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Winter Modelling of Green Roofs in Cold Climates Using SWMM

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Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU), Department of Civil and Environmental Engineering, June 2020. This study is the end result of course TVM4905 Water and Wastewater Engineering: Master Thesis. The purpose of this thesis was to develop a suitable model for green roof winter simulations, with data from a monitored green roof located at Høvringen, Trondheim, as input.

The direction and topic of the study were chosen based on my interest in stormwater management and green roofs. I have made use of knowledge I have previously acquired in my studies, but in addition I have had to gain new knowledge through the last semesters to be able to execute this study. Before doing this assignment, I had little to no knowledge and experience with SWMM and hydrological modelling. Therefore, many hours were spent just learning the software, which I hopefully get to use moving on to the next chapter after graduating.

It would not be able for me to do this study without the help and tips from PhD Candidate Vladimir Hamouz and Candidate Elhadi Mohsen Hassan Abdalla. The same goes to my supervisor, associate Professor Tone Muthanna, at the Department of Civil and Environmental Engineering. I want to thank her for steering me into the right direction, giving me ideas, help and guidance through the work of this master thesis.

Finally, I want to extend my gratitude to Anette Overrein and Håvard Dahl Mediaas for the tedious work of proofreading my thesis.

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Abstract

Green roofs have been identified as a measure for reducing and delaying stormwater runoff in densely developed urban areas. Altough extensive work has been carried out to predict and improve their function, there is a lack of knowledge about green roof performance and function in cold and wet climates. Several modelling tools have shown good abilities to reproduce observed green roof runoff. Nevertheless, due to the lack of knowledge, few of these models are applied among practitioners. Johannessen et al. (2019) made a SWMM model with the aim to make a transferable model for green roofs, while winter data was left out of the calibration. This study will attempt to modify their model to be able to simulate runoff from winter precipitation and snow melt, whereas the objective is to (1) evaluate SWMMs ability to model snowmelt and rain-on-snow events from a green roof during cold periods, (2) perform a performances sensitivity analysis of the model under winter conditions and identify most sensitive parameters in the model and (3) suggest revised winter modelling routines for long-term continuous and event-based simulations. The model was modified using different parameter values taken from literature and similar studies, including adding a snow pack module. The model was assessed by comparing simulated runoff to observed runoff and precipitation, calculating NSE values and volume errors. A sensitivity analysis was conducted to identify sensitive parameters. It is found that the model generally works better for event-based simulations than long-term continuous simulations. The model shows good performance on rain and melting, but has an issue when it comes to snow events. It is observed that the model generates consistently too little runoff. Parameters in the soil layer were found to have the highest uncertainty, whereas porosity and field capacity showed highest uncertainty, followed be conductivity and conductivity slope. Parameters in the drainage mat and the snow pack were found to have low impact on the model uncertainty. It remains challenging to find an optimal level of complexity, making SWMM an accurate tool for winter modelling as well as being user friendly. One identified suggestion is to find a way make auto calibration possible in SWMM, as this could solve several issues and limitations without decreasing the level of complexity. Issues relating the large data and input demand, would still however remain unsolved.

Sammendrag

Grønne tak har blitt identifisert som et mulig tiltak for å redusere og forsinke avrenningen av overvann i tett utbygde byområder. Selv om det er utført omfattende arbeid for å forutsi og forbedre grønne tak sine funksjoner, mangler det fortsatt kunnskap om ytelse og funksjon for bruken av grønne tak i kaldt og vått klima. Flere modelleringsverktøy har vist gode evner til å reprodusere observert avrenning av grønt tak. På grunn av mangelen på kunnskap er likevel få av disse modellene brukt blant forbrukere og utbyggere. Johannessen et al. (2019) utviklet en SWMM-modell med den hensikten å lage en overførbar modell for grønne tak. Vinterdata ble holdt utenfor kalibreringen i den studien. Denne studien vil prøve å endre modellen slik at den kan simulere avrenning fra vinternedbør og snøsmelting. Målet er å (1) evaluere SWMM sin evne til å modellere snøsmelting og regn-på-snø-hendelser fra et grønt tak i kalde perioder, (2) utføre en prestasjonsfølsomhetsanalyse av modellen under vinterforhold, identifisere de mest sensitive parameterne i modellen og (3) foreslå reviderte vintermodelleringsrutiner for langsiktige kontinuerlige og hendelsesbaserte simuleringer (3). Modellen ble endret ved å bruke andre parameterverdier hentet fra litteratur og lignende studier, inkludert å legge til en snø-modul. Modellen ble vurdert ved å sammenligne simulert avrenning med observert avrenning og nedbør, beregne NSE-verdier og volumfeil. En sensitivitetsanalyse ble gjennomført for å identifisere sensitive parametere. Det er funnet at modellen generelt fungerer bedre for hendelsesbaserte simuleringer enn langsiktige kontinuerlige simuleringer. Modellen viser god ytelse på regn og smelting, men sliter mer når det kommer til snø. Modellen genererer gjennomgående for lite avrenning. Parametere i jordlaget ble funnet å ha høyest usikkerhet, hvor porøsitet og feltkapasitet viste høyest usikkerhet, etterfulgt av ledningsevne og conduticity slope. Parametere i dreneringsmatten og snø-modulen ble funnet å ha liten innvirkning på modellusikkerheten. Det forblir utfordrende å finne et optimalt nivå når det kommer til kompleksitet, med tanke på å gjøre SWMM til et nøyaktig verktøy for vintermodellering samt å la det forbli et brukervennlig program. Et forslag er å utvikle en funksjon for automatisk kalibrering i SWMM, da dette kan løse flere problemer og begrensninger uten å redusere kompleksitetsnivået. Problemstillinger knyttet til et stort behov for datamengde og input, vil imidlertid fortsatt være uløst.

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List of Abbreviations

A1	Pervious runoff sub-area
A2	Impervious w/ depression storage runoff sub-area
A3	Impervious w/o depression storage runoff sub-area
A	Area
ADC	Areal Depletion Curves
ASC	Areal snow coverage ratio
ATI	Antecedent temperature index
BGR	Blue green roof
CC	Cold content
COLDC	Cold content depth
DHM	Melt coefficient
DHMAX	Melt coefficient for June 21
DHMIN	Melt coefficient for December 21
EBM	Energy balance model
FW	Free water depth
FWFRAC	Free water fraction that produces liquid runoff from the snow pack.
GR	Green roof
HEC-HMS	Hydrologic Engineering Centre- Hydrologic Modelling System
HOV	Høvringen wastewater treatment plant
HOV3	Høvringen 3: Full scale blue green roof test site
i	Precipitation rate
IMELT	Immediate melt

LID	Low Impact Development
LID-GR	Green roof module in SWMM
NSE	Nash–Sutcliffe model efficiency coefficient
RI	Overall equivalent precipitation input
RNM	Negative melt ratio
SA1	Pervious snowmelt sub-area
SA2	Plowable impervious snowmelt sub-area
SA3	Remaining impervious snowmelt sub-area
SCF	Rain gage snow capture factor
SI	Depth at which surface remains 100% snow covered
SMELT	Snowmelt rate
SNN	Fraction of impervious area that is plowable
SNOTMP	Dividing temperature between snowfall and rainfall
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
Ta	Air temperature
Tbase	Temperature at which snow begins to melt
TIPM	ATI weighting factor
U	Wind speed
WEPLOW	Depth that initiates snow redistribution
Win-SLAMM	Win-Source Loading and Management Model
WSNOW	Sow pack depth

1 Introduction

1.1 Background

Due to global warming, the frequency and intensity of large rainfall events are expected to increase, and the increasing urbanization results in natural soil being lost and replaced with impervious surfaces. Loss of natural soil and vegetation increases stormwater runoff, runoff time, peak flows and is consequently affecting the hydrologic cycle. It is assumed that roofs may account for approximately 40 – 50% of the impermeable urban surface area in developed cities (Stovin et al., 2012). Therefore, there is a great potential for improved stormwater management by replacing impermeable roofs with pervious surfaces, such as green roofs.

Green roofs can possibly have a great effect on the stormwater retention and detention. However, the performance depends on various factors, whereas climate is probably one of the most crucial ones. Even though extensive work has been carried out to predict and improve their function, there is a lack of knowledge about green roof performance and function in cold and wet climates (Johannessen et al., 2017). Several modelling tools have shown good abilities to reproduce observed green roof runoff, especially when simulating green roof runoff from specific small-scale rest roofs. Nevertheless, due to the lack of knowledge, few of these models are applied among practitioners, who need generic tools to estimate runoff from green roofs to further combine with other stormwater measures for system design purposes (Johannessen et al., 2019). A model that combines this is therefore preferable.

Johannessen et al. (2019) did a study where they investigated the model performance of the EPA Storm Water Management Model (SWMM) Green Roof Module (LID-GR), with respect to long-term retention performance and event-based reproduction of the runoff hydrograph across geographical different climates. Their ambition was to use the SWMM green roof module to make a generic tool by comparing estimated parameters across different sites, roof build-ups and geometries. The transferability of parameters in the study was investigated by cross-validation of parameters among the study sites and by implementing a multi-site calibration procedure. Johannessen et al. (2019) found that the individual models in the study reproduced runoff hydrographs well, with Nash–Sutcliffe Model Efficiency

(NSE) Coefficients between 0.56–0.96. However, the long-term modelling showed relatively large volume errors, most likely due to insufficient representation of evapotranspiration in the model. All winter data from the field sites was excluded from the study due to challenges with snow accumulation and melt. Nevertheless, challenges associated with winter is a significant factor in cold climates and this cannot be excluded if one wants to make a model intended for colder climates like in Norway. Therefore, to be able to produce a generic tool for practitioners to use in cold and wet climates, winter data also need to be investigated and calibrated for.

This thesis is a continuation of a specialization project where it was concluded that the existing calibrated model from Johannessen et al. (2019) did not perform well during winter conditions as it is and had to be recalibrated using winter data and a snow pack function. This thesis will therefore attempt to develop the existing model from Johannessen et al. (2019) and see if SWMM is an adequate tool for modelling snowmelt and rain-on-snow events from a green roof during cold periods.

1.2 Objective

As revealed initially, the objective is to modify the existing green roof model from Johannessen et al. (2019) to perform better during winter conditions and to evaluate if SWMM is an adequate tool for modelling snowmelt and rain-on-snow events. It will be done by applying the EPA Storm Water Management Model (SWMM). This provides an opportunity to evaluate SWMMS ability to model retention and runoff during cold periods and attempt to identify limitations and sensitive parameters to the model so that the result can be used as an aid make the model fit for winter modelling of green roofs.

The objectives of the study are listed as follows:

1. Evaluate SWMMs ability to model snowmelt and rain-on-snow events from a green roof during cold periods.
2. Perform a performances sensitivity analysis of the model under winter conditions and identify most sensitive parameters in the model.
3. Suggest revised winter modelling routines for long-term continuous and event-based simulations.

1.3 Limitations

Due to changes done to the green roof in June 2018, this study will include data from one winter only: winter 2018-2019. Data from the latest winter 2019-2020 is not yet complete. Johannessen et al. (2019) used several roofs around the country, with various structures and build up when attempting to make a transferable model. In this case only one of the roofs used in their study will be used for calibrating the model: HOV3. This roof has however changed since they used it. HOV3 used to be a green roof with 30 mm substrate but was changed to a blue green roof with 30 mm substrate and an additional layer with 100 mm LECA.

The sensitivity analysis in this thesis had to be done manually and is therefore one of a simpler form. Thus, suggested parameters from the analysis should be examined and investigated further for future work and calibration of the model. The results are however adequate for identifying sensitive parameters.

