-grey roof

K_e is the empirical coefficient that accounts for a reduction in evaporation due to limited soil water availability. An in-built function in Hydrus already accounts for this effect during the simulations. $K_{cb}$is the crop coefficient that divides the evapotranspiration into evaporation and transpiration separately. K_{cb} will be zero for the blue-grey roof since there are are no plants present. The crop coefficient was set to 0.5 as a simplification in this thesis.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(\frac{900}{T+273})u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{21}$$

The method and equation is fully described in Allen et al. (1998).

Hydrus database for root water uptake parameters were used in this case. The database includes parameters for a number of different plants/crops. The Pasture [Wessling, 1991] parameters for root water uptake was used as a simplification. Osmotic stress was not accounted for in this case. That would have required simulations of solute transport as well.

4.4 Initial parameters

There was limited data available for the soil hydraulic parameters that were required to run Hydus. The saturated water content and saturated hydraulic conductivity was available for the blue-grey roof. A value for the residual water content was found from Eriksson, A.O. (2013), which modeled a similar leca material. A value of 0.5 for the pore connectivity parameter, l, was also found by Mualem (1976) to be an average for many soils. The in-built neutral network prediction module for sand was initially used to determine the values of the curve fitting parameters α and n. The neutral network prediction was also used to determine the initial input values for the green roof, with a soil texture of 100% sand. The saturated volumetric water content was increased compared with the suggested value from the neutral network model. Values for ϑ_s were generally set higher for similar substrate in literature, and water content measurements also point to a higher saturated water content. Values for the saturated hydraulic conductivity was also available for the green roof.

4.5 Calibration procedure

The soil hydraulic parameters were first calibrated against water content measurements in the soil. This required the lower boundary condition to be set to free drainage. The model was first calibrated against data from the first two weeks of July, and then validated against runoff measurements from the second half of July and first half of August. This was done for both the blue-grey and green roof.

After the model was calibrated against water content measurements, a calibration procedure against runoff measurements was also conducted. This calibration method was initially limited by a lack of knowledge about seepage face modeling. The lower boundary condition was switched from free drainage to seepage face. The seepage face boundary condition will activate runoff when the substrate is fully saturated, unless the boundary condition is modified. A setting that activates runoff at a certain pressure head was set to -200 cm. This value was found after running a large number of test simulations.

During the initial calibration procedures, only α and n were calibrated. This was due to higher uncertainties in these values, and the attempts to avoid over-parameterization. However, Ksat was calibrated the same way as α and n during the seepage face calibrations.

4.6 Seasonal variations

Attempts were also made to simulate runoff from the blue-grey and green roof during a winter period. The calibrated parameters from the summer period were validated against runoff measurements from January and February. A seepage face was used as a lower boundary condition. A pressure head of -200 cm was also applied to activate runoff. Hydrus-2D/3D do not contain any specific accommodations for winter climate, except for the snow accumulation module. The snow module was activated, and also required heat transport through the substrate to be simulated due to the snow melt function. The initial heat transport parameters were set for a soil texture of 100% sand for both the blue-grey and green roof. These parameters were not calibrated since heat simulations are outside the scope of this thesis, and requires a certain amount of skill and knowledge about heat transport. However, this may have caused some inaccuracies in the snow melt simulations.

5 Results and discussion

5.1 Calibration against water content measurements

The model was calibrated against water content measurements during the first two weeks of July, and then validated against roughly four weeks in July/August. Both sensors of each roof were used for the calibration separately. The most accurate were used for further calibration. Only the curve fitting parameters α and n were calibrated and optimized. Results indicate that the model was only able to predict the runoff from the blue-grey and green roofs during the calibration period. The NSE coefficient was 0.79 and ~0.5 respectively. The NSE coefficients of the validation period indicate that the model was not able to predict runoff with NSE coefficients generally below 0.5. The initial and optimized parameters are presented in table 1. For hydrographs from all the calibration and validation periods, see the appendix.

The statistical results suggest that the model was unable to predict runoff for either of the roofs. By visually assessing the hydrographs (see appendix A and B), it is also obvious that the simulated runoff peaks are significantly underestimated during all of the runs. Some of the inaccuracies may be due to how the model is set up. The water storage and lateral water transport is for example neglected. However, lack of accurate initial soil hydraulic input parameters could also be a significant source of error. Ksat should also have been calibrated in addition to α and n. If the input value of Ksat was inaccurate, that will also make the curve fitting parameters converge towards inaccurate values.

The base flow was also overestimated for both roofs, especially during dry periods (see validation period in August). This is probably not due to inaccurate soil hydraulic parameters, but an hCrit value that was set too low. As mentioned in the theory part, this will cause a water flux on the upper boundary condition. This keeps the pressure head within the maximum allowed. A pressure head corresponds to a volumetric water content depending on the water retention curve of the substrate. A high negative pressure head will for instance correspond to a low water content. By setting a too low maximum allowed (negative number) pressure head, that also forces the water content to be artificially high. This is most likely what has happened where the base flow is overestimated. Attempts to adjust this value also resulted in numerical problems in the simulation of dry periods.

Generally, it seems that the free drainage boundary condition in the model is not able to predict runoff from a green or blue-grey roof. These simulations were calibrated against water content measurements from one sensor in the vertical direction. In contrast, Li, Y. et al. (2015) had two sensors in the vertical direction. The calibration procedure was otherwise conducted the same way as in this case. Li, Y. et al. (2015) used water content profiles to assess the hydrological performance of the green roof. Outflow was not verified. Findings from the roof at Høvringen suggest that a free drainage lower boundary condition is not able to predict outflow from the substrate. Attempts to account for the water storage by adding a porous media on the bottom of the roof was also attempted. No reasonable results were obtained. The authors experience is that the open water storage is very difficult to account for in Hydrus-2D.

Soil hydraulic properties			Optimized values
Residual water content	WCR	0.05	-
Saturated water content	WCS	0.606	-
First coefficient	ALPHA	0.25	0.16
Second coefficient	N	1.26	1.43
Saturated conductivity	CONDS	60 [cm/min]	-
Pore connectivity factor	L	0.5	-

Table 1: Water content measurement calibration results

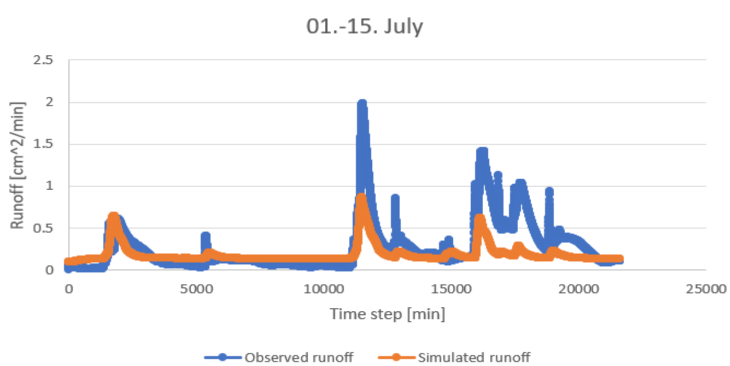

Figure 11: Runoff diagram from the blue-grey calibration period

5.2 Calibration against runoff measurements

The model was also calibrated against runoff measurements in early July, and validated against runoff measurements in late July and early August. A seepage face was set as a lower boundary condition. A setting that allowed runoff to begin at a certain pressure head was applied. This was set to a negative number of -200 cm, which had not been done in any of the other studies from the literature review. hCrit was also adjusted in an attempt to avoid overestimation of the base flow. Ksat was also calibrated in addition to the curve fitting parameters α and n. The optimized values for these parameters were significantly different than the initial values, compared to other studies. This is probably because the comparable studies used laboratory tests to determine the initial soil hydraulic parameters.

