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Modelling detention performance of green roofs in cold climates

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Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU), Department of Civil and Environmental Engineering. It is a product of the course "TVM4905" Water and wastewater engineering, Master's Thesis". The purpose of this thesis was to develop a suitable model for green roof short-term simulations, with data from a monitored green roof located in Oslo as input.

I would like to express my gratefulness to PhD candidate Birgitte G. Johannessen and Postdoctoral Fellow Ashenafi Grange. Johannessen was of great support through the whole period. Thank you for discussing green roof processes with me every week. Grange has contributed to the R scripting and has been of great help. The model would not have been as well-developed without his contribution. I would also like to thank associate professor Tone M. Muthanna for feedback and guidance, and Bent Braskerud, VAV, for sharing knowledge and information on the green roofs. The data used in this study is from the green roof experimental site located on his garage roof. Lastly, I would like to thank Researcher Jardar Lohne for help with manuscript editing and writing tips.

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Sammendrag

Oslo er preget av økt urbanisering, hyppigere intensive nedbørshendelser og et underdimensjonert avløpsnett. Som en konsekvens er det nødvendig å tenke nytt når det kommer til overvannshåndtering. Grønne tak er sett på som et virkemiddel for å dempe avrenningstopper og bidra til økt naturlig hydrologisk balanse. Det finnes enormt potensiale i å utnytte takflater ettersom en antar at 40-50% av urbane strøk består av takarealer. Det er imidlertid gjort lite forskning på reelle avrenningsmengder fra grønne tak i Oslo-klimaet, og fysiske modeller kan være et tiltak for å anslå takets virkninger.

I denne studien er det blitt utviklet en fysisk modell som simulerer avrenning fra et forsøksfelt på Nordberg i Oslo. Forsøksfeltet består av to grønne tak med ulike dreneringsegenskaper (Figur A.1 og A.2 i vedlegg A), hver på 8 m^2. GT2 er bygd opp av tre lag; vegetasjon, substrat og filt. GT1 er bygd opp på samme måte, men med et underliggende dreneringslag formet som eggekopper i tillegg. Feltet har vært i drift siden 2009 og består dermed av lange nedbør-avrenningsserier.

Modellen er bygd opp i US EPAs Stormwater management model (SWMM) ved hjelp av en overvannsmodul for grønne tak (LID-GR). LID-GR består av vegetasjon, substrat og dreneringslag. Hvert lag er definert med et sett av parametere.

De mest intensive nedbørshendelsene, med jordfuktighetsmålinger tilgjengelig, er brukt som inngangsdata i modellen. Til sammen har fire nedbørshendelser med varierende varighet, maksimum intensitet og totalt volum vært grunnlag for kalibrering av modellen. Syv hendelser ble brukt for å evaluere hvor godt modellen gjengir virkelige hendelser.

Resultatene av studien viser at modellen klarer å gjenskape observert avrenning fra det grønne taket med filtmatte som det nederste laget (GT2). Ved kalibrering øker modellens ytelse, men også i ukalibrert tilstand er simuleringene tilfredsstillende. Modellen fungerer best for nedbørshendelser med 1 års returperiode og overestimerer generelt avrenningen for større hendelser. For grønne tak med dreneringsbrett formet som eggekopper opptrer modellen upresist og er ute av stand til å etterligne den reelle avrenningen.

Studien viser at modellen simulerer nedbørshendelser med returperiode 1-2 år (18701 Blindern). Som tommelfingerregel skal grønne tak ta unna nedbør fra trinn 1 og til dels trinn 2 i tretrinnsstrategien. Det innebærer at SWMMs LID-GR modul er egnet for å simulere avrenning fra grønne tak. Ved hendelsesbasert simulering er det viktig at (i) kalibreringshendelser har lignende karakteristikk som den dimensjonerende nedbøren og (ii) de fysiske egenskapene til taket er identiske eller ligner så mye som mulig som LID-GR modulen. Videre forskning bør overføre og verifisere modellen på større tak og undersøke modellens holdbarhet på vinterstid.