1.4 Structure

This thesis is written in the form of a scientific report. The thesis has six main chapters. Chapter 1 gives a brief introduction to the topic and problem. Chapter 2 presents information and theoretical background of the topics. Chapter 3 describes the method and materials used to conduct the study. For establishing narrative clarity and to make this thesis a complete and independent unit, much of the content from Chapter 2, and some from Chapter 3, is a replication of the specialization project. However, with suitable extensions where it was deemed necessary. Chapter 4 presents the results found when running and calibrating the model. In chapter 5, the findings from chapter 4 are interpreted, explained, and discussed. Finally, the study is summed up in chapter 6; Conclusion. Extra material can be found in the Appendix, at the end.

2 Theoretical Framework

2.1 Blue green roof

Blue Green Roofs (BGR) are vegetated roofs combined with elements of stormwater management in the roof structure, as some suggest that a green roof becomes a BGR if it is built as part of a stormwater management system (Andenæs et al., 2018). A BGR is basically a green roof with an extra water storage layer, beyond what is required for the plants to survive (Shafique et al., 2016). Being a LID-facility, green roofs have the ability to handle and treat stormwater at its source, preventing stormwater sewer systems from overflowing and exciting pipes from overloading. In addition to delayed runoff, reduced peak flows and flooding events green roofs have proven to have a positive effect when concerning urban heat island effect, energy conservation, biodiversity, pollution, noise reduction and the lifespan of the roof membrane (Getter and Rowe, 2006). BGR can be installed on existing rooftops if the construction of the building allows it. BGR have been found economically beneficial, due to their water retention capacities and a positive influence on human well-being (Thodesen et al., 2018). Given their performance in stormwater management, BGR are found to particularly be economically favourable for cities (Jansson, 2014). The BGR will also extend the service life of the roof membrane, because the vegetation and substrate will reduce the temperature fluctuations at the roof membrane (Andenæs et al., 2018).

2.2 Høvringen

Høvringen Wastewater Treatment Plant (HOV) is a test site with three full scale test areas established to develop solutions and products to deal with stormwater. The test site has a traditional black roof, a blue-grey roof, and a blue-green roof. Each roof is equipped with their own meteorological measurement station and an advanced system for measuring the amount of water passing through the roof drain from each of the test areas (Klima 2050, 2019). The main aim of the HOV pilot project is to investigate how the local climate affects roofs, developing materials, solutions and concepts for blue-green and blue-grey stormwater measures, and provide examples and data for use in planning of future stormwater management. Not only are the results from HOV used to plan roofs, but could also be used during the development of other outdoor facilities, such as rain beds and parks, which will be important for management of surface water in urban areas in the future (Klima 2050, 2019).

The pilot is owned by Trondheim Municipality, but has made HOV available to Klima 2050, who are responsible for the research related to the pilot project (Trondheim kommune, 2017). NTNU and SINTEF have been responsible for the planning and execution of instrumentation, measurement setup and data (Klima 2050 and Trondheim kommune, 2017).

2.3 Urban Green Roof Runoff Modelling

2.3.1 In General

A runoff model is a mathematical model describing the water in – water out relations of a subcatchment and calculates the conversion of precipitation into runoff. The idea of an urban green roof runoff model is to be able to predict the hydrologic performance and the runoff given an amount of precipitation. However, it remains difficult to predict the hydrological performance in general as urban hydrology is a complex system. The model must account for an array of possible physical processes, such as surface runoff, infiltration, groundwater, snowmelt, flow routing, surface ponding, and water quality routing (Hamouz and Muthanna, 2019).

Several approaches for modelling performance for Green Roofs (GR) and attempts to simulate GR runoffs have been explored. Models can either be data based, where runoff is calculated as an empirical function of rainfall or process based, where the flow is calculated from the green roof water balance (Carson et al., 2017). Regression models can make good runoff predictions at specific sites, but have not proven to be transferable to other roofs, unless they are similar in build-up, geometries and climate conditions (Carson et al., 2013). Conceptual water balance models have been proven successful for modelling green roof retention. However, these models are highly dependent on adequate implementation of evapotranspiration estimates (Johannessen et al., 2017). Just like regression models, conceptual models are not transferable to other green roofs with different materials, build-up and geometry, because they rely on laboratory or field testing (Johannessen et al., 2019). Physically based models are considered useful in reproducing GR runoff. They include the possibility to model several consecutive substrate layers, which is optimal for modelling a green roof, which may well be a simple system, but consist of several layers where all the processes within each layer must be controlled dynamically (Hamouz and Muthanna, 2019). Physically models are based on a several physical parameters, that can be defined from laboratory measurements or from model calibration (Johannessen et al., 2019). This means that physically models can potentially have a high accuracy, but due to high computational requirements and challenging calibration with variability in calibrated parameters this can be difficult to achieve (Soulis et al., 2017).

Existing models have diverse capabilities and applications, making it complicated to select the best-suited model for a particular application (Jayasooriya and Ng, 2014). However, when it comes to modelling, LID structures and GR the selection of models decreases. HEC-HMS, Hydrologic Engineering Centre- Hydrologic Modelling System, is a hydrologic rainfall-runoff model developed by the U.S. Army Corps to model the hydrological response of dendritic watershed systems (Feldman, 2000). HEC-HMS combined with HEC-RAS is used for calculation of both the hydrology and hydraulics of a stormwater system or network (Minnesota Stormwater Manual Contributors, 2020).

MIKE Urban is a modelling system for analysis of urban drainage and sewer systems, and is a parent computer program, which is powered by SWMM, Model for Urban Sewers (MOUSE) and a water distribution model (DHI Inc, 2017a). When using MIKE Urban for urban green roof modelling, the SWMM module is the component in which the LID is modelled. MIKE Urban have extra features to SWMM which allows for 2D presentation of flooded plane by linking SWMM and MIKE Urban FLOOD 2D model (DHI Inc, 2017b).

SWMM is a dynamic rainfall-runoff and water quality simulation model, for hydrology and hydraulic modelling of catchments (Kaykhosravi et al., 2018). SWMM includes LID modelling tools and is primarily, but not exclusively, for urban areas (Minnesota Stormwater Manual Contributors, 2020). SWMM is one of the most popular models among researchers, due to the diversity of hydrologic and hydraulic computation methods and free access to the model. SWMM allows the user to control each layer of the GR dynamically, simulate snowmelt and has shown promising results when simulating green roof runoff from specific small-scale test roofs. However, there are concerns on the generality of the SWMM green roof module as a design tool, due to the large variability in obtained model parameters and volume errors when trying to make a transferable generic model (Johannessen et al., 2019).

SWAT (Soil and Water Assessment Tool) primary objective is to quantify and predict the impact of land management practices in large complex watersheds, and is mainly a climatic and hydrological process model with a major focus on sediment and contaminant transport (Arnold et al., 2011). Because of its capability of modelling BMPs and LIDs, SWAT is one of the most popular models for hydraulic modelling of surface runoff in large-scale basins. SWAT also presents one of the most complex water balance models, in terms of hydrological modelling (Kaykhosravi et al., 2018).

Win-SLAMM (Win-Source Loading and Management Model) were developed for interpreting the relationship between runoff quality and the sources of pollutants in urban areas (Pitt and Voorhees, 1995). The main focus of the model is on small storm hydrology and particulate wash off (Minnesota Stormwater Manual Contributors, 2020). Win-SLAMM is simplified, but includes a cost calculation value and an uncertainty analysis tool (Jayasooriya and Ng, 2014).

A more detailed presentations of the LID models above, which were found to be able to model GR, can be found in Appendix A. The presentation shows the level of complexity, capabilities, applications and etc. of the respective models.

2.1.2 Urban Green Roof Runoff Winter Modelling

Research on green-blue solutions in general is found to be rich, but is proven to be limited concerning the specific conditions in cold climates (Thodesen et al., 2018). Modelling urban green roof runoff is a complex procedure in itself, and winter brings more challenges as snow may accumulate on roofs and ice freezes in the substrate. Winter also comes with highly fluctuating temperatures over relatively short time periods, widely varying amounts of precipitation, spring snowmelt and daily freeze-thaw cycles (Andenæs et al., 2018). Furthermore, flood risk in urban areas due to mixing of rainfall and snowmelt when heavy snowfall is followed by rainfall events (Moghadas et al., 2018). Rainfall events on snowmelt baseflow may produce higher runoff peaks and volumes as well as add to the melt rate of the snow. When it comes to long-term continuous simulations, runoff is distributed quite differently in time between the cases when snowmelt is and is not simulated. The water storage that occurs during winter months in colder climates cannot be simulated without including snowmelt (Rossman and Huber, 2016a).

There are several ways to model urban snow cover and snowmelt. However, finding an optimal level of complexity is proven to be challenging. More sophisticated models do not necessarily provide better results in a diverse urban environment, as they are highly dependent on sufficient data (Moghadas et al., 2016). When simulating snow processes, energy balance method and degree day method, which have achieved fairly good simulations compared with the observed data, are often applied (Li, 2019). However, because of the dramatic variability conditions, it is found that the energy balance model (EBM) is more suitable for open areas when sufficient data source is accessible (Anderson, 1976). The degree-day method does not have the excessive data requirements like EBM has. They are found to be reliable for computing total snowmelt depths for longer periods, but need to be combined with an adequate snowmelt runoff model to measure the daily snowmelt depths (Rango and Martinec, 2007). It is found that urban runoff models with snowmelt subroutines offered best operational flexibility, however in order to achieve satisfactory simulations modifications and guidance on input values is required (Moghadas et al., 2016). While some models are developed for highly specific purposes when it comes to challenges with winter and snow, snowmelt models can also be featured as components of more comprehensive hydrological models, like in SWMM, where the model is intended for general use (Moghadas et al., 2016). SWMM also features options for representation of plowing and piling of snow in urban areas, and the change in the nature of its albedo and density, which are important considerations (Rossman and Huber, 2016a). Other significant considerations in urban snowmelt modelling are temperature, precipitation, wind, radiation, topography, vegetation, insulation conditions and anthropogenic activities. All these factors influence the snow pack distribution, making urban snowmelt modelling challenging and the snow characteristics in urban areas vary substantially from rural areas (Bengtsson and Westerström, 1992). Semadeni-Davies (2000) performed a review of snowmelt components of urban drainage models. Three models using degree-day methods was used was reviewed: SWMM (version 4), MouseNAM (Danish Hydraulic Institute, 1994) and HBV (Bergström, 1976, Lindström et al., 1997). Semadeni-Davies (2000) found that limited information was available regarding coefficients in urban areas and that urban snowmelt routines may not represent urban conditions well, since these routines have been adapted directly from models developed for rural situations.

2.4 SWMM

2.4.1 In General

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model, developed in 1971, used for single event or continuous simulation of runoff quantity and quality from primarily urban areas (Rossman, 2015). Version 5 of SWMM was produced by the Water Supply and Water Resources Division of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory. Version 5 provides an integrated environment for editing study area input data, running hydrologic, hydraulic and water quality simulations, and viewing the results in a variety of formats, like color-coded drainage area and conveyance system maps, graphs, tables, profile plots and statistical frequency analyses (Rossman, 2015). SWMM is widely used throughout the world for planning, analysis and design related to storm water runoff. By using precipitation as input, SWMM simulates runoff and pollutant loads for mainly urban subcatchments (Carson et al., 2017).

2.4.2 Green Roof Modelling in SWMM

The latest version of SWMM includes a new low-impact development green roof module, LID-GR, which makes it possible to model the hydrological performance of a GR with a soil moisture model by directly defining the physical parameters of the three layers of the roof; surface layer, substrate layer and drainage layer (Peng and Stovin, 2017). The surface layer ensures runoff generation and infiltration into the soil or storage layer. The surface layer will optionally provide a surface storage. The storage layer provides storage volume for stormwater retention. The drainage layer conveys the percolated stormwater away from the roof (Leimgruber et al., 2018). All layers are defined by a set of parameters (Johannessen et al., 2019). It is found that the substrate and drainage layers are most important when modelling detention routines, because there is usually no ponding on a GR due to the high permeability found in GR soils (Krebs et al., 2016, Peng and Stovin, 2017). Figure 1, adapted from Leimgruber et al. (2018), illustrates SWMM's layer concept and simulated processes for a green roof.