The NSE coefficients for the blue-grey roof indicate that the model was able to predict runoff, with an NSE generally above 0.75. Visually, there seemed to be no difference in the accuracy of large and small events. The model was also able to simulate base flow, runoff peak and time to runoff peak with an

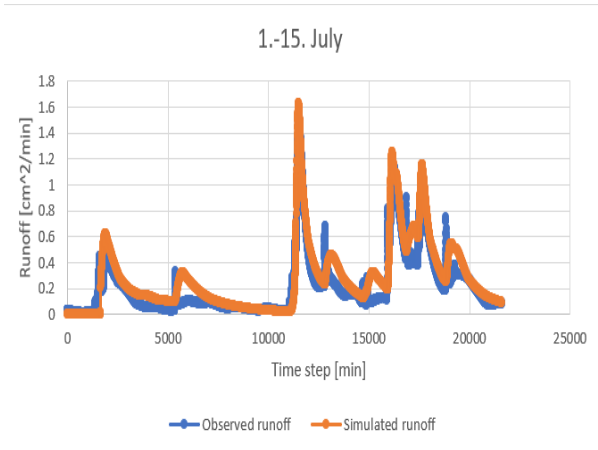

Figure 12: Blue-grey calibration period

acceptable accuracy. The first couple of days in August are not included in this statistic and is counted as a "warm up" period. The initial water content conditions were likely set too high.

The only obvious weakness in the runoff simulations of the blue-grey roof, is that the model does not seem to reproduce the runoff peaks after intense rain events. Approximately 10,000 minutes into August, the simulated runoff is simulated smoother than the observed. A possible explanation for this error may be inaccurate soil hydraulic properties. More likely is it that not all of the water flows through the substrate, as assumed in the model. The measuring bucket is located below the open area at the end of the roof, illustrated in figure 14. If the precipitation water takes a quicker path to the bucket than through the substrate, that may explain why the observed runoff responds quicker to intense precipitation than the simulated runoff. It may very well happen that infiltration rate of the sand between the openings of the pavers is not high enough for all the water to infiltrate through the cracks. If that is the case during extreme events, some of the precipitation will quickly drain on top of the pavers instead of going through the substrate.

The green roof was also modeled more accurately with an NSE of 0.60 for the calibration period and 0.57 for the validation period in July. Runoff events were generally overestimated during the calibration period, but underestimated during the validation. In addition to already mentioned potential uncertainties in soil hydraulic properties, the neglect of the storage layer may explain the shifting over- and underestimation of the peak runoff. After a dry period, the storage will likely retain a significant amount of water. After a wet period (see late in the calibration period), the storage is likely full and will no longer retain water. The simulated runoff will then overestimate the runoff peak when the storage layer is dry, and underestimate when the storage layer is full. The validation period that also included the first two weeks of August was modeled with

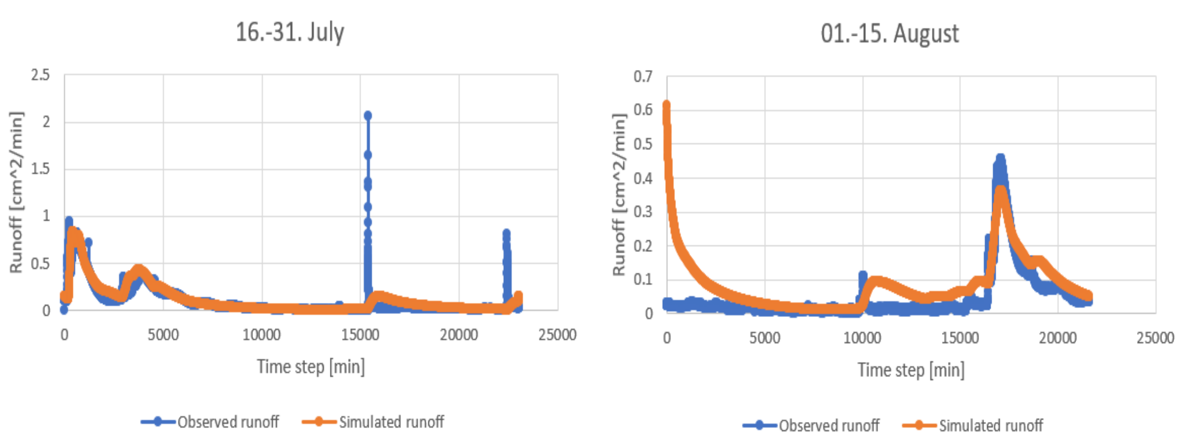

Figure 13: July and August, validation period of the blue-grey roof

Figure 14: Outlet of the blue-grey roof

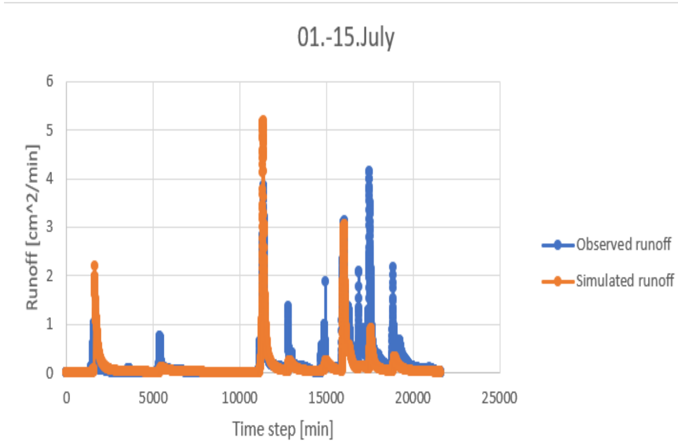

Figure 15: Green roof calibration period

an NSE of -0.18. This shows yet again that dry periods are very hard to model accurately, even when the model is calibrated against runoff measurements.

The observed and simulated peak delay, peak reduction and volume reduction for a selected number of events can be found in appendix H. There has been no specific criteria for the events except a antecedent dry weather period of six hours or longer. The hydrological performance is compared against the runoff measurements of the black reference roof, where nearly all of the precipitation is converted to runoff. For information about the equations that are used, see chapter 2.2. Generally, Hydrus seems to underestimate the total runoff volume reduction for both the green and blue-grey roof. The reduced runoff peak however, seems to match the observed data for most events. During some events, the peak delay is modeled quite inaccurately in the appendix. This is mostly due to the fact that one precipitation event might have several runoff peaks, where one peak is bigger than the other. This is visually best illustrated at time step ~16,000 - ~17,500 in figure 16, where the peak runoff for one event is simulated and observed at a different time. However, this issue only seems to occur during wet periods.