Thesis Structure

This master’s thesis is written as a scientific article and submitted to the International Hydroinformatics Conference, HIC 2018 in Palermo, Italy. The main content of this master’s thesis is an extended version of the article submitted.

Much of this thesis’ work was conducted using scripts written in the programming language R. The main script is found in Appendix D, while the remaining can be accessed at Daim.

Abbreviations

GR	Green roof
IDF	Intensity, duration, frequency
LID	Low Impact Development
LID-GR	Low Impact Development – Green roof (module in SWMM)
NSE	Nash-Sutcliffe Efficiency
PFE	Peak flow error (in minutes)
SWMM	Stormwater Management Model
SuDS	Sustainable urban Drainage System

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Modelling green roof detention performance in cold climates

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Key words: Cold climates, detention, green roof, SuDSs, stormwater management model (SWMM)

Abstract

Green roofs (GRs) have become a popular sustainable drainage system (SuDS) technology in urban areas. As many countries and regions experience political encouragement and substitution schemes in implementing GRs, there is a need for reliant models that can support designing purposes.

The stormwater management model's (SWMM) Low Impact Development Green Roof (LID-GR) control is used to simulate the hydrological detention performance of two GRs, GR1 and GR2, with different drainage properties located in Oslo, Norway. This study uses event-based data to replicate GR runoff. Accordingly, four event-models were calibrated using the Shuffled Complex Evolution algorithm with the Nash-Sutcliffe criteria (NSE) as the objective function. Eight events were used for model validation. In addition, sensitivity to the model parameters was analysed in relation to model input (precipitation characteristics and roof initial saturation levels). Simulation results revealed that SWMM's LID module can capture response of the GRs even though the adequacy varies among events.

Parameter sensitivity analysis exhibited significant correlation between conductivity slope and maximum precipitation intensity. During calibration two GR1 (0.55 and 0.72) and three GR2 (0.73, 0.88 and 0.51) event-models yielded NSE>0.5. However, only parameter sets of two GR2 event-models yielded NSE>0.5 when applied to the validation events.

The study shows potential of SWMM as a design tool if supplemented with a calibration algorithm. However, calibration is required and some adjustments to the LID-GR module should be made in the future. This concerns particularly the module's drainage layer.

1 Introduction

Green roofs (GRs) have the potential to solve more than one engineering problem. Besides mitigating stormwater runoff (among others Mentens et al., 2006), green roofs supply aesthetic values, enhanced ecologic habitat (Schrader et al., 2006) and reduced cooling/heating needs in buildings (among others Jaffal et al., 2012). Green roofs allow for a natural water balance in urban areas and lessen the urban heat island effect. The extent to which roofs occupy space (40-50% of the impermeable surface) in urban areas render green roof performance particularly interesting for addressing stormwater management challenges. Their behaviour, however, is not adequately understood from a hydrologic perspective. This concerns particularly predicting their detention capacities.

Considering the complexity of GR performance, the traditional hydrologic design criteria (rainfall events with different intensities, durations, and frequencies) do not prove sufficient. GR retention and detention processes are site specific and factors such as climatic conditions (Johannessen et al., 2017) seasonal variations (Voyde et al., 2010) and rainfall characteristics (Hakimdavar et al., 2014) influence their performance. Considering this, stormwater engineers and local municipalities need reliable and precise methods for quantifying green roof performance in advance of construction (Carson et al., 2017).

Physical modelling based on site-specific characteristics is one manner by which the performance can be predicted before construction. The suitability of such modelling will depend to a significant degree on the quality of the models used.

SWMM is a frequently used model for predicting runoff from subcatchments. After the upgrade in 2015, LID control modules were included, rendering it possible to model SuDS controls such as porous pavements, bioretention cells, and infiltration trenches (Rossman, 2015). The controls consist of layers whose properties are defined by different parameters. Evapotranspiration (ET) can be specified by choice, making the modules applicable for single-event and continuous simulations (Rossman, 2015). Its frequent use, flexibility, and the fact that it is based on open source renders SWMM the preferred choice for this study.