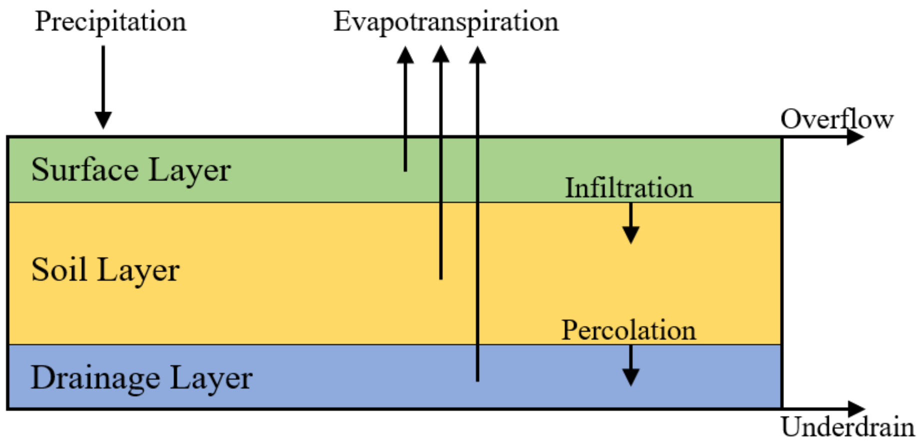

Figure 1: Layer concept and simulated processes in SWMM for a green roof

As Figure 1 is demonstrating, SWMM considers the processes of runoff, infiltration, and evapotranspiration, and subsequently the water balance can be calculated like this (Leimgruber et al., 2018):

$$\Delta S + GR = P - ET - R \tag{2.1}$$

where ΔS is the change in system storage, GR is the groundwater recharge, P is the precipitation, ET is the evapotranspiration and R is the runoff volume given by the overflow and underdrain.

2.4.3 Snowmelt Modelling in SWMM

Moghadas et al. (2016) conducted a review of models and procedures for modelling urban snowmelt and found that, among the 14 models reviewed, SWMM was one of the most comprehensive urban models to simulate precipitation runoff, including snowmelt, from an urban area. Much because of its spatial considerations and its ability to simulate all parts of the catchment.

A snowmelt routine was placed in SWMM for single event simulation as part of a broad program of testing and adaptation to Canadian conditions (Rossman and Huber, 2016a). The current SWMM implementation uses the Canadian SWMM snowmelt routines as a starting point and extends their capabilities to model long-term continuous simulations. In addition, features were added to adapt the snowmelt process to urban conditions, since the snowmelt routines had been adapted for rural situations.

There are many variables and parameters involved when calculating snowmelt, making it a complicated routine. To help reduce the amount of input provided by the user, SWMM uses a snow pack object to bundle together a common set of these parameters that can be applied to an entire group of subcatchments (Rossman and Huber, 2016a).

SWMM separates a subcatchment into three distinct sub-areas for computing runoff. Pervious area (A1), impervious with depression storage (A2) and an area for impervious without depression storage (A3). Snowmelt is computed in the same way where the partitioning is made to facilitate the modelling of the areal depletion phenomenon and snow removal operations. The areas are separated in the same fractions of pervious and total impervious areas as for runoff. However, the impervious area is divided based on snow removal capability instead of dividing the impervious area on the presence or absence of depression storage. SWMM therefore separates a subcatcment into one pervious area (SA1), plowable impervious area (SA2) and one remaining impervious area (SA3) when calculating snowmelt. Each of the fractions, SWMM keeps a separate accounting for snow accumulation and melting. At the start of each time step, calculations of snowmelt are made. Then the net precipitation over the plowable and remaining impervious areas are summed up. To calculate the runoff, the net precipitation is then redistributed between the fractions of impervious areas (A2 and A3). The pervious area for runoff (A1) and snowmelt (SA1) are the same, and the snowmelt result over SA1 can be directly used to calculate the runoff in A1 (Rossman and Huber, 2016a).

SWMM determines snowfall rates directly from precipitation inputs by using a dividing temperature parameter SNOTMP. If the current air temperature is at or below SNOTMP, the precipitation falls as snow. Otherwise it falls as rain. In natural areas, a surface temperature of 1° to 2°C provides the dividing line between equal probabilities of rain and snow (Eagleson, 1970). Due to warmer surface temperatures the separation temperature might need to be somewhat lower in urban areas (Rossman and Huber, 2016a). In many models, the point in which the water phase changes from liquid to solid, is predefined and cannot be changed by the user, whereas in SWMM the user can set a modified constant freezing point value into the model (Moghadas et al., 2016).

SWMM determines snowmelt by using a degree-day type equation during dry weather and a heat balance equation during rainfall periods. The latter equation makes an adjustment for wind speed, where you have higher melt rates at higher wind speeds. Moghadas et al. (2016) found that SWMM was the only model allowing inclusion of the wind speed, which is an important factor for snow on roofs. The coefficients used in the degree-day melt equation vary sinusoidally, from a maximum on June 21 to a minimum on December 21. In addition, a record of the cold content of the snow is maintained. Thus, before melt can occur, the pack must be “ripened,” that is, heated to a specified base temperature, Tbase. Prediction of melt follows from prediction of the heat storage of the snow pack. Energy budget techniques are the most exact formulation since they evaluate each of the heat budget terms individually, requiring as meteorological input quantities such as solar radiation, air temperature, dew point or relative humidity, wind speed, and precipitation. Assumptions must be made about the density, surface roughness and heat and water storage (mass balance) of the snow pack as well as on related topographical and vegetative parameters. Further complications arise in dealing with heat conduction and roughness of the underlying ground and whether it is permeable.

The computations for snowmelt in SWMM are presented in detail in the reference manual for SWMM: Volume I - Hydrology (Revised) (Rossman and Huber, 2016a). Their computation scheme for snowmelt can be found in Appendix B but will also be described in the following.

When calculating snowmelt in SWMM the melt coefficient DHM for each snow pack surface for the current day of the year is computed using following equation:

$$DHM = \left(\frac{DHMAX + DHMIN}{2}\right) + \left(\frac{DHMAX - DHMIN}{2}\right) \cdot \sin\left(\frac{\pi}{182}(day - 81)\right) \tag{2.2}$$

where DHMAX is the maximum melt coefficient, occurring June 21 (mm/hr-°C), DHMIN is the minimum melt coefficient, occurring Dec. 21 (mm/hr-°C) and *day* is the number of the day of the year. The immediate melt IMELT on each surface is set to 0. If the air temperature (T_a) is lower or equal to the dividing temperature SNOTMP the precipitation will fall as snow and the model will update the snow pack depth WSNOW on each snow surface:

$$\mathrm{WSNOW} \leftarrow \mathrm{WSNOW} + \mathrm{i} \times \mathrm{SCF} \times \Delta\mathrm{t} \tag{2.3}$$

where SCF is the rain gage snow capture fraction (ratio) and *i* is the precipitation rate (mm/h). If the WSNOW over a snow surface is below 0.025 mm (0.001 inches) the entire pack is converted into immediate melt:

$$\mathrm{IMELT} \leftarrow \mathrm{IMELT} + \frac{\mathrm{WSNOW} + \mathrm{FW}}{\Delta\mathrm{t}} \tag{2.4}$$

where FW is the free water depth (mm water equivalent). The pack’s state variables are reset to 0.

Albedo is one of the most important urban snow cover characteristics. SWMM includes albedo change in the snowmelt algorithm through a time-varying snowmelt coefficient, and was the only model in the review by Moghadas et al. (2016) with this capability to be design for not only non-urban conditions, but also urban conditions. To compute the areal snow coverage ratio, ASC, for the pervious (SA1) and non-plowable impervious snow surfaces (SA3), SWMM uses Areal Depletion Curves (ADC), which defines the extent of snow cover in the catchment and changes as the melting season progresses. ADC supplied for these surfaces is used to define the areal extent of snow over the catchment area and to compute a new areal snow coverage ratio ASC. ASC for the plowable impervious surface is always 1.0. There are four different cases that can occur when computing ASC during the snowmelt calculations at a particular time step. The first case is if WSNOW = 0 and there is no snow accumulation, ASC and AWE is set to 0. The second case is when the updated snow accumulation WSNOW is greater than the SI. SI is the depth at which surface remains 100% snow covered (mm). In this case both ASC and AWE are set to 1.0. The third case is when there is snowfall during the time step. ASC is in this case set to 1.0. To find the parameters of a temporary linear ADC, the AWE value for the accumulated depth at the start of the time step is found using following equation:

$$\mathrm{AWE} = \frac{\mathrm{WSNOW1}}{\mathrm{SI}} \tag{2.5}$$

where WSNOW1 is the accumulated depth before the new snowfall was added on. The ADC is used to look up the areal coverage SBA for this prior AWE value. The relative depth SBWS is then calculated at which 75% of the new snow still remains, meaning 25% has melted:

$$SBWS = AWE + \frac{0.75(\mathrm{WSNOW}-\mathrm{WSNOW1})}{\mathrm{SI}} \tag{2.6}$$

AWE, SBA and SBWS is saved for use in the fourth case. The fourth case is when the accumulated snow depth WSNOW is below SI and there is no snowfall. AWESI is defined as the current ratio of WSNOW to SI. In this case there ae three possible conditions. The first one is if AWESI < AWE, the original ADC applies. ASC is then set to the curve value for AWESI and AWE is set to 1.0. In the second case AWESI ≥ SBWS and the limit of the temporary ADC for new snowfall has been reached, and ASC is set to 1.0. If neither the first or the second case does not apply, ASC is computed from the temporary ADC which is the third and last case. ASC is calculated as follows:

$$\mathrm{ASC} = \mathrm{SBA} + (1-\mathrm{SBA}) \times \frac{\mathrm{AWESI}-\mathrm{AWE}}{\mathrm{SBWS}-\mathrm{AWE}} \tag{2.7}$$

Further on, a snowmelt rate SMELT is computed for the snow pack. If T_a > SNOTMP and the precipitation fall as rain, a heat budget equation, Equation 2.8, is used. If T_a ≥ Tbase degree-day equation, Equation 2.9, is used. Tbase is the base melt temperature (° C), meaning the temperature at which snow begins to melt. If neither one is the case SMELT is set to be 0.

$$SMELT = (0.001167 + 7.5\gamma \mathrm{U_A} + 0.007i)(\mathrm{T_a} - 32) + 8.5\mathrm{U_A}(\mathrm{e_a} - 0.18) \tag{2.8}$$

where γ is the psychrometric constant (mm Hg/° C), U_A is the wind speed adjustment factor (mm/mm Hg – hr) and e_a is the saturation vapor pressure at air temperature (mm Hg).

$$\mathrm{SMELT} = \mathrm{DHM}(\mathrm{T_a} - \mathrm{Tbase}) \tag{2.9}$$

SMELT is multiplied by its respective surface's fraction of area that is snow covered (ASC) to account for any real depletion. If the SMELT for each snowpack surface is 0 the pack's cold content is updated in several ways depending on the circumstances. If $T_a \leq$ SNOTMP and $i = 0$ and precipitation falls as snow, T_a can be set as the Antecedent Temperature Index, ATI (°C). Otherwise ATI is found using Equation 2.10 or is set to the smaller of Tbase. $TIMP_t$ can be found using Equation 2.11 (Anderson, 2006):

$$\mathrm{ATI} \leftarrow \mathrm{ATI} + \mathrm{TIPM_t}\ (\mathrm{T_a} - \mathrm{ATI}) \tag{2.10}$$

$$\mathrm{TIPM_t} = 1 - (1 - \mathrm{TIPM})^{\frac{\Delta t}{6}} \tag{2.11}$$

The updated ATI is used to calculate ΔCC (Equation 2.12) and ΔCC used to calculate cold content depth COLDC (millimetre water equivalent) (Equation 2.13). RNM is the ratio of negative melt coefficient to melt coefficient.