5.3 Lower boundary conditions for different substrates

The validation period showed that the simulations were more accurate when the model was calibrated against runoff measurements rather than water content measurements, as expected. As long as the substrate is in contact with atmospheric pressure, a seepage face should by used as lower boundary condition. With the standard settings for this module, runoff would not be activated before the soil was fully saturated. A pressure head of -200 cm was applied to activate runoff and was found through a number of test runs. There are still uncertainties about this runoff activation pressure head. The calibration with a

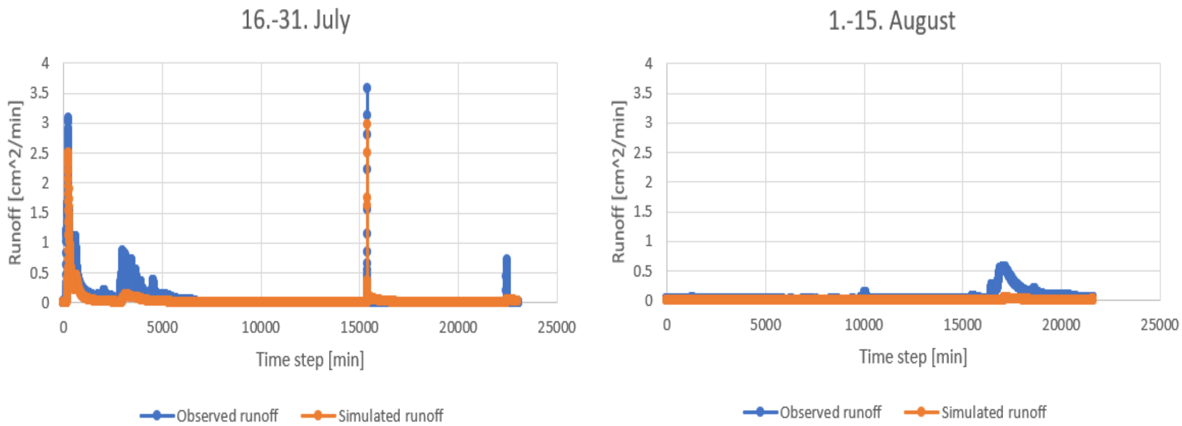

Figure 16: Green roof validation period

seepage face as lower boundary condition, and a pressure head of -200 cm still gave the most accurate simulations. A zero head boundary condition, which is most widely used for green roof modeling, gave very inaccurate results for the blue-grey roof. What usually happened was that runoff was not produced, because of the time it took for the lower parts of the substrate to become fully saturated. The retention capacity of the blue-grey roof was therefore heavily overestimated when the seepage face boundary condition was not adjusted.

Once the pressure head of -200 cm was reached, the seepage face would function the same way as the free drainage boundary condition. The seepage face flux is then a function of the area and hydraulic conductivity. There is still a significant risk that the model is “over-parameterized” as both the input parameters and the seepage pressure head is uncertain.

The simulation results for the blue-grey and green roof have already been discussed in the previous sections, along with the uncertainties. Different problems and uncertainties occurred for the two roofs. As mentioned, these issues are more likely related to the geometry and water flow path of the roofs, rather than the difference in the soil hydraulic properties of the substrates. Modeling different substrates in Hydrus is therefore possible as long as the difference in the soil hydraulic properties is accounted for.

5.4 Seasonal variations

Runoff from the blue-grey roof was in January and February modeled with an NSE of 0.21 and 0.31, respectively. This is slightly below the acceptable threshold value of 0.5. Some of the runoff peaks are modeled highly inaccurate, where neither the peak time or maximum peak runoff match the observed values. This is illustrated in figure 17. The green roof runoff was in the first half of January simulated with an NSE of less than -6, and is considered very inaccurate. When

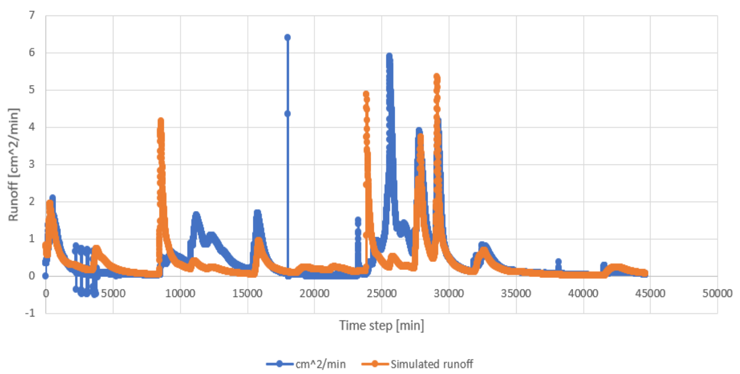

Figure 17: Blue-grey roof in January

the simulations reached the second half, numerical problems occurred. Simulations in February were also attempted, but gave useless results due to even lower temperatures.

Generally, the accuracy of the winter simulations were better than expected for the blue-grey roof. Especially since the runoff observations were more uncertain than for the summer period. See for example the beginning of January, where there is obviously something wrong with the tipping bucket that measured runoff from the blue-grey roof.

There are several assumptions and uncertainties that can explain the inaccurate results from the winter period. Inaccurate snow accumulation may cause large deviance in simulated peak time and maximum runoff peak, compared to the observations. The simulations are also based on the assumption of unfrozen soil. As mentioned in the theory part of this thesis, the unmodified Richards equation will then no longer apply for water transport in the soil. The blue-grey roof is also covered with pavement blocks, where the the cracks may also freeze. The frozen conditions may very likely lead to a significant shortcut in the water transport to the measuring device, which the normal module in Hydrus is not able to model. It is difficult to determine where the simulations are inaccurate due to error in snow accumulation, or if the frozen soil is the source of error. However, an overestimated peak in the simulated runoff is likely due to precipitation in form of snow that is modeled as rain in Hydrus. The observed runoff peak will then occur later when the snow melts. When the soil or cracks in the pavements are frozen, the water may not infiltrate through the substrate, but flow directly to the outlet. The simulated runoff will then be significantly underestimated compared to the observed runoff. This will though remain as speculations without observations of the snow layer.

It is also worth noting that the measuring errors of both precipitation and runoff may have played a significant role in the inaccuracies of the model. Measurements of runoff have been especially inaccurate, with values that make no sense. See for example negative values for runoff. Some extremely high values

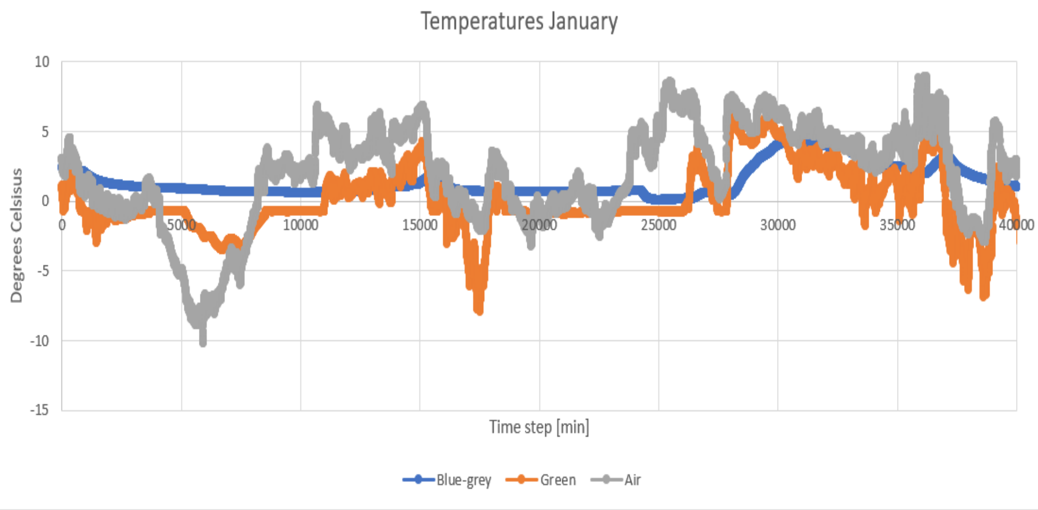

Figure 18: Substrate temperatures

for a single minute have also been removed from the graph, as they make no sense in light of precipitation and temperatures.

The temperatures in the air and the sensors located in the middle of the substrates show a significant difference in temperature variations in the substrates. The temperature is generally lower in the green roof compared to the blue-grey, and usually follows the air temperature. The temperature often drops below zero, which explains why the simulations are so inaccurate. The core of the blue-grey roof does not drop below zero degrees in January, which can explain why the blue-grey roof was modeled more accurate than the green roof. Even though the core temperatures were above zero, the edges of the substrate may have been frozen during cold periods.