1.1 Objectives of the study

This study aims to answer the following research questions:

1. How accurately does the SWMMs LID-GR module predict detention performance of two extensive GRs with different drainage properties?
2. How does model input in form of precipitation characteristics and initial conditions affect the model parameters?

The theoretical framework of the study is described in section 2. Section 3 specifies the methods and procedures to investigate the research questions. The results of the study are presented and discussed in section 4 and 5 respectively. Lastly, conclusions are drawn and proposals on further research are given.

2 Theoretical framework

There is an increased interest for GRs in many regions and countries (among others Berndtsson, 2010; Johannessen et al., 2017), including Nordic countries such as Norway where runoff mitigation has been actualized in several municipalities, e.g. the municipality of Oslo. Oslo is experiencing that the combined sewage system is under pressure in many areas, stimulating to find new technologies to improve runoff mitigation (Municipality of Oslo, 2013). Stormwater management is often categorized by the three-step approach (S3SA) with steps 1. infiltration, 2. attenuation and 3. safe flood ways. GRs are generally placed as a measure in step 1 and to some extent step 2. Step 1 is believed to account for 95% of annual precipitation which highlights the importance of structures such as GRs. Additionally, GRs are considered as a measure to account for population growth and climatic challenges (Municipality of Oslo, 2015).

A system's response to locally derived design storms in form of quantity of water the system can detain is widely considered when designing SuDSs. These processes differ from continuous retention processes, where the GR's behaviour between storms are important. GR detention performance is dependent on initial conditions affecting moisture content in the different GR layers upon precipitation events (Carson et al., 2013; Stovin et al., 2012; Voyde et al., 2010). These conditions are decided by a GRs retention performance, i.e. the GRs ability to remove stormwater through evapotranspiration and storage, implying that detention mechanisms cannot be fully understood without considering retention processes. However, separating the two processes and assessing consistent performance terms allow for improved consistency when addressing specific objectives for GRs (Stovin, 2017).

In literature, several approaches for modelling detention performance have been presented. Examples are simple reservoir routing methods (Kasmin et al., 2010; Villarreal et al., 2005), commercial groundwater models such as HYDRUS 1-D (Hakimdavar et al., 2014; Hilten et al., 2008; Palla et al., 2012), MIKE URBAN (Locatelli et al., 2014) and SWMM (Burszta-Adamiak et al., 2013; Krebs et al., 2016; Palla et al., 2015; Versini et al., 2016).

SWMM is a dynamic precipitation-runoff model used to simulate runoff quality and quantity mainly in urban subcatchments but has also been used to simulate runoff from GRs. This has mainly been done through the GR module, (Carson et al., 2017; Cipolla et al., 2016; Palla & Gnecco, 2015; Peng et al., 2017), but the BRC-module has also been applied (Cipolla et al., 2016). The LID-GR module is expressed by a surface layer, substrate layer and a drainage layer. All layers are defined by a set of parameters. The surface layer parameters are shown to have little effect on detention processes as there is normally no ponding on the surface of a GR (Peng & Stovin, 2017) due to the high permeability found in GR soils (Krebs et al., 2016). This implies that the substrate and drainage layers are most important when modelling detention routines.