$$\Delta\mathrm{CC} = \mathrm{RNM} \times \mathrm{DHM} \times (\mathrm{ATI} - \mathrm{T_a}) \times \Delta\mathrm{t} \tag{2.12}$$

$$COLDC \leftarrow COLDC + \Delta CC \times ASC \tag{2.13}$$

If SMELT > 0 and the snow pack surface is under melting conditions the COLDC and SMELT for the snow pack is reduced as shown in the following equations. COLDC and SMELT are limited to be ≥ 0.

$$\Delta\mathrm{CC} = \mathrm{SMELT} \times \mathrm{RNM} \times \Delta\mathrm{t} \tag{2.14}$$

$$\mathrm{COLDC} \leftarrow \mathrm{COLDC} - \Delta\mathrm{CC} \tag{2.15}$$

$$\mathrm{SMELT} \leftarrow \mathrm{SMELT} - \Delta\mathrm{CC} \tag{2.16}$$

The snow pack depth WSNOW and free water depth FW on each snow surface is then updated:

$$WSNOW \leftarrow WSNOW - SMELT \times \Delta t \tag{2.17}$$

$$\mathrm{FW} \leftarrow \mathrm{FW} + (\mathrm{SMELT} + i_{\mathrm{RAIN}}) \times \Delta\mathrm{t} \tag{2.18}$$

If precipitation falls as rain $i_{\mathrm{RAIN}} = i$. If the precipitation does not fall as rain i_{RAIN} is set to 0. Each snow surface is then checked to see is the free water content is high enough to produce liquid runoff. If $FW \geq FWFRAC \times WSNOW$, where FWFRAC is free water fraction that produces liquid runoff from the snow pack, following happens:

$$\Delta FF = FW - FWFRAC \times WSNOW \tag{2.19}$$

$$FW \leftarrow FW - \Delta FF \tag{2.20}$$

$$SMELT = \Delta FF \tag{2.21}$$

If not, SMELT = 0. The overall equivalent precipitation input RI (mm/h) is then computed for each snow surface:

$$\mathrm{RI} = \mathrm{SMELT} + \mathrm{IMELT} + i_{\mathrm{RAIN}} \times (1 - \mathrm{ASC}) \tag{2.22}$$

To compute runoff, the precipitation rate *i* needs to be adjusted for each of the sub-areas. For the pervious area (A1) Equation 2.23 is used. Equation 2.24 calculates the adjusted precipitation rate *i* for the impervious areas (A2 and A3).

$$i = \mathrm{RI[SA1]} \tag{2.23}$$

$$i = \frac{\mathrm{RI[SA2]} \times \mathrm{A_{S2}} + \mathrm{RI[SA3]} \times \mathrm{A_{S3}}}{\mathrm{A_{imperv}}} \tag{2.24}$$

where RI[SAj]is the value of RI for snow surface SAj, A_{sj} is the area of snow surface j, and A_{imperv} is the total impervious area.

3 Materials and Methods

3.1 Site description

The study is based on the blue green roof at Høvringen, HOV3, in Trondheim, Norway (63°26′47.5″ N 10°20′11.0″ E). HOV3 used to be a GR but was changed to a BGR the summer of 2018. In addition to the 30 mm substrate, it now also has a 100 mm layer of LECA for extra storage, under the textile retention mat. The structure of the roof is illustrated in Figure 2. Below the LECA there is geotextile to protect the asphalt and the existing roof. The roof is 100 m^2, where 88 m^2 (8×11 m) is occupied by the BGR and the remaining 12 m^2 is impervious area covered by a standard asphalt roofing. The roof is considered a flat roof, with a longitudinal slope of 2%. The roof is approximately 10 m above ground and 50 m.a.s.l. The roof is equipped with its own advanced meteorological measurement station.

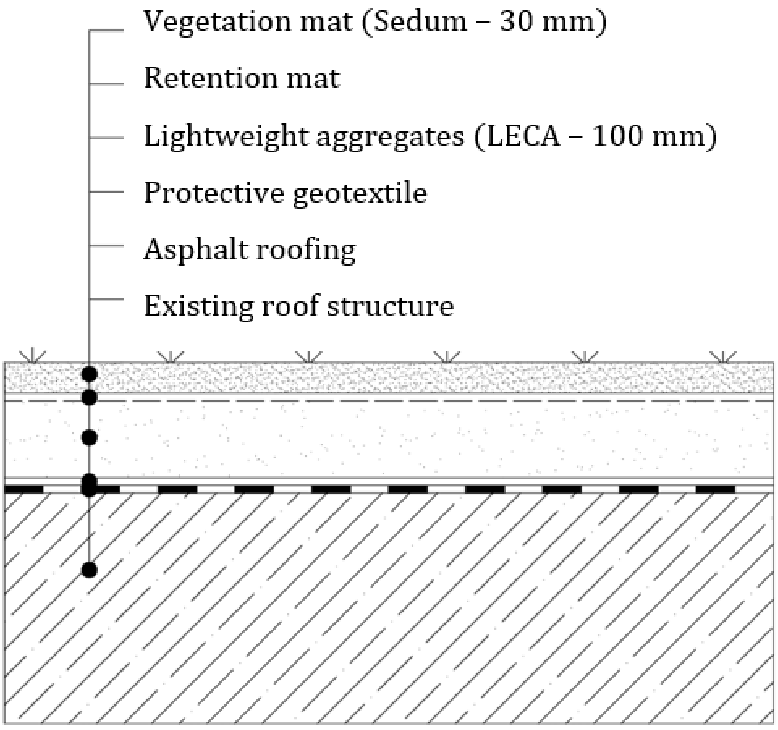

Figure 2: HOV3 Blue Green Roof build-up (July 2018 - to date)

3.2 Data collection

Continuous time series and data are used to run and evaluate the model were collected from the field station at HOV3. The simulation starts at 01.10.18 and ends at 30.04.2019 to include the whole cold period, containing the first snow and spring snowmelt. Data input used to run the model was daily data of wind speed (km/h) and maximum and minimum temperatures (°C), in addition to high-resolution 1-min data of precipitation (mm). Precipitation on site was measured with a heated tipping bucket rain gauge with a resolution of 0.1 mm at 1-min intervals and with accuracy ± 2%. Runoff was measured with a weight-based system with two tanks downstream of the drainage outlets, which were automatically emptied every 30 min and when the collected water reached the capacity of the tank. Air temperature was registered using a thermosensor and wind speed using an ultrasonic anemometer.

Snow depth measures for the period was not available, and therefore pictures from the roof were used to evaluate the accuracy of the simulated snow depth when adding the snow pack function to the model. The same pictures were used to decide whether the precipitation measured on the roof was in the form of rain or snow and identify rain-on-snow and spring melting events.

Due to several extreme test runs, some of the runoff data had to be altered to give the correct representation of the actual runoff made by precipitation. The extreme tests make the observed runoff much higher than it normally would be, because of the large amount of water poured on the roof. Hence, to make the calculations and comparisons most accurate, the runoff in these situations was set to be 0 because of the lack of precipitation on the dates where extreme test occurred. Within the selected period, four extreme tests were performed and consequently altered. These being October 8th and 26th and November 1st and 9th.

3.3 Model Application and Parameters Estimation

The model is based on the model made by Johannessen et al. (2019), which was made using the SWMM version 5.1.012, with the LID-GR module. To make the model fit for modelling cold periods, a snowpack function was added to simulate runoff made from snowmelt, etc. The model was used for long-term and short-term simulation of runoff quantity using the rainfall/runoff process with 1-min reporting time step. The rooftop was modelled as a subcatchment where 88% was occupied by LID. The remaining 12% was modelled as impervious area.

3.3.1 LID-GR Parameters Estimation

The LID module in the model consists of three layers: surface, soil, and drainage mat. However, parameters from the surface layer were left out from the calibration since the surface layer is assumed not to contribute to the retention or detention performance in the LID module due to the high infiltration capacity (Hamouz and Muthanna, 2019). Also, parameters affecting the physical shape of the roof, like thickness, berm height and surface slope, were left out of and kept fixed to preserve the physical description of the field setup and avoid overparameterization.

Within the soil layer, following parameters were calibrated:

- *the porosity:* potential space within soil layer for storing stormwater
- *field capacity:* the amount of water in the soil layer after free water drainage
- *wilting point:* the soil moisture content at which plants can no longer extract moisture to meet their transpiration requirements
- *conductivity:* the velocity which the water can flow through a porous medium
- *conductivity slope:* the slope of the curve of log (conductivity) vs. soil moisture content

Whereas in the drainage mat following parameters were calibrated:

- *void fraction:* the ratio of void volume to total volume in the mat
- *roughness:* used to compute the lateral flow rate of drained water through the mat

The initial values of the parameters, as well as their range, are presented in

Table 1 on next page.

Table 1: LID-GR parameters with initial values with lower and upper bounds

PARAMETERS	INITIAL	RANGE	SOURCE
Soil Layer:			
Porosity (fraction)	0.56	0.45 – 0.6	a, b, c, e
Field Capacity (fraction)	0.3	0.2 – 0.45	a, b, c, d
Wilting Point (fraction)	0.1	0.05 – 0.2	a, b
Conductivity (mm/hr)	11.1	10 – 1000	a, c, b, f
Conductivity Slope	15	5 – 60	a, b, d, f
Suction Head (mm)	75	50 – 100	a, b
Drainage Layer:			
Void Fraction	0.3	0.2 – 0.4	a, b
Roughness (Mannings n)	0.2	0.01 – 0.4	b, e

a	Rossman and Huber (2016b)	Peng and Stovin (2017)	**d**
b	Rossman (2015)	Rosa et al. (2015)	**e**
c	Hamouz and Muthanna (2019)	Palla and Gnecco (2015)	**f**

3.3.2 Snow Pack Parameters Estimation

The Snow Pack Module contains parameters that characterize the build-up, removal and melting of snow over three types of sub-areas within a subcatchment: the plowable snow pack area, the impervious snow pack area and the pervious snow pack area. Parameters from the plowable snow pack area has been left out since there is now plowing or snow removal on the roof. Since there are not any human made snow redistribution, the depth, at which snow removal begins, was set to 1000 mm. This was done to avoid any snow redistribution when modelling the roof.

Within the Snow Pack Module following parameters were calibrated:

— *min. melt coefficient:*	minimum melt coefficient, occurring Dec. 21
— *max. melt coefficient:*	maximum melt coefficient, occurring June 21
— *base temperature:*	temperature at which snow begins to melt

- *fraction free water:* free water fraction to produce liquid runoff from pack

The initial values of the parameters, as well as their range, are presented in Table 2 next page.

Table 2: Snow Pack parameters with initial values with lower and upper bounds

PARAMETERS	INITIAL	RANGE	SOURCE
DHMIN (mm/hr- C°)	0.01	–	a
DHMAX (mm/hr- C°)	0.123	–	a
Tbase (C°)	-1.0	-4 – 0	b
FWFRAC	0.1	0.02 – 0.1	b

a Hamouz and Muthanna (2019) Rossman and Huber (2016a) **b**

The initial parameters, as well as lower and upper bound used during the calibration, were taken from literature and similar studies. The melt coefficients are taken from a study by Hamouz and Muthanna (2019) where the coefficients were derived from observed snowmelts from the same test field. The initial value of the base temperature Tbase is often set to 0 (Rossman and Huber, 2016a, Hamouz and Muthanna, 2019). However, because Tbase is included in the calibration, a value different from 0 was chosen so that values $\pm$ 10–50% of the initial value differs from the initial value.