5.5 Some remarks concerning the soil hydraulic properties

Lab results for the leca-material in the blue-grey roof were received late in this study. The water content at the pressures, 2, 10, 100 and 1500 kPa was measured. According to Hilton et. al, the pressure 1500 hPa represents the wilting point of the material. Hilten, R. N., et al. (2008) also used the water contents at pressure head 33 kPa and 1500 kPa as input parameters in the neutral network model along with soil texture data to gain the soil hydraulic parameters. Measuring the curve fitting parameters directly from the water retention curve is difficult in this case because of the few points available on the water retention curve. The method to obtain these parameters is dependent on several measurements to accurately determine the slope at a point S. The point S and the rest of this procedure is completely described in chapter 3.4.1. In

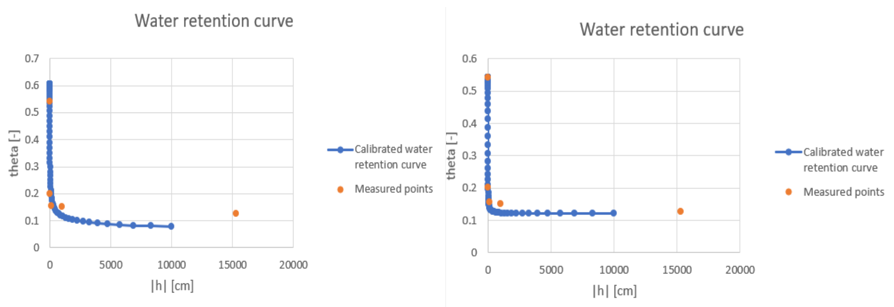

Figure 19: Water content versus pressure head. The diagram to the left is the calibrated water retention curve compared with measurements from the laboratory test. The diagram to the right is adjusted to fit the measured points from the laboratory test.

short, the curve fitting parameters are not possible to calculate accurately due amount of data about the water retention curve. However, the measured points on the water retention curve from the lab were compared to the calibrated curve in Hydrus (see figure 16). For future modeling, the water content at pressures 33 and 1500 kPa can also be used to obtain more accurate initial soil hydraulic parameters in the in-built neutral network prediction model. The lab results were not thoroughly analyzed, but quickly assessed. The most obvious deviance in the simulated curve compared to the measured points on the curve, is the residual and saturated water contents. The residual water content is set too low, and the saturated water content is set too high. Reading of the measured points the values for these parameters should have been changed from 0.606 to 0.542 for the saturated water content, and from 0.05 to a value above 0.1. These parameters were unfortunately locked at inaccurate values during the simulations in this thesis. The other input parameters were probably also affected by this, since the unsaturated hydraulic conductivity is a function of all the five parameters.

5.6 Hydrus as a simulation tool

Overall, the results show that Hydrus is a suitable model to simulate both substrates in the blue-grey and green roof. The typical problems that were found through the literature review also occurred while modeling the test roofs at Høvringen. Dry periods were especially problematic due to numerical problems and inaccurate results. Despite several attempts, the open water storage could not be modeled in this study, which coincide with the literature review. The accuracy of the model also decreased during the extremely wet periods. However, Hydrus was still successful in modeling the green and blue-grey roofs, in spite of several uncertainties and simplifications in this case study. The biggest concern with the obtained results is perhaps the risk over-parameterization. It is important to remember that the calibration procedure in Hydrus is trying to minimize the difference between measured and simulated outflow. The calibrated parameters don‘t necessarly reflect the actual hydraulic properties of the substrate. Possible improvements of the model that was implemented in this thesis, is first of all to describe the lateral flow of water from the substrate. Palla, A., et al. (2012) did this by describing the water flow by a two stage linear reservoir. The obtained results in this study were also considered accurate.

A tendency of overestimating runoff peaks has also been typical for the model (Brunetti, G., et al. (2016), Hilten, R. N., et al. (2008)). This was not generally experienced in the application of the model at Høvringen.

In theory, Hydrus should be able to predict runoff for different substrates and substrate depth, as long as the soil hydraulic properties of the material are known. A weakness of the other existing models can be that they are very case specific. Meaning that a calibrated model will only apply for the roof it was calibrated against. In contrast, Hydrus models the actual physical processes in the roof. A major advantage is that Hydus also takes into count available soil moisture, when actual evapotranspiration is modeled. This can play a significant role in terms of accuracy in the modeling of retention capacity. The model can therefore offer assistance in the planning of a blue-grey or green roof as a BMP, as long as the soil hydraulic properties of the material is known. Models such as a conceptual model can be very useful when there is limited information about the soil hydraulic properties of the substrate, as Palla, A., et al. (2012) mentions. However, an advantage with conceptual models and SWMM is also that all the layers of the green roof can be modeled. The storage layer has usually been neglected when Hydrus has been applied in recent studies.

The program does not require any special programming skills. However, this is a program that models the actually physical processes in the green and blue-grey roof. The user must therefore be familiar with the water retention curve and water transport through the unsaturated zone. Both the input data and the calibration process depends on this knowledge by the users.

6 Conclusion

A blue-grey and green roof was modeled with satisfactory results, by the use of Hydrus-2D/3D. There were a lot of uncertainties prior to this study due to missing soil hydraulic properties and simplifications in the model. The water transport time from the substrate to the measuring bucket was neglected for both roofs. The storage layer below the green roof substrate was also neglected. Accurate results were still obtained during the summer period by calibrating against runoff measurements. However, numerical problems and inaccurate simulations could occur during very dry or wet periods. The soil hydraulic parameters that were calibrated against water content measurements in the substrate were not able to predict runoff during the validation period. Generally the blue-grey roof was also modeled more accurately than the green roof.

Hydrus was also tested during a winter period. The results were generally inaccurate due to a frozen soil and simplifications in the in-built snow module. There was also a huge difference in the accuracy between the blue-grey and green roof during the winter period. Since the blue-grey had a thicker layer of substrate and was covered with pavers, the temperatures rarely dropped below zero degrees Celsius. Hence, the soil would remain unfrozen and Richards equation for water transport in an unsaturated zone would still apply. The temperatures in the green roof substrate followed the air temperature more closely than the blue-grey roof. This lead to a quicker freezing of the substrate.

The hydraulic soil properties were simplified in this thesis, and it may be possible that the calibration was over-parameterized. Hydrus changes each parameter by one step until the objective function is minimized. The optimized parameters may therefore not necessarily represent the most realistic parameters, but the parameters that fit best with the measured runoff or water contents. The laboratory tests of the leca material in the blue-grey roof suggests that the estimation of residual and saturated water is inaccurate. The other calibrated soil hydraulic properties were also affected negatively by this. The inaccuracies in the simulations are likely due to a combined effect of model setup, hydraulic properties and measuring error, that is not optimal.

7 Future work

The modeling in this thesis has been conducted without laboratory measurements of the initial input parameters. These values have been taken from literature where similar material has been used, and others have been assumed. With more accurate data of the soil hydraulic properties, all the parameters can be calibrated, with a lower risk of over-parameterization.

The snow accumulation simulations were also inaccurate. It is difficult to know for sure whether this is mostly due to the simplified snow module, or simplifications in the heat transport. Future work may include gaining a better understanding of this process.

The greatest potential in terms of modeling improvements lies in accounting for the lateral flow of runoff. Water will flow from the substrate, across an impervious layer, before it ends up in the measuring bucket. This water transport is neglected in this study. The storage layer below the green roof substrate is also neglected. Future work may also include adding this storage layer to the model. The authors experience is that Hydrus is incapable of modeling the storage. Another model must therefore be combined with Hydrus in order to do this.