3 Methods

3.1 GR test site in Oslo, Norway

The GR test site is located on a 24 m^2 garage roof with a slope of 5.5% in northern Oslo and has been operating since 2009. A residence south of the site and the roof's north-faced orientation makes it exposed to shade. These factors, including the site's high elevation (215 m.a.s.l.), makes the test site "a worst-case scenario" (Braskerud, 2014). The site consists of two vegetated roofs, GR1 and GR2, and a reference roof, RR. Each plot with 2m width and 4 m length. GR1 is built up of a 25 mm Nophadrain 5+1 drainage board under a 30 mm ready-made moss-sedum vegetation mat. The drainage board has a water holding capacity of 5.8 l/m^2 (Veg Tech, 2018). On the 8th of August 2011, a VT-felt of 10 mm was added between the drainage board and substrate layer to improve the water holding capacity (Braskerud, 2014). GR2 is constructed of a 10 mm VT-felt under a 30 mm moss-sedum mat. The roofs are in other words identical, except from the plastic board in GR1. A laboratory analysis measured an average water holding capacity of 7-10 mm for the VT-felt. Soil moisture content was recorded every 15 min in both GRs using Vegetronix sensors. The sensors were installed and calibrated in august 2010 (Braskerud, 2014). Runoff from GR1, GR2 and RR flows through separate gutters into a 220 l isolated oil barrels. The water level is measured by a pressure sensor at the bottom of the barrels. The barrels are emptied when the water level reaches 80 cm. In cases where runoff is generated during emptying, missing data points are filled by interpolation.

Precipitation is monitored by a heated Lambrecht 1518 H3 tipping bucket with a time resolution of 1 min and 0.1 mm sampling resolution. See Appendix A for photos of the experimental site and GR built-up.

3.2 Modelling GR detention performance

The roofs were modelled by applying an LID-GR module to two subcatchments, S1 and S2, each being 100% occupied by their respective LID-GR control. Two outlets were added and connected to the LID-module to obtain closed systems. The model analysis started one hour before reporting time to assure model burn-in.

Very few GR monitoring programs have data sets of similar lengths as the presented experimental test site (8 years). This indicates that factors as initial soil moisture conditions, seasonal variations and different rainfall characteristics are well represented in the data series. Earlier studies define events as the antecedent dry period is at least 6 hours (Stovin et al., 2012; VanWoert et al., 2005; Voyde et al., 2010). To easily compare GR performance, this definition is also used in this study. Consequently, 680 events were recorded from August 2009 to June 2016. Events before august 2010 were excluded as soil moisture measurements were missing before this. Events with more than one contributing rainfall and events with durations larger than 24 hours were removed, resulting in 160 remaining events. The event durations were plotted with respect to rainfall depth and maximum intensity. Events with high maximum intensity were chosen for calibration and validation purposes. More detailed descriptions on event selection can be found in Appendix B. Event descriptions are found in Table 1.

Table 1 Events chosen for calibration and validation. ^{C} denotes calibration set. The calibration events vary in intensity, duration, return period and initial moisture content.

Event #	Start time (dd/mm/yy HH:MM)	Duration (h)	Total prec. (mm)	Maximum intensity (mm/h)	Return period¤ (years)	GR1/GR2 initial moist[†]	GR1 runoff (mm)	GR2 runoff (mm)
1^{C}	07.06.11 07:09	2.75	29.5	1.22	5	D/D	19.2	15.4
2	19.07.11 02:26	6.02	17.4	0.54	<2	W/W	13.4	13.5
3	01.07.12 07:59	9.37	11.8	0.86	<2	W/M	9.9	9.4
4	17.09.12 03:03	4.82	9.9	0.47	<2	W/W	6.8	6.7
5^{C}	04.08.13 17:24	0.80	9.0	0.53	<2	M/M	4.0	4.1
6	12.08.13 11:34	2.45	14.0	0.62	<2	M/M	7.3	6.3
7	07.07.14 10:47	3.80	17.6	0.91	<2	M/M	5.6	5.6
8	25.08.14 11:06	5.60	10.2	1.07	<2	W/W	7.9	7.4
9	02.08.15 00:37	4.40	12.6	0.63	<2	M/D	6.1	6.5
10^{C}	28.08.11 21:05	20.50	56.4	0.43	20	W/W	50.5	47.8
11^{C}	26.06.14 15:47	14.35	45.0	2.06	5	D/D	23.8	26.4
12	03.08.14 19:49	22.05	40.4	0.97	2	M/M	21.1	22.0

[†] Initial moisture: D = Dry (0-30% water content); M = Medium (30-40% water content); W = Wet (>40% water content)