3.4 Model performance

To evaluate the model during winter, the model was run with data and time series from 01.10.18 to 30.04.19. The simulated runoff was compared to the observed runoff and, and the performance of the model was evaluated primary by using the Nash–Sutcliffe Model Efficiency (NSE) Coefficient (Nash and Sutcliffe, 1970). Volume Error (VE) was also included regarding water balance evaluation and was used to calculate discrepancies between observed and simulated runoff.

The NSE is a way to assess the predictive power of a hydrological model, and is the most widely used performance measure in hydrological modelling (Ritter and Muñoz-Carpena, 2013). The coefficient ranges from $-\infty \leq NSE \leq 1$, where $NSE = 1$ indicates a perfect fit between the observed runoff and simulated runoff, while $NSE = 0$ indicates that the models prediction is as accurate as the average observed runoff $\bar{O}$. That means, with $NSE \leq 0$, that the average observed runoff $\bar{O}$ is a better predictor than the model (Ritter and Muñoz-Carpena, 2013). For a model to be acceptable, the threshold value is set to be in the interval $0.5 \leq NSE \leq 0.65$ (Moriasi et al., 2007). Moreover, a $NSE < 0$ should not generally happen unless there are severe errors in the input or output data, assuming there is a reasonably conceptualized model structure (Gupta and Kling, 2011). NSE can be calculated as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{N}\left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \tag{3.1}$$

where is the observed runoff at timestep i, and $Q_{sim,i}$ is the simulated runoff at timestep i. $\overline{Q_{obs}}$ is the average observed runoff and N being the number of timesteps included in the calculation. Volume error is calculated as follows:

$$\mathrm{VE} = \frac{\mathrm{V_{obs}} - \mathrm{V_{sim}}}{\mathrm{V_{obs}}} \times 100 \tag{3.2}$$

where $\mathrm{V_{obs}}$ is the observed runoff volume and $\mathrm{V_{sim}}$ is the simulated runoff volume for the whole simulated period.

3.5 Model calibration and validation

Data between 01.10.18 and 16.01.19 served as calibration period to make the model produce most accurate results, while 17.01.19 to 30.04.19 was used for validation and is used to provide evidence that the model produces consistent results. In order to prevent eventual validation issues while comparing events with different characteristics, a long-term continuous calibration was chosen. Each period included three larger events. The model was evaluated by the NSE value and VE in both the calibration and validation period. Since the winter contains many different routines and phases, it could have been more accurately to compare calibration and validation periods from the same phases in winter, but from different years, instead of comparing late fall and early winter to late winter and early spring as done in this case. However, due to lack of data, partly because the structure of the roof was altered in 2018, it was only possible to use data from one winter.

3.6 Sensitivity Analysis

A sensitivity analysis is a typical measure to quantify the impact of parameter uncertainty on overall simulation uncertainty (Saltelli et al., 2000). The analysis was done manually by changing one parameter at the time. While doing these adjustments, one can see how the change in parameter changes the output. By plotting the parameters one can identify patterns that helps identifying which parameters are sensitive and not. The clearer the pattern in the plot, the higher might be the sensitivity.

Note that the values used in the sensitivity analysis does not necessary fall within the upper and lower bound allocated to the parameters, since the values used in the analysis is ± 10–50% of the initial value.

4 Results

4.1 Model performance

By using parameters taken from literature and similar studies, the model was calibrated, and simulations were made to be able to calculate NSE, VE and compare with observed values. Figure 3 gives a graphical representation of the whole cold period from October 1st to April 30th. Figure 3 demonstrates the measured precipitation and runoff, compared to the simulated runoff produced by the model using the initial parameters taken from literature and other studies.

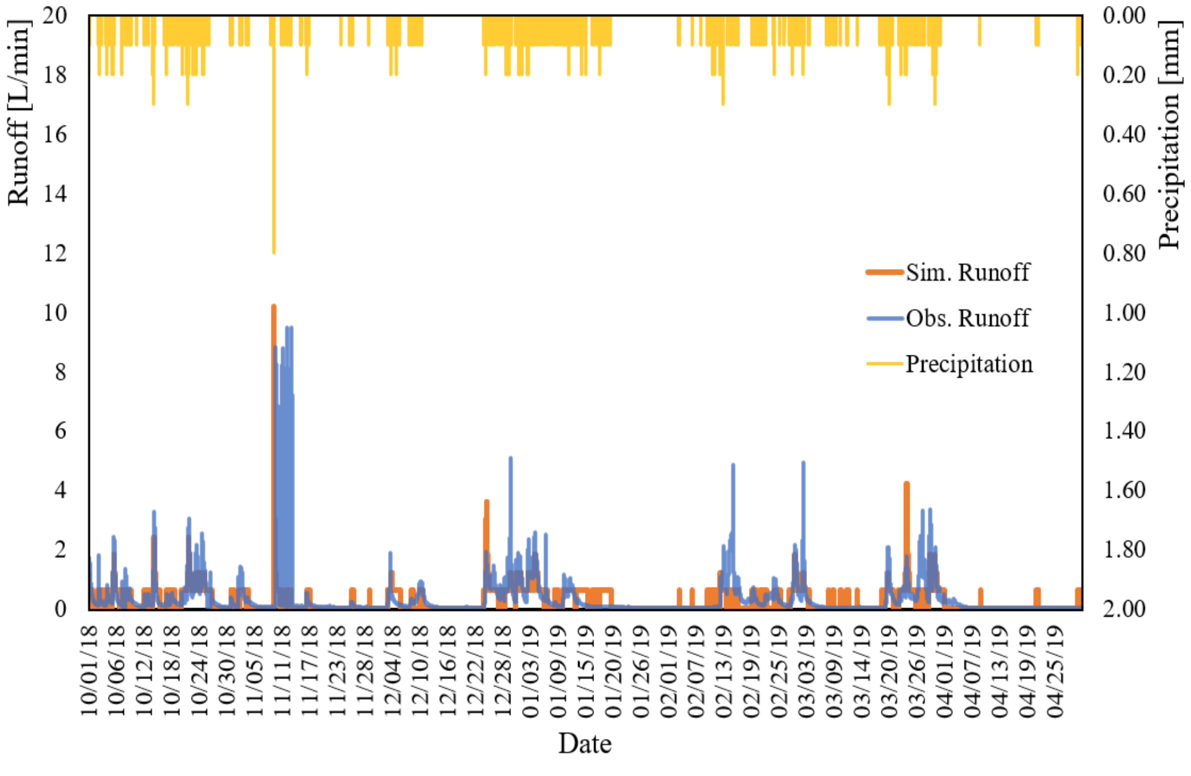

Figure 3: Time-series precipitation with observed and simulated runoff

The cold period contains several larger events. Individual events used for evaluating the model performance within calibration (C) and validation (V) period are listed in Table 3. There are three events occurring in each period.

Table 3: Events used for evaluating model performance

	PRECIPITATION		RUNOFF		PERIOD
nr	Start [dd.mm.yy]	[hh:min]	End [dd.mm.yy]	[hh:min]	Calibration / Validation
1	12.10.18	16:54	30.10.18	20:52	C1
2	09.11.18	12:15	13.11.18	12:27	C2
3	24.12.18	06:40	17.01.19	23:59	C3
4	10.02.19	01:03	27.02.19	00:50	V1
5	27.02.19	11.12	07.03.19	17:37	V2
6	18.03.19	18:25	06.04.19	23:38	V3

Table 4: Hydrometeorological properties and mTable 4 shows their hydrometeorological properties as well as the model performance, including the long-term continuous periods, being the calibration period, validation period and the whole cold period.

odel performance for events and periods

	PRECIPITATION			RUNOFF PEAK	RUNOFF VOLUME			
nr	Duration [hh:min]	Depth [mm]	Mean intensity [mm/h]	Max [L/min]	Obs. [mm]	Sim. [mm]	NSE [–]	VE [%]
1	435:2	119.4	0.3	3.27	120.8	116.5	0.73	3.5
2	96:12	38.8	0.4	9.46	88.1	34.8	-0.92	60.5
3	593:19	196.3	0.3	5.05	205.5	192.1	0.43	6.5
4	409:47	42.3	0.1	4.85	119.6	48.1	-0.34	59.8
5	198:25	47.3	0.2	4.93	53.8	44.9	0.76	16.6
6	461:13	124.3	0.3	3.33	153.0	122.4	0.20	20.0
Total calibration period					551.6	459.0	0.14	16.8
Total validation period					336.2	252.9	0.32	24.8
Total cold period					887.8	711.9	0.21	19.8

Table 5 gives a detailed description of the precipitation situation occurring during each event. It describes the already condition on the roof, if the first precipitation falls as rain or snow, and whether the precipitation changes its form during the event. Pictures, taken of the roof around the beginning of each event, displaying the then situation, can be found in APPENDIX C.

Table 5: Type of precipitation registered at the beginning and during each event

EVENT	INITIAL PREC. TYPE	CHANGE IN PREC.TYPE	
1 – C1	Rain on bare ground	No change	-
2 – C2	Rain on bare ground	No change	-
3 – C3	Rain on shallow snow	Snow	08.01.19
		Rain	01.10.19
		Snow	01.13.19
4 – V1	Snow on snow	Rain	13.02.19
		Snow	20.02.19
		Rain	23.02.19
5 – V2	Rain on bare ground	Snow	01.03.19
6 – V3	Rain on snow	Snow	24.03.19
		Rain	28.03.19
		Snow	30.03.19

Two events, the first (C1) and fifth (V2), result in satisfactory performance with NSE over 0.5. C1 has a nearly ideal VE, whereas V2 is slightly poorer. Event C3 is not far from satisfying the requirement when it comes to NSE and has a decent VE. Two events, C2 and C1, have negative NSE values and has the worst VE results. The simulated and observed runoff for these events are illustrated graphically in Figure 4. From Figure 4, one can see that the model provides fairly accurate rendering for event C1 and C3. V2 and V3 is less so, but not far from reality. V1 and C2 are the worst events for the model, where C2 has significant errors. For the long-term continuous periods one can see that the overall NSE values for the whole period and validation period are better than the period used when selecting and calibrating the parameters. However, the calibration period provides the lowest VE.