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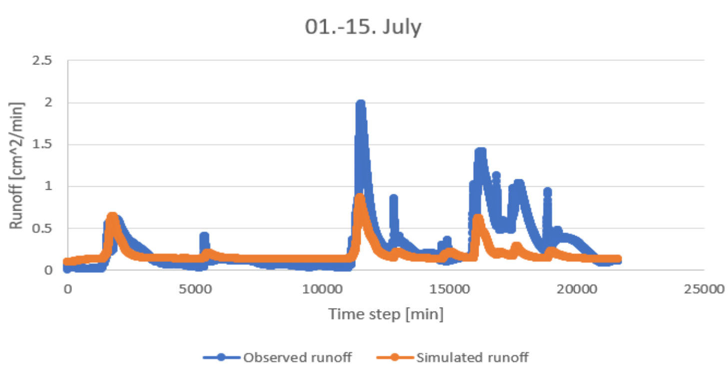
9 Appendixes

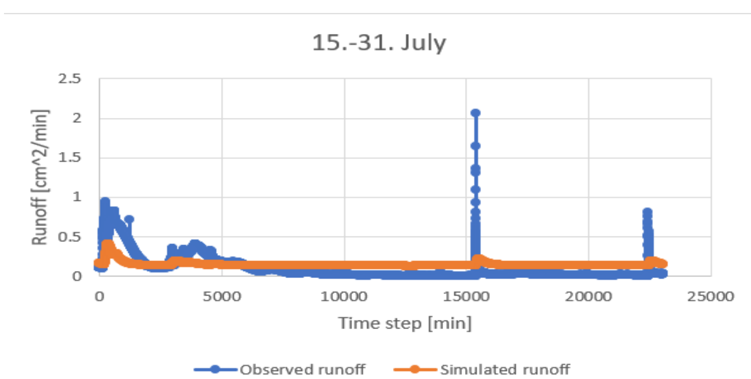
Appendix A Blue-grey calibration against water content measurements, validation against runoff

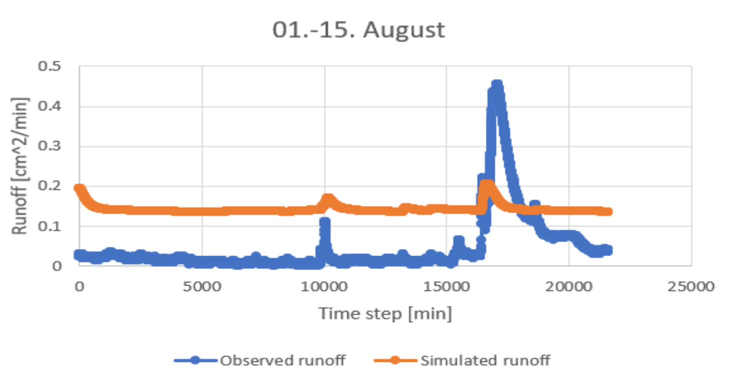
Soil hydraulic properties		Initial value	Optimized value
Residual water content	WCR	0.05	-
Saturated water content	WCS	0.606	-
First coefficient	ALPHA	0.25	0.16
Second coefficient	N	1.26	1.43
Saturated conductivity	CONDS	60 [cm/min]	-
Pore connectivity factor	L	0.5	-

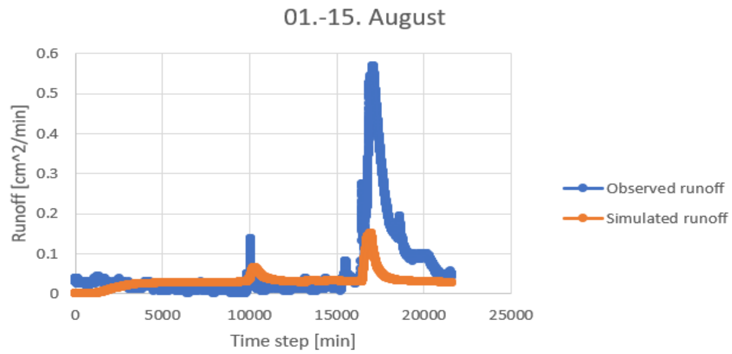
Calibration period



Validation period







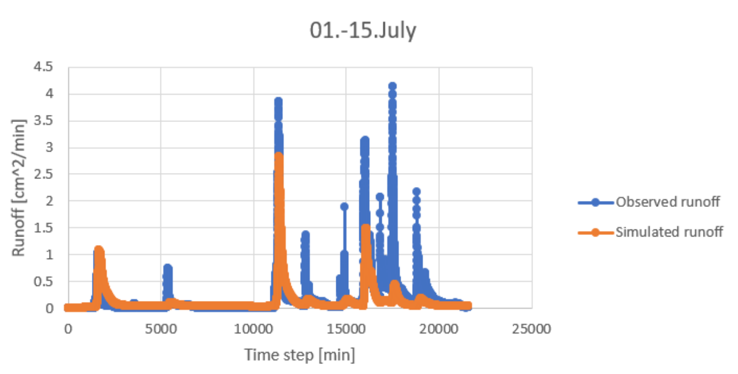
Error coefficients

Period	NSE	RSR
01.-15 July	0.79	0.46
16.-31. July	0.38	0.78
01.-15. August	-1.5	1.58

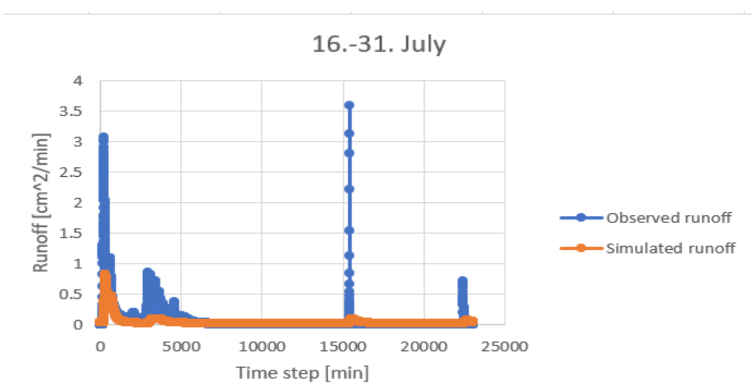
Appendix B Green calibration against water content measurements, validation against runoff

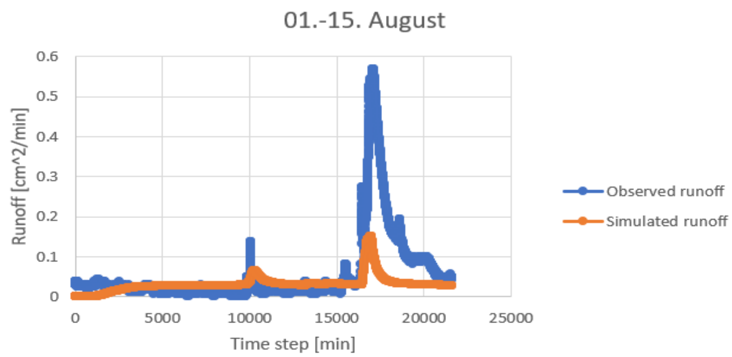
Soil hydraulic properties		Initial value	Optimized value
Residual water content	WCR	0.04	-
Saturated water content	WCS	0.66	-
First coefficient	ALPHA	0.25	0.16
Second coefficient	N	1.26	1.43
Saturated conductivity	CONDS	0.08 [cm/min]	-
Pore connectivity factor	L	0.5	-