¤ According to 18701 Blindern MET IDF curve

3.2.1 SWMM parameter evaluation

All initial parameters required by SWMM LID-GR and sources for parameter estimation are listed in Table 2. They were either obtained by literature, laboratory analysis, set as default as proposed by SWMM, or set according to the physical properties of the GRs. The climatologic parameter C_{PET} defined as the potential evaporation coefficient was set to zero as evapotranspiration is not considered in this event-based study. Berm height is set to 3 mm to avoid system overflow. As GR substrate media is very porous, water ponding on the surface is assumed not to occur. Furthermore, the drainage mat in SWMM's LID-GR module only accounts for water transportation and no storage. To represent the storage capacity in the felt mat of both roofs and the plastic board of GR1, extra thickness was added in the substrate layer of both roofs, see * in Table 2.

3.3 Evaluating model performance

Uncalibrated runoff from the 4 chosen calibration events was simulated for both GRs, using initial values found in Table 2. Performance was evaluated through the Nash-Sutcliffe criteria (NSE) (Nash et al., 1970) and peak flow time error (PFE), calculated as the time difference in minutes between observed and simulated time to peak. This study defines model performance as sufficient when NSE ≥ 0.5. NSE is defined by eq. 1:

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(Q_{o,i}-Q_{m,i}\right)^2}{\sum_{i=1}^{N}\left(Q_{o,i}-\overline{Q_o}\right)^2} \qquad (1)$$

where $Q_{o,i}$ = observed runoff at timestep i; $Q_{m,i}$ = modelled runoff at timestep i; $\overline{Q_o}$ = average observed runoff.

3.3.1 Model calibration and validation

Model calibration aimed at finding the optimal parameter set that simulates runoff flow rates as closely as possible to the observed ones. Optimal parameter search was accomplished by applying the Shuffle Complex Evolution algorithm (Duan et al., 1992). The Nash-Sutcliffe Efficiency index (NSE) NSE was used as the objective function in the calibration exercise. Eight events were applied to validate the model. Model performance was assessed through NSE and PFE. As time delay is of concern when designing SuDSs, model accuracy assessment should be based on criteria concerning time as well as volume. This was accounted by PFE. The four optimal parameter sets found in the calibration procedure were applied for model validation of the eight validation events.

Table 2 Parameters required by SWMM GR and BRC-LID modules. The exponent C denotes parameters subject to calibration. Parenthesis represent values applied in GR1. * denotes extra storage capacity in the drainage layers of the GRs, which are represented in the substrate.

Parameter	GR1/GR2		Source
	Initial value	Range	
LID SURFACE			
Berm height (mm)	3	-	Assumed
Vegetation volume (0-1)	0.1	-	Default
Surface roughness (Manning's n)	0.2	-	(Cipolla et al., 2016)
LID SOIL			
Thickness (mm)	(65)/40*	-	Manufactural
PorosityC (0-1)	0.65	0.55-0.75	Laboratory analysis
Field capacityC (0-1)	0.45	0.35-0.55	Laboratory analysis (Bengtsson, 2005)
Wilting point (0-1)	0.1	-	Assumed
ConductivityC (mm/h)	(80) 1000	36-4200	(Rossman, 2015)
Conductivity slopeC	(50)/40	5-60	(Cipolla et al., 2016; Peng & Stovin, 2017)
Suction head (mm)	(110) 60	-	(Krebs et al., 2016; Peng & Stovin, 2017)
LID-GR DRAIN			
Thickness (mm)	10	-	Manufactural
Void fractionC (0-1)	0.72	0.01-1	Manufactural
Surface roughnessC (Manning's n)	0.2	0.02-0.4	(Peng & Stovin, 2017; Rossman, 2015)

3.3.2 Parameter sensitivity to model input

Parameter variations and sensitivity were investigated with respect to model inputs. To obtain an adequate number of samples, GR2 was calibrated for all events, with aim at finding their respective optimal parameter set. Relations between parameter values, rainfall characteristics and initial conditions are examined.