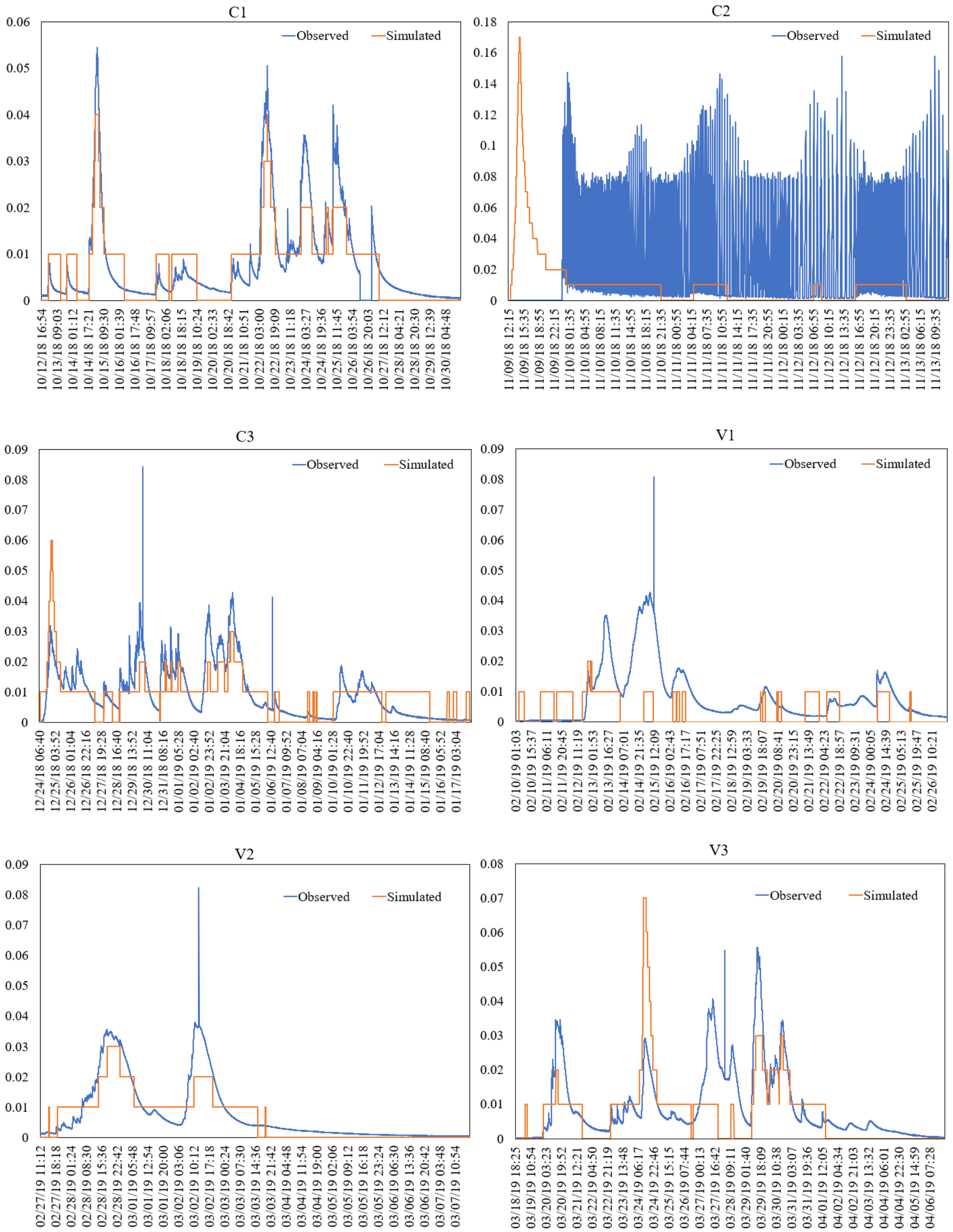

Figure 4: Comparison of observed and simulated runoff [L/s] during six events

4.2 Parameter Sensitivity

A simple sensitivity analysis was performed using data from the calibration period. One parameter was changed at the time, altering the initial parameter from –50 to 50 %. The results from the sensitivity analysis are illustrated graphically in Figure 5.

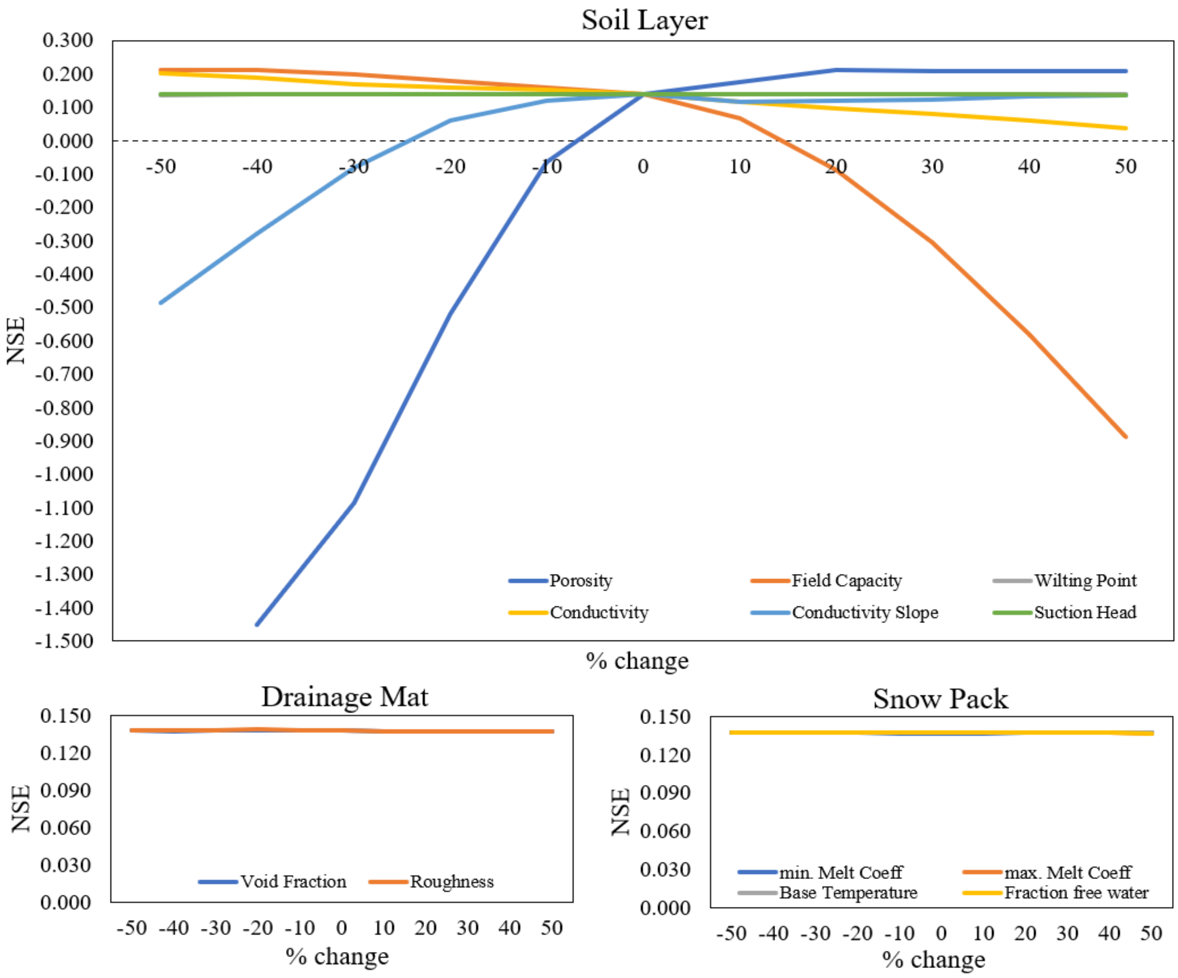

Figure 5: Sensitivity analysis for selected lid controls and snow packs parameters

One can see from Figure 5 that parameters in the soil layer have the largest variations, indicating high sensitivity when modelling GR in SWMM. However, wilting point and suction head is showing no impact on the analysis. The same applies concerning parameters selected from the drainage mat and snow pack. From Figure 5 one can see that these hardly even change, indicating a low impact on the overall simulation uncertainty.

Table 6 displays the new values found by the sensitivity analysis, which provided the best NSE value for each parameter in the calibration period.

Table 6: Parameter values after sensitivity analysis

PARAMETER	INITIAL VALUE	NEW VALUE	% CHANGE
Porosity	0.56	0.67	+ 20 %
Field Capacity	0.3	0.18	- 40 %
Wilting Point	0.1	No considerable change	–
Conductivity	11.1	5.55	- 50 %
Conductivity Slope	15	15	0 %
Suction Head	75	No considerable change	–
Void Fraction	0.3	No considerable change	–
Roughness	0.2	No considerable change	–
min. Melt Coeff	0.1	No considerable change	–
max. Melt Coeff	0.123	No considerable change	–
Base Temperature	-1	No considerable change	–
Fraction free water	0.1	No considerable change	–

By inserting the new values presented in

Table 6 into the model, new NSE values and VE were calculated. The model performance in the aftermath of the sensitivity analysis are listed in

Table 7.

Table 7: Model performance after recalibration with values from sensitivity analysis

PERIOD	INITIAL CALIBRATION		CALIBRATION AFTER S.A.	
	NSE [–]	VE [%]	NSE [–]	VE [%]
Calibration period	0.14	16.8	0.23	43.0
Validation period	0.32	24.8	0.17	55.4
Total cold period	0.21	19.8	0.22	47.7

By using a sensitivity analysis for NSE values in the calibration period, one can see from Table 7 that the NSE value for the calibrated period has increased. NSE for the total period has slightly improved, whereas the NSE value for the validation period deteriorated. VE was not included in the sensitivity analysis and one can see that VE for all parts of the period got considerably worse.

5 Discussion

5.1 Model performance

In this study, SWMMs ability to model snowmelt and rain-on-snow events from a green roof during cold periods, using the LID-GR module, was investigated. The results indicates that runoff can be simulated accurately, but with certain limitations. In general, one can see from Table 4 that the runoff volume constantly throughout the whole period is underestimated. Figure 4, except for C2, shows that the peak flows simulations in general have a good fit to the observed peak flows considering the timing. Considering the values of the peak flows, it is most often underestimated, but also occasionally overestimated for certain events.

When calibration the model, using values taken from literature and similar studies, it proved difficult to achieve satisfactory results, considering the NSE value for the calibration period. The best result for the whole calibration period was found to be 0.14, which indicates that the model is just slightly better than the average observed runoff at predicting the runoff. However, the NSE value for the validation period and the whole cold period turned out better than the calibrated period, with 0.21 for the whole period and 0.32 for the validation period. Considering VE, the calibration period had the lowest value. Even though the model provided better results when simulating the whole period, opposite of simulating just the calibration period, it would be more beneficial if the calibration and validation period involved situations with the same characteristics. In that way, the certainty of the model would be better. Although the NSE values proved to be better for the validation period as well as the whole period, the NSE values considering long-term continuous periods are too low for the model to be an acceptable tool for predicting future runoff.

Table 4 shows that 2/6, nearly 3/6, events provide adequate NSE values when doing a simple calibration of the model. C1 and V2 have satisfactory NSE values that are over 0.5, which indicates that the model’s prediction for these events is more accurate than the average observed runoff. By comparing Table 4 with Table 5 one could get a better understanding of the results. Event C1, C2 and V2 are all events starting with rainfall on a roof free from snow. C1 and V2 provide the best result when it comes to NSE values, whereas C2 delivers the worst result. Comparison of event C2, its results and similar events, suggest that there might by issues with the dataset during the given event, more than model-related issues. The presentation of C2 in Figure 4 shows an extremely large amount of measured runoff during this period, and even though Figure 3 shows there being heavy rainfall during C2, the simulated runoff seems to respond better to the precipitation than the observed runoff does. Following C1 and V2, C3 has the best results with NSE value of 0.43 and a VE of 6.5%. There was an inconsiderable amount of snow on the roof at the time when the rainfall started, therefore this event could also be classified as *rain on bare ground.* This indicates that the model does well when it comes to modelling rain during winter and cold periods.

By comparing V1 and V3, considering values and type of event, it may seem like the model does a better job modelling rain on snow and spring snow melt, than modelling snow on snow events in the middle of the winter. By looking at event V2 in Figure 4, one can see that the curves get a deteriorated fit when the rain turns to snow March the 1st, amplifying that the model does not simulate snow as well as rain.

5.2 Parameter Sensitivity

A sensitivity analysis was done primary to identify the uncertainty of the various parameters. Figure 5 shows that the parameters in the soil layer have the largest variations and are consequently the most sensitive when modelling GR in SWMM. The porosity was the parameter with the largest variation and the analysis indicated that a higher porosity would be better for the NSE values. Field capacity was the parameter with the second largest difference. Contrary to the porosity, the analysis indicated that a lower value would improve the NSE. The conductivity slope follows the somewhat same pattern as the porosity, however not as sensitive. The conductivity does not vary as much as the previously mentioned parameters, nevertheless there is still some uncertainty associated with this parameter. Just like the field capacity, the analysis indicates a lower value would be better for the NSE values. These are the parameters with the largest impact on the overall simulation uncertainty and these parameters therefor need to be as accurate as possible to make decrease the model uncertainty. Wilting point and suction head showed no variation of the NSE when changing its values and are therefore considered not to be sensitive.