Calibration period



Validation period





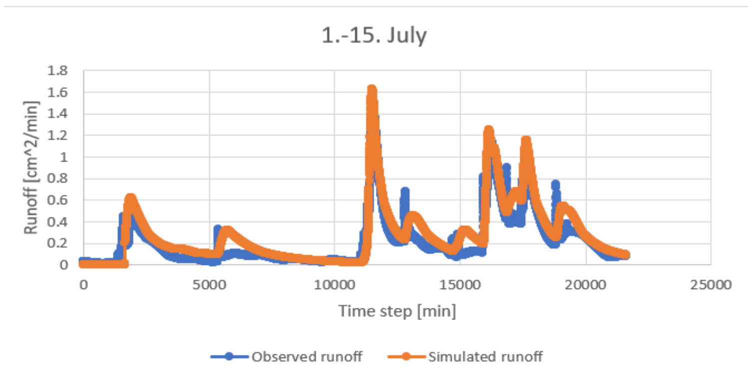
Error coefficients

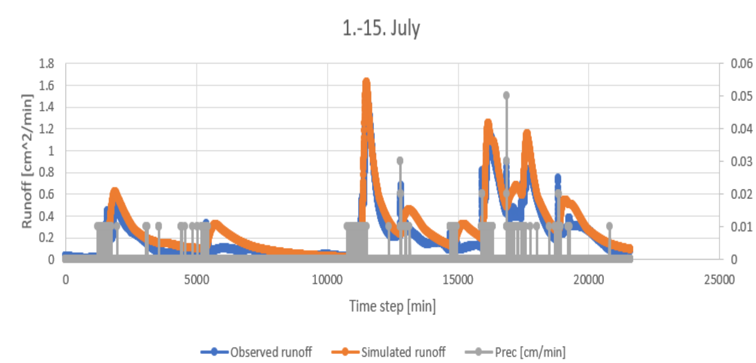
Period	NSE	RSR
01.-15. July	0.47	0.73
16.-31. July	0.29	0.85
01.-15. August	0.20	0.90

Appendix C Blue-green calibration and validation against runoff measurements

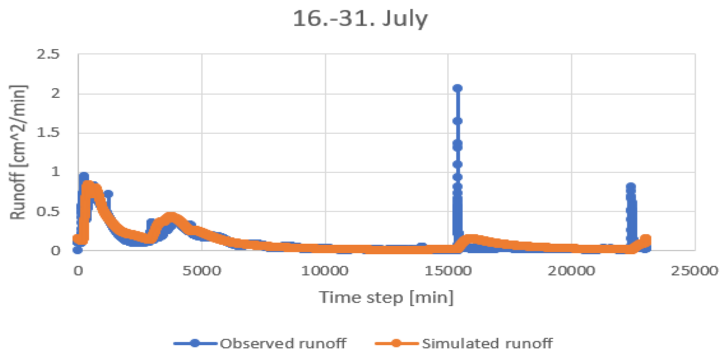
Soil hydraulic properties		Initial value	Optimized value
Residual water content	WCR	0.05	-
Saturated water content	WCS	0.606	-
First coefficient	ALPHA	0.16	0.26
Second coefficient	N	1.43	1.38
Saturated conductivity	CONDS	60 [cm/min]	19.3
Pore connectivity factor	L	0.5	-

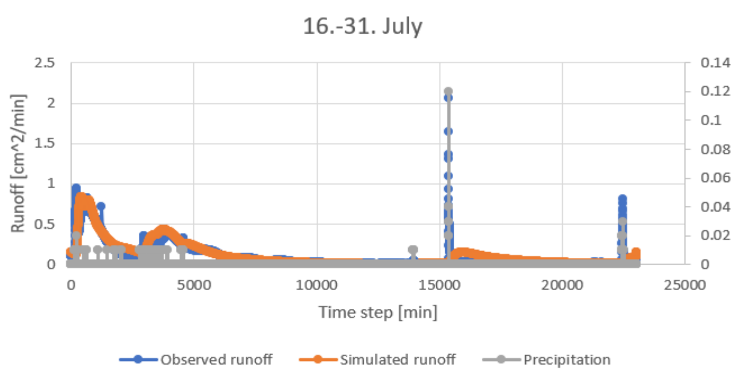
Calibration period

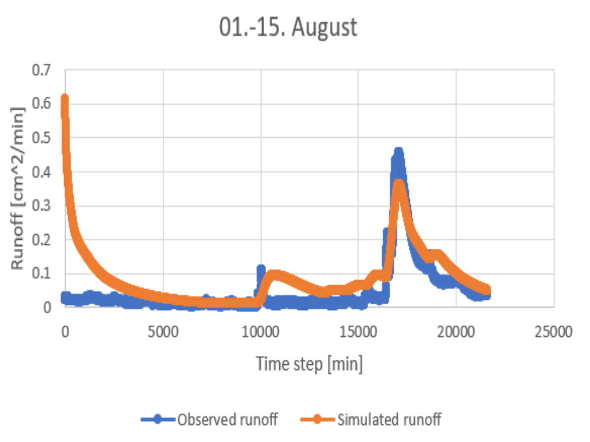


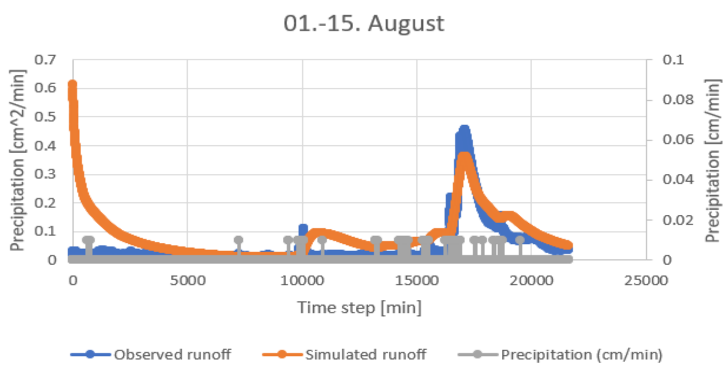


Validation period









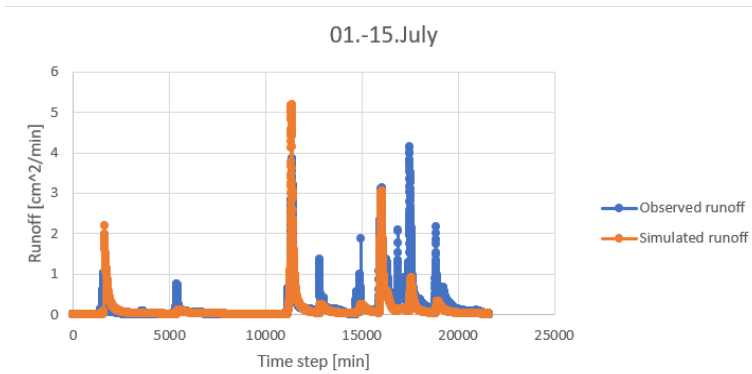
Error coefficients

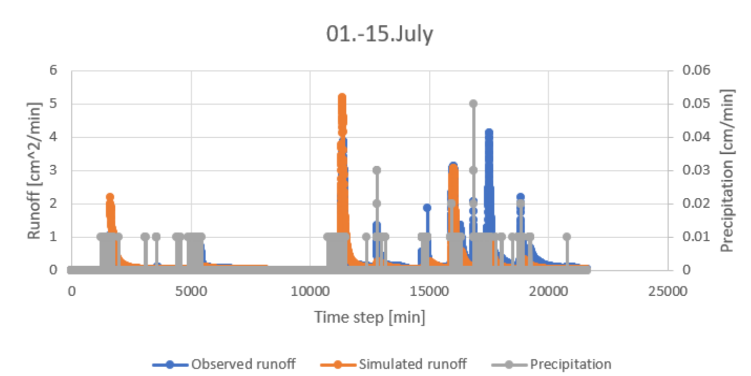
Period	NSE	RSR
01.-15 July	0.78	0.47
16.-31. July	0.81	0.43
1.-15. August (without 2500 first minutes)	0.75	0.50