4 Results

4.1 Uncalibrated model performance

For GR2, two events, 1^C and 10^C, result in satisfactory model performance, with NSE = 0.55 and 0.72 respectively (Table 3). Time to peak has a good fit for both events (PFE = -1 and -5 min for event 1^C and 10^C). Uncalibrated simulations form the latter calibration events are poor, with NSE values < 0 (event 5^C and event 11^C) and skewed peaks (PFE = -43 and 7 min).

Considering GR1, the uncalibrated model performs insufficiently, with NSE ranging from <0 (event 5^C) to 0.43 (event 10^C). Peak flow is overestimated in all simulations.

Figure 1 shows the hydro-hyetograph of uncalibrated simulations and observed runoff for the two uncalibrated events with NSE > 0.50.

Table 3 NSE and PFE (peak flow error in minutes) before and after calibration. Bold text denotes satisfactory model performance.

	GR1				GR2			
	Pre calibration		Post calibration		Pre calibration		Post calibration	
Event #	NSE	PFE	NSE	PFE	NSE	PFE	NSE	PFE
1^C	<0	-9	**0.62**	**-2**	**0.55**	**-1**	**0.73**	**-2**
5^C	<0	n.a	<0	-3	<0	-43	0.33	-9
10^C	0.43	-6	**0.72**	**-5**	**0.72**	-5	**0.88**	-3
11^C	0.17	-12	0.40	-9	0.40	7	**0.51**	**-3**

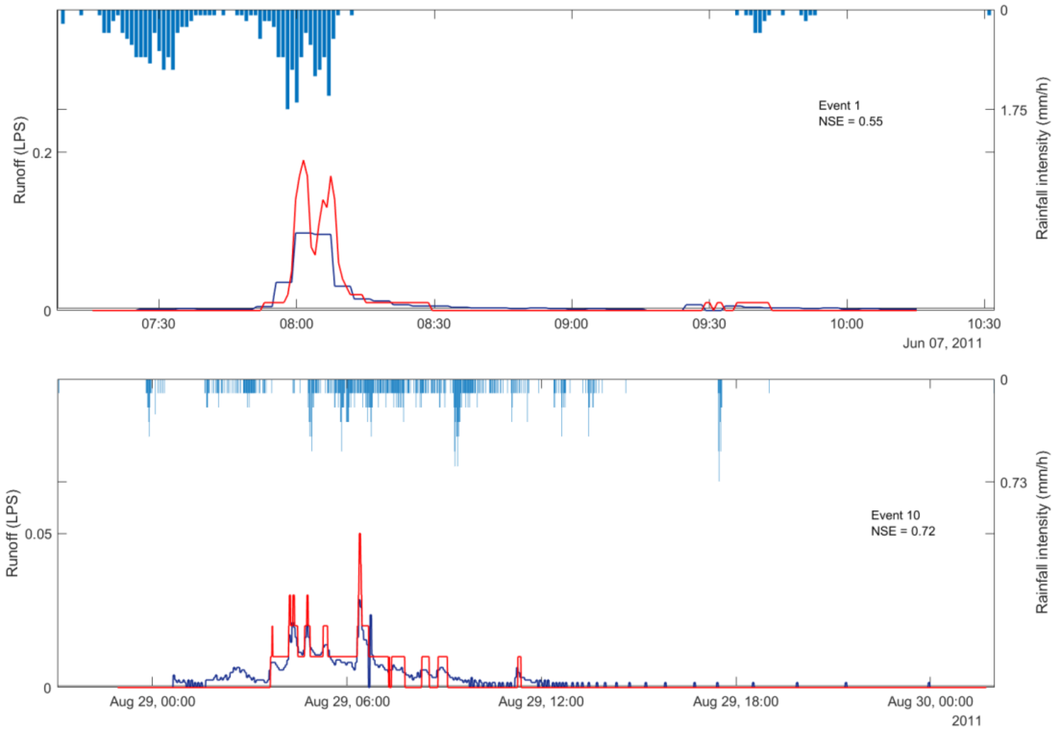

Figure 1 Uncalibrated simulations for the two calibration events with NSE > 0.50, performed on GR2. Observed (blue), simulated (red) runoff together with corresponding NSE values are shown

4.2 Calibrated model performance

In general, simulation results from the calibrated SWMM LID-module of GR2 have satisfactory performance, with the exception of event 5^C. Calibration improves the NSE and PFE for all events compared to the uncalibrated event simulations (Table 3). This also applies for GR1, although the NSEs are generally lower. Calibration results from GR1 are good for event 1^C and 10^C, but poor for the two others.