Similar to the last two parameters in the soil layer, the parameters in the drainage layer; void fraction and roughness, revealed to be less sensitive. Even though Figure 5 shows some minor variation, the change is considered to be inconsiderably, signifying that these parameters are not sensitive.

The parameters in the snow pack editor proved to be unexpectedly little sensitive, where the analysis indicates that these parameters have low too no impact on the overall simulation uncertainty. One might believe when modelling runoff during winter with snow and snowmelt, the snow pack parameters would have a greater effect on the simulated runoff.

As declared, the analysis was performed mainly to identify sensitive parameters. This analysis was done manually with 120 different runs. If doing a more extensive sensitivity analysis using a computer to run 10 000 iterations, the results could be used to calibrate the model further. When using the sensitivity analysis done in this study to recalibrate the model, the new NSE value for the calibrated period does improve. This does however lead to worsened NSE values for the validation period. The new values for the long-term continuous periods are listed in Table 7. Table 7 also shows how the VE for all the periods have significantly worsened, making the model produce even less runoff. To be able to use the sensitivity analysis to improve the model, one would have to use a program running the analysis to decrease the uncertainty of the results, as well as including several performance measures, like VE, to find the most ideal parameters for the model.

5.3 Further Work and Future Winter Modelling Routines

The model, with parameters taken from literature and other studies, demonstrated that SWMM can be suitably used for assessing the continuous performance with further calibrations, and consequently for supporting local authorities or designers in the evaluation of the hydrological efficiency of green roofs. If one were to improve the model performance by doing a more extensive sensitivity analysis and calibration, the calibrated parameters for the model would only be valid for a green roof that has the same components and build-up as the BGR used in this study. Many parameters are required by SWMM and although literature and the SWMM manual provides reference values for each parameter, more accurate simulations will be obtained if each roof had system-specific calibrations and values. Therefore, the SWMM model appears not to be generic and many uncertainties exist in estimating the values of the parameters, as many parameters are required.

In addition to a large set of parameters, a lot of input data is required when mathematically modelling snowmelt in urban catchments. This is rarely available among common practitioners and one could therefore question the ease of SWMM, despite having easy access. The key is to find the perfect balance point when it comes to the level of complexity. Less parameters and data input would make the usability better for practitioners, though the accuracy of the model would decline. This is an even bigger problem when it comes to winter modelling, because runoff made by snow is so much more complex than runoff just made from rain. This suggests that SWMMs routines for winter modelling should be even more complex than it already is in order to be able to produce more accurate results for winter modelling. For instance, a more accurate winter modelling needs to be able to distinguish the snow properties change patterns for different urban snow covers, and the parameters set in the snow pack controls in SWMM should generate higher sensitivity when modelling snow pack. A recommendation is to have varying snow melt coefficient for different snow covers and snow pile shapes, by making a generalization of snow cover characteristics. The snow melt coefficient is something that is determined by the local conditions and climate. Local quality temperature data is therefore important. With future climate change in mind, there is also a need for good downscaled temperature data at a local scale.

SWMM uses air temperatures to distinguish between rain and snow, and accordingly simulates runoff from rainfall or snow accumulation from snowfall. SWMM does not however, take the substrate or soil temperature into account, even though this can significantly affect the process. SWMM could therefore be simulating snow accumulation because of negative air temperatures, while there is actual runoff because of positive temperatures in the medium.

As discussed, SWMM has shown to have several shortcomings that needs to be improved in order to produce better winter simulations. However, these improvements will increase the level of complexity and decrease the usability. It is difficult to find the correct balance and therefor challenging to make a model that is transferable for common practitioners. The best identified solution in this thesis is to make a SWMM base model for different roofs; green, blue green and grey, where the transferable parameters are set. Thence, practitioners could change the site-specific parameters and would have to do an adequate sensitivity analysis to calibrate their model and find the best corresponding values.

This is, however, not an easy task unless you have more than basic programming skills and access to a program that is compatible with SWMM. The best-case scenario would therefore be a function for automatic calibration in SWMM. Instead of using an independent programming script, which requires a particular set of skills that few of the population possess, SWMM could run a sensitivity analysis and calibration of the model using maximum and minimum input values. This is of course easier said than done, but the possibility to do automatic calibration in SWMM would solve several issues considering both model performance and usability. It would make it less complicated for users, but the level of complexity would still remain. This would improve modelling routines for long-term continuous and event-based simulations, not only for winter runoff modelling, but for all uses of SWMM.

6 Conclusion

It is found that the SWMM model generally works better for event-based simulations than long-term continuous simulations. The model shows good performance on rain and melting but has a larger issue when it comes to snow events. The model generates consistently too little runoff. The result indicates that SWMM has the potential to be a useful tool to model snowmelt and rain-on-snow events from a green roof during cold periods with more extensive work and calibration.

Parameters in the soil layer were found to have the highest uncertainty, whereas porosity and field capacity showed highest uncertainty, followed be conductivity and conductivity slope. Parameters in the snow pack were found to have unexpectedly low impact. There is a suggestion that these should be higher when modelling periods including snow.

Results show that, despite already being very complex, the level of complexity when it comes to the parameters in SWMM needs to be higher to produce more accurate results. To handle the increased complexity of the parameters, one should find a way to make the calibration of these parameters easier. A function for automatic calibration in SWMM could solve several issues and limitations without decreasing the level of complexity. Issues relating the large data and input demand, would still however remain unsolved. A transferable model as a generic tool or practitioners appears to be difficult to achieve in SWMM because as there are many site-specific parameters. An auto calibration tool included in SWMM would however make it easier for practitioners to recalibrate transferable base models to fit their site-specific values. It remains challenging to balance the amount of data, input and complexity to usability, but SWMM has shown potential to be suitably used for assessing the continuous LID performance, and consequently for supporting local authorities or designers in the evaluation of the hydrological efficiency of green roofs.

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APPENDIX

APPENDIX A – Low Impact Development Models

APPENDIX B - Computational Scheme for Snowmelt

APPENDIX C – Surveillance Photos of the Green Roof

APPENDIX A – Low Impact Development Models

Table comparing different Low Impact Development Models which can be used to modelling green roofs:

CAPABILITIES	**HEC-HMS**	**MIKE Urban**	**SWMM**	**SWAT**	**Win-SLAMM**
Public domain	X		X	X	
Input complexity					
Medium	X	X	X	X	X
High		X	X	X	
Simulation type					
Event	X	X	X	X	X
Continuous	X	X	X	X	
Applications					
Conceptual design	X	X	X	X	
Preliminary and detailed design/analysis	X	X	X	X	X
LID Modelling					
Built-in BMPs		X	X	X	X
Multiple layer modelling		X	X	X	X
Underdrain modelling		X	X		X
Water ponding modelling	X	X	X	X	X
Sloped catchment modelling	X	X	X	X	X
Resolution					
Min/Sec	X	X	X	X	
Hourly	X	X	X	X	X
Daily	X	X	X	X	X
Monthly		X	X	X	
Annually		X	X	X	

Water balance parameters					
Run-on	X	X	X	X	X
Snow melt	X	X	X	X	
Evaporation	X	X	X	X	X
Water uptake by plants				X	
Runoff Generation Method					
Unit hydrograph methods	X	X	X		X
Rational method				X	
Infiltration Method					
Experimental infiltration rate					X
Green-Ampt method	X	X	X	X	
SCS CN	X	X		X	
Other Methods	X	X	X		
Flow Routing Method					
Dynamic wave		X	X		
Kinematic wave or other hydrologic methods	X	X	X	X	X
Loop networks modelling		X	X		
Steady state (no flow routing) method	X	X	X	X	X

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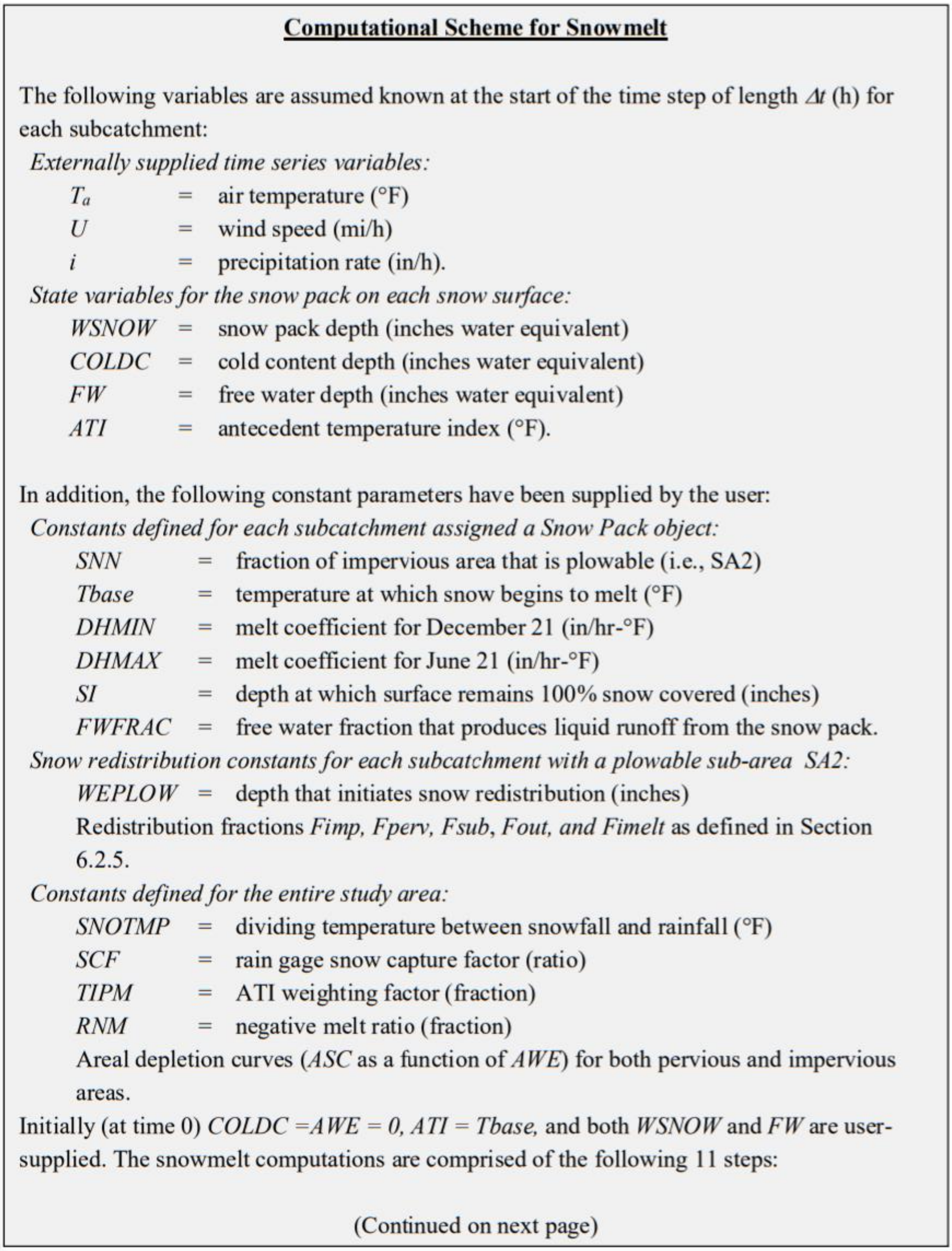
APPENDIX B - Computational Scheme for Snowmelt

Computational scheme for snowmelt from Storm Water Management Model Reference Manual Volume I – Hydrology (Revised):



Computational Scheme for Snowmelt

The following variables are assumed known at the start of the time step of length Δt (h) for each subcatchment:

Externally supplied time series variables:

T_a = air temperature (°F)
U = wind speed (mi/h)
i = precipitation rate (in/h).