Appendix D Green calibration and validation against runoff measurements

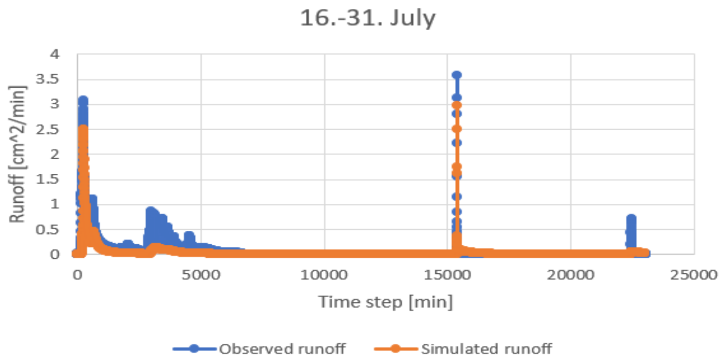
Soil hydraulic properties		Initial value	Optimized value
Residual water content	WCR	0.05	-
Saturated water content	WCS	0.66	-
First coefficient	ALPHA	0.16	0.33
Second coefficient	N	1.43	1.17
Saturated conductivity	CONDS	0.08 [cm/min]	0.07
Pore connectivity factor	L	0.5	-

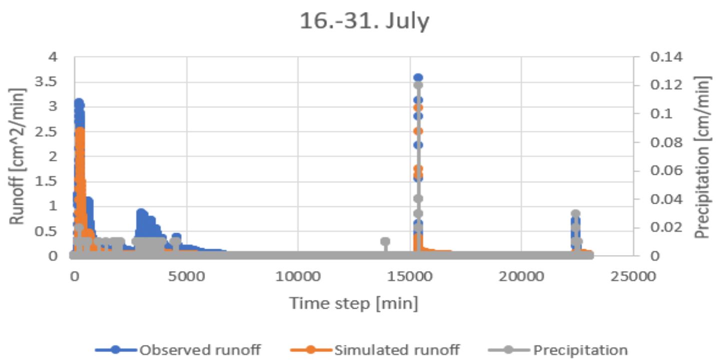
Calibration period

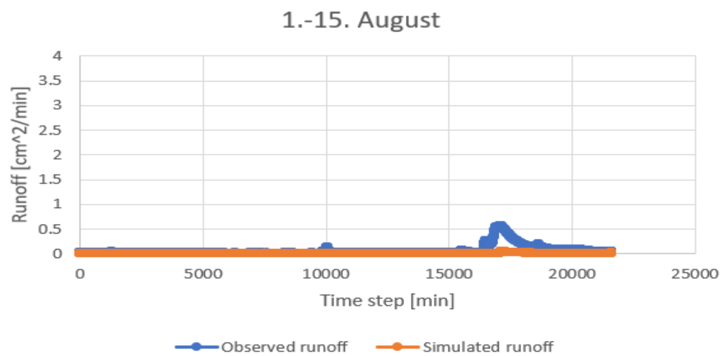


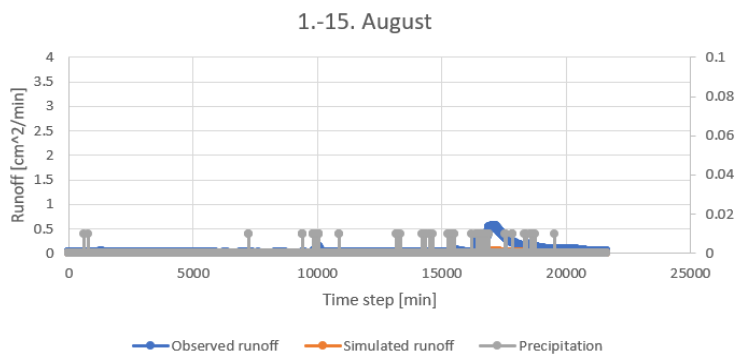


Validation period







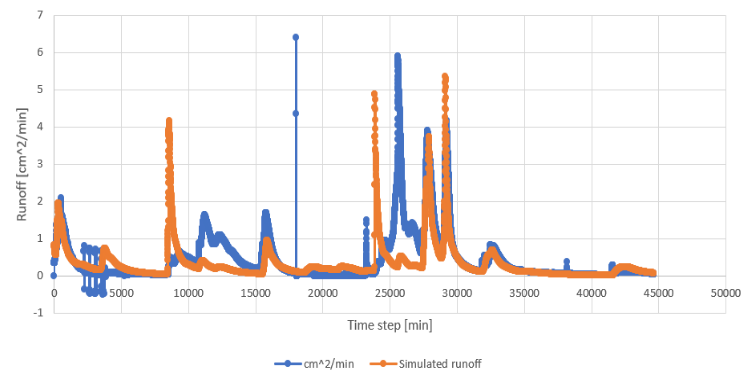


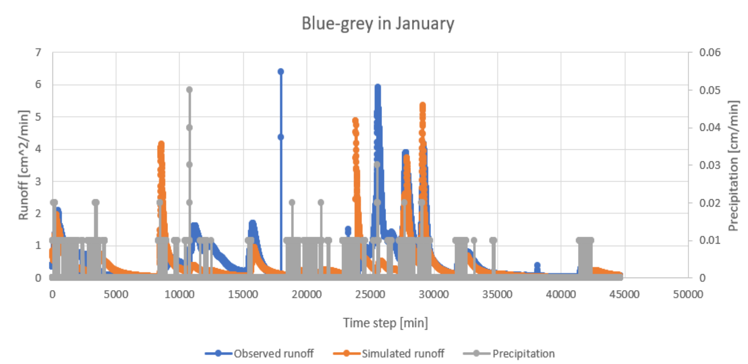
Error coefficients

Period	NSE	RSR
01.-15. July	0.60	0.63
16.-31. July	0.57	0.66
01.-15. August	-0.18	1.08

Appendix E Blue-green and grey winter period

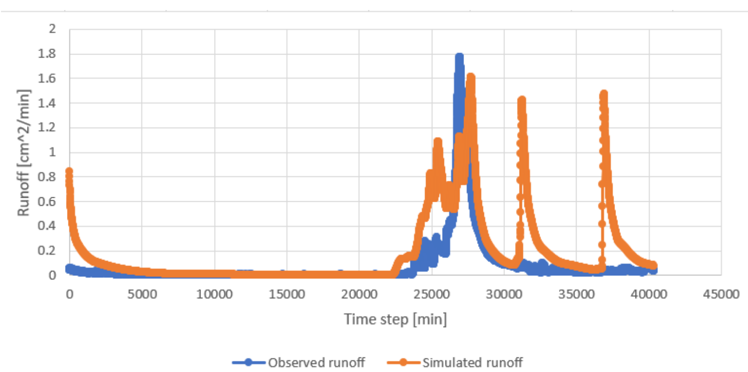
Blue-grey January

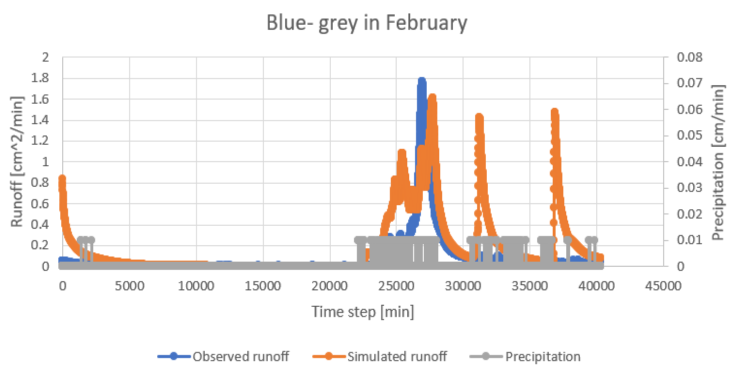




Period	NSE	RSR
January	0.21	0.89

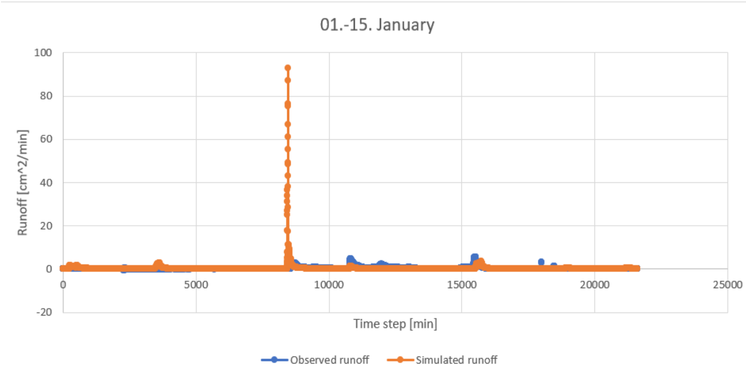
Blue-grey February

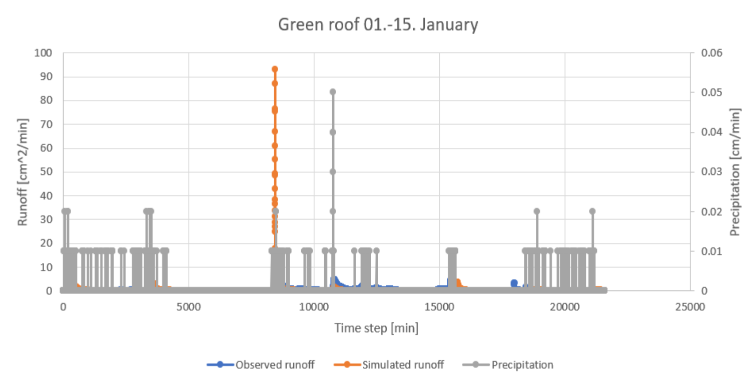




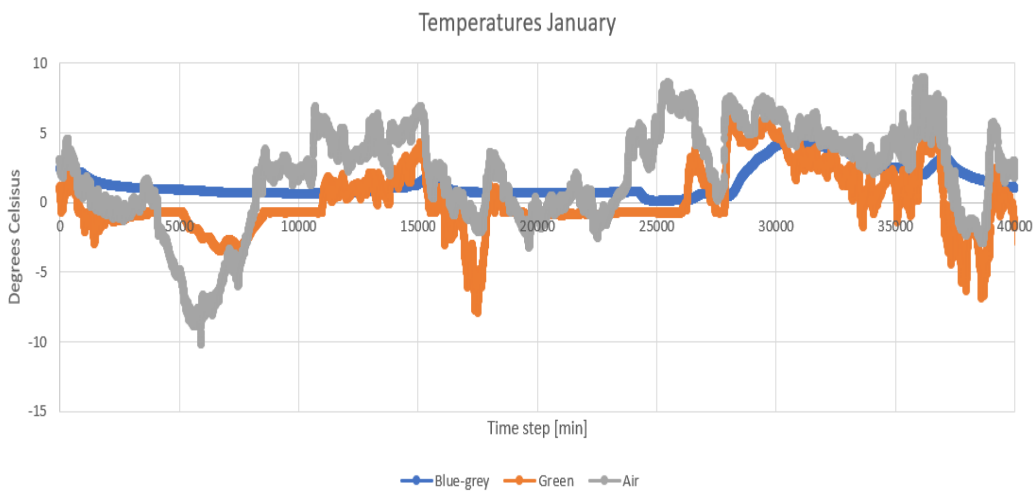
Period	NSE	RSR
February	0.31	1.14

Green January

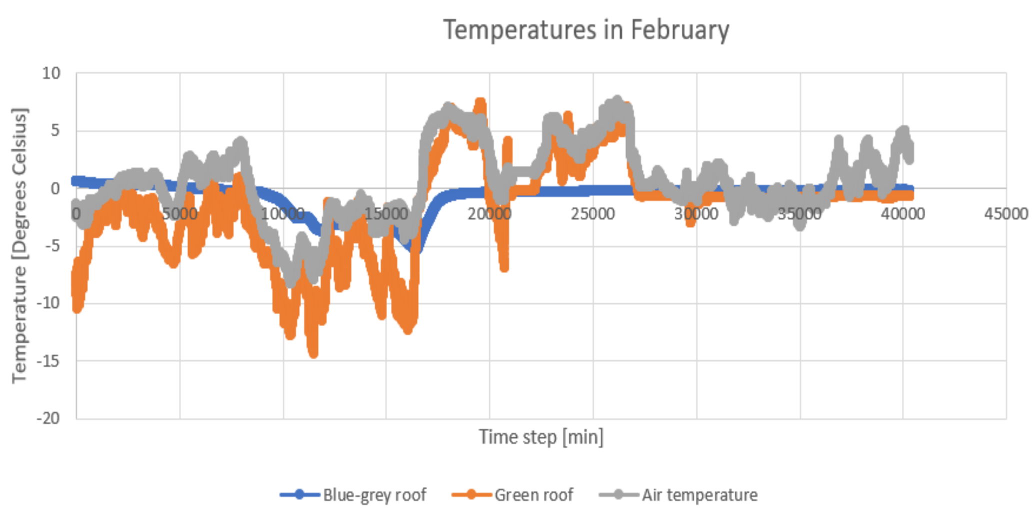




Temperatures in January



Temperatures in February



Appendix F Peak reduction, peak delay and volume reduction for selected events

Blue-grey roof

	Observed		
Events	Peak delay [%]	Peak reduction [%]	Volume reduction [%]
Event 1 (Early July)	15.33	93.17	39.56
Event 2 (Later July)	36.86	84.39	13.40
Event 3 (Late July)	10.17	99.14	39.88
Event 4 (Late August)	114.76	95.56	45.71
Event 5 (January)	81.07	80.24	52.18
	Simulated		
Events	Peak delay [%]	Peak reduction [%]	Volume reduction [%]
Event 1 (Early July)	56.00	93.90	38.83
Event 2 (Later July)	45.55	84.39	1.27
Event 3 (Late July)	927.11	99.80	-37.68
Event 4 (Late August)	114.33	96.44	46.05
Event 5 (January)	0.65	-30.30	-26.23

Green roof

	Observed		
Events	Peak delay [%]	Peak reduction [%]	Volume reduction [%]
Event 1 (Early July)	27.80	81.73	39.23
Event 2 (Mid July)	160.71	87.35	34.69
Event 3 (Late July)	-20.23	98.54	98.02
Event 4 (Late August)	130.47	94.46	29.95
Event 5 (January)	-	-	-
	Simulated		
Events	Peak delay [%]	Peak reduction [%]	Volume reduction [%]
Event 1 (Early July)	27.60	77.96	57.78
Event 2 (Mid July)	-83.33	97.93	83.68
Event 3 (Late July)	79.73	99.88	96.10
Event 4 (Late August)	124.67	99.47	94.89
Event 5 (January)	-	-	-