State variables for the snow pack on each snow surface:

WSNOW = snow pack depth (inches water equivalent)
COLDC = cold content depth (inches water equivalent)
FW = free water depth (inches water equivalent)
ATI = antecedent temperature index (°F).

In addition, the following constant parameters have been supplied by the user:

Constants defined for each subcatchment assigned a Snow Pack object:

SNN = fraction of impervious area that is plowable (i.e., SA2)
Tbase = temperature at which snow begins to melt (°F)
DHMIN = melt coefficient for December 21 (in/hr-°F)
DHMAX = melt coefficient for June 21 (in/hr-°F)
SI = depth at which surface remains 100% snow covered (inches)
FWFRAC = free water fraction that produces liquid runoff from the snow pack.

Snow redistribution constants for each subcatchment with a plowable sub-area SA2:

WEPLOW = depth that initiates snow redistribution (inches)
Redistribution fractions *Fimp, Fperv, Fsub, Fout, and Fimelt* as defined in Section 6.2.5.

Constants defined for the entire study area:

SNOTMP = dividing temperature between snowfall and rainfall (°F)
SCF = rain gage snow capture factor (ratio)
TIPM = ATI weighting factor (fraction)
RNM = negative melt ratio (fraction)
Areal depletion curves (*ASC* as a function of *AWE*) for both pervious and impervious areas.

Initially (at time 0) *COLDC* = *AWE* = *0, ATI* = *Tbase,* and both *WSNOW* and *FW* are user-supplied. The snowmelt computations are comprised of the following 11 steps:

(Continued on next page)

APPENDIX B - Computational Scheme for Snowmelt

1. Compute the melt coefficient *DHM* for each snow pack surface (SA1, SA2, and SA3) for the current day of the year using Equation 6-7 and set the immediate melt *IMELT* on each surface to 0.

2. If $Ta <= SNOTMP$ then precipitation is in the form of snow so update the snow pack depth on each snow surface:

   $WSNOW \leftarrow WSNOW + i \times SCF \times \Delta t$

3. For the plowable impervious snow surface (SA2), if $WSNOW > WEPLOW$ then *WSNOW* is reduced to reflect the redistributions produced by the fractions *Fimp, Fperv, Fsub, Fout, and Fimelt*. If $Fimelt > 0$ then the immediate melt for surface SA2 is set to:

   $IMELT = Fimelt \times WSNOW / \Delta t$

4. If the snow pack depth over a snow surface is below 0.001 inches then convert the entire pack for that surface into immediate melt:

   $IMELT \leftarrow IMELT + (WSNOW + FW) / \Delta t$

   and reset the pack's state variables to 0.

5. Use the Areal Depletion Curves supplied for the pervious (SA1) and non-plowable impervious (SA3) snow surfaces to compute a new areal snow coverage ratio *ASC* for these surfaces (*ASC* for the plowable impervious surface is always 1.0). The details are supplied below.

6. Compute a snowmelt rate *SMELT* for the snow pack on each surface:

   a. If rain is falling ($Ta > SNOTMP$ and $i > 0.02$ *in/h*) use the heat budget equation, Equation 6-1, converted from a 6-hour to a 1-hour time base.

   b. Otherwise, if $Ta >= Tbase$, use the degree-day equation, Equation 6-6.

   c. Otherwise set *SMELT* to *0.*

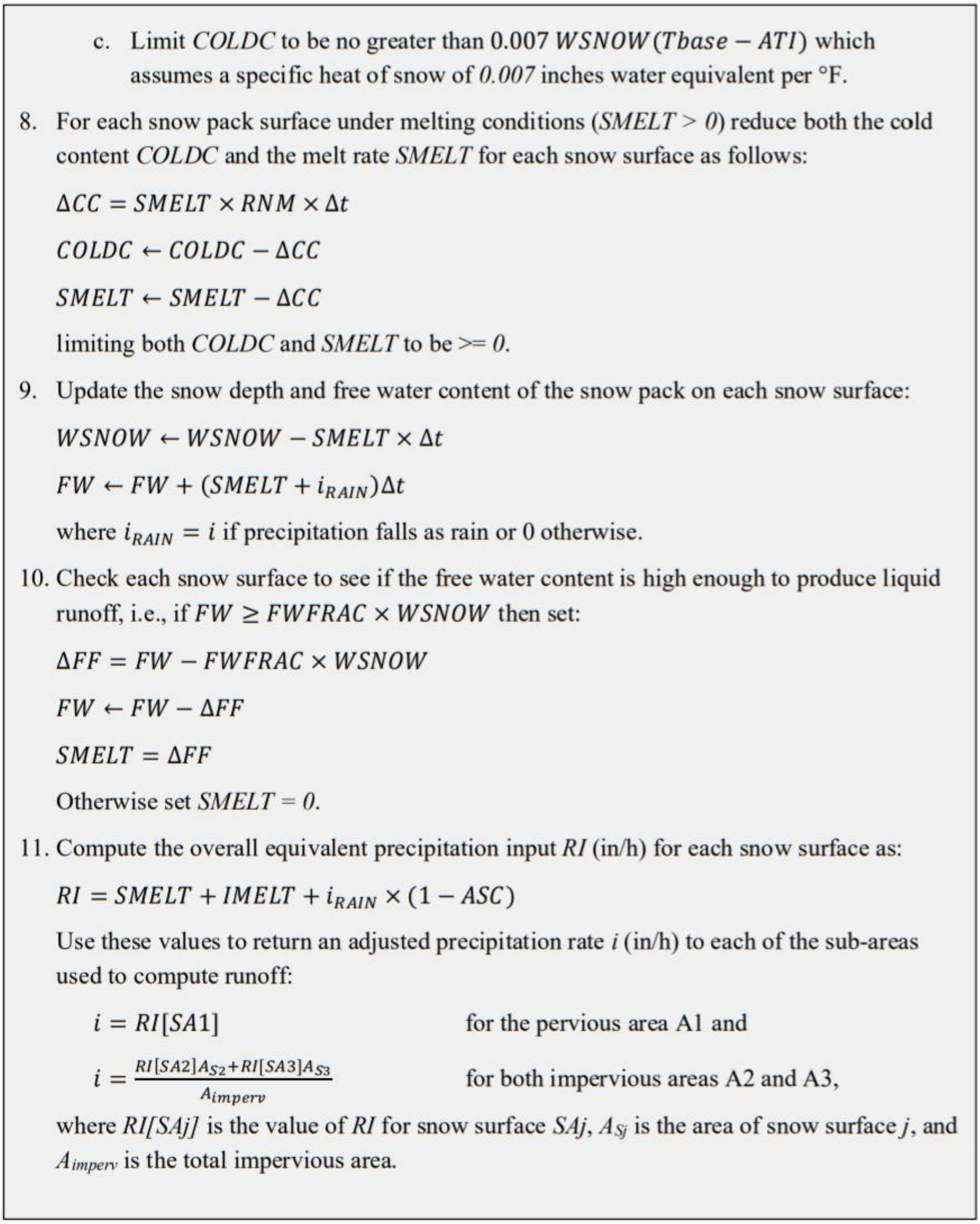
   d. Multiply *SMELT* by its respective surface's *ASC* value to account for any areal depletion.

7. For each snow pack surface, if *SMELT* is *0*, then update the pack's cold content as follows:

   a. If snow is falling ($Ta <= SNOTMP$ and $i > 0$), set *ATI* to *Ta*. Otherwise set *ATI* to the smaller of *Tbase* and the result of Equation 6-8.

   b. Use Equation 6-10 with the updated *ATI* value to compute ΔCC and add $\Delta CC \times ASC$ to *COLDC*.

(Continued on next page)



   c. Limit *COLDC* to be no greater than 0.007 $WSNOW(Tbase - ATI)$ which assumes a specific heat of snow of *0.007* inches water equivalent per °F.

8. For each snow pack surface under melting conditions (*SMELT > 0*) reduce both the cold content *COLDC* and the melt rate *SMELT* for each snow surface as follows:

   $\Delta CC = SMELT \times RNM \times \Delta t$

   $COLDC \leftarrow COLDC - \Delta CC$

   $SMELT \leftarrow SMELT - \Delta CC$

   limiting both *COLDC* and *SMELT* to be >= *0*.

9. Update the snow depth and free water content of the snow pack on each snow surface:

   $WSNOW \leftarrow WSNOW - SMELT \times \Delta t$

   $FW \leftarrow FW + (SMELT + i_{RAIN})\Delta t$

   where $i_{RAIN} = i$ if precipitation falls as rain or 0 otherwise.

10. Check each snow surface to see if the free water content is high enough to produce liquid runoff, i.e., if $FW \geq FWFRAC \times WSNOW$ then set:

    $\Delta FF = FW - FWFRAC \times WSNOW$

    $FW \leftarrow FW - \Delta FF$

    $SMELT = \Delta FF$

    Otherwise set *SMELT = 0*.

11. Compute the overall equivalent precipitation input *RI* (in/h) for each snow surface as:

    $RI = SMELT + IMELT + i_{RAIN} \times (1 - ASC)$

    Use these values to return an adjusted precipitation rate *i* (in/h) to each of the sub-areas used to compute runoff:

    $i = RI[SA1]$ for the pervious area A1 and

    $i = \frac{RI[SA2]A_{S2} + RI[SA3]A_{S3}}{A_{imperv}}$ for both impervious areas A2 and A3,

    where *RI[SAj]* is the value of *RI* for snow surface *SAj*, A_{Sj} is the area of snow surface *j*, and A_{imperv} is the total impervious area.

ROSSMAN, L. A. & HUBER, W. C. 2016. Storm Water Management Model Reference Manual: Volume I – Hydrology (Revised). Cincinnati: Office of Research and Development: Water Supply and Water Resources Division. Available from: http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100NYRA.txt

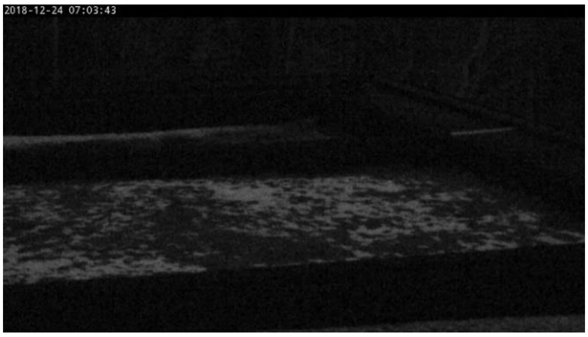
APPENDIX C – Surveillance Photos of the Green Roof

Surveillance photos showing the green roof around the time of the beginning of each event:

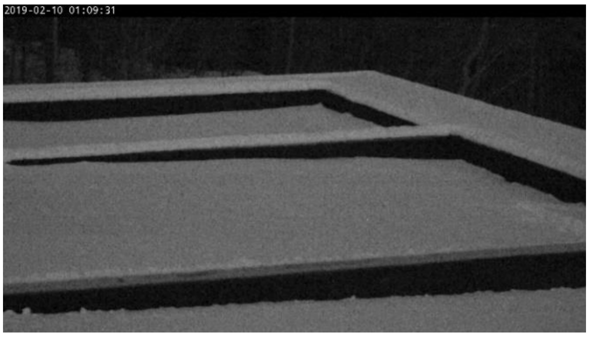
1. C1

2. C2

3. C3



4. V1



5. V2

6. V3