4.3 Transferring calibrated parameter sets for model validation

NSE and PFE values for the validation events with parameter transfer from all calibration events are found in Table 4. Considering GR2, parameter values transferred from events 5^C result in acceptable model performance with an NSE > 0.55 for all validation events, except for the significant event 11 (return period 5 years). Calibrated parameters from this event are also the only ones able to provide adequate model performance on GR1 (event 4 and 9). Even though this event was poorly calibrated for both GRs, it is noteworthy that its parameter set gives the most satisfactory simulations for the validation events. Event 5^C has low duration (0.8h), lower rainfall volume (9 mm) and a lower maximum intensity (0.53 mm/h) than other calibration events. The successful transfer of event 5^C's parameter set might be explained by a considerable number of events having similar rainfall characteristics as this one. Figure 2 shows validation runs performed on GR2 using the parameter set derived from event 5^C.

The model does a better job reproducing events with lower precipitation depths and relatively short durations, such as event 4, 6, 8 and 9. Some have no distinct peaks and for those that do maximum intensity occurs rather late (event 1^C event 8).

Event 2 modelled on GR2 is best fitted by the set derived from event 10^C. These events have large return periods (5 and 20 years, respectively) and complex hydrographs. The parameter set from event 11^C fail in the validation procedure for both roofs. This event has a high maximum intensity (2.06 mm/h) occurring early in the event. Assumingly, the model struggles with such sudden intensity, leading to unfitting optimal parameters. No runoff is simulated for validation events derived from event 11^C, resulting in no PFE calculations.

Generally, peak flows are systematically simulated lagging the observed ones for both roofs (negative PFE values, see Table 3). The model fails to simulate the storage capacity causing peak flow overestimation and delay of time to peak compared to observed ones.

Event 7 generates very little observed runoff from both GRs and the neighbouring black roof (8 mm), which gives reasons to assume measuring error in the precipitation gauge for this day. Precipitation records studied from Blindern Meteorological Institute, located 3 km south of the experimental site, have also been studied. Analysis for this event are therefore not shown.

Table 4 Nash-Sutcliffe Efficiency (NSE) index and difference between start of observed and simulated runoff for rainfall events used for calibration and validation. Analysis for event 7 are not shown. Values in bold indicate satisfactory model performance. Parentheses denote GR1. Calibration results for event 5^C and 10^C are shown for GR1. PFE referrers to time in minutes between simulated and observed peak flows. Negative values indicate delayed simulated flows.

Validation events	Calibration events							
	1^C		5^C		10^C		11^C	
	NSE	PFE	NSE	PFE	NSE	PFE	NSE	PFE
2	0.29	-7	(0.27) **0.51**	(-7) **2**	(<0) **0.61**	(-13) **-4**	<0	-9
3	0.46	-8	(0.32) **0.55**	(-7) -11	(<0) 0.46	(**-3**) **-3**	<0	n.a
4	**0.63**	**-5**	(**0.63**) **0.77**	(-6) **-3**	(0.35) **0.76**	(6) **-2**	<0	n.a
6	**0.57**	**-2**	(0.41) **0.56**	(-9) **-1**	(<0) <0	(**5**) **-2**	<0	n.a
8	**0.56**	**-3**	(0.39) **0.69**	(-7) **-3**	(0.17) **0.59**	(-6) **-3**	<0	n.a
9	**0.63**	-6	(**0.54**) **0.80**	(**-1**) **-2**	(<0) **0.50**	(**-1**) **0**	<0	n.a
12	<0	9	(<0) <0	(**-4**) 6	(<0) <0	(12) **4**	<0	-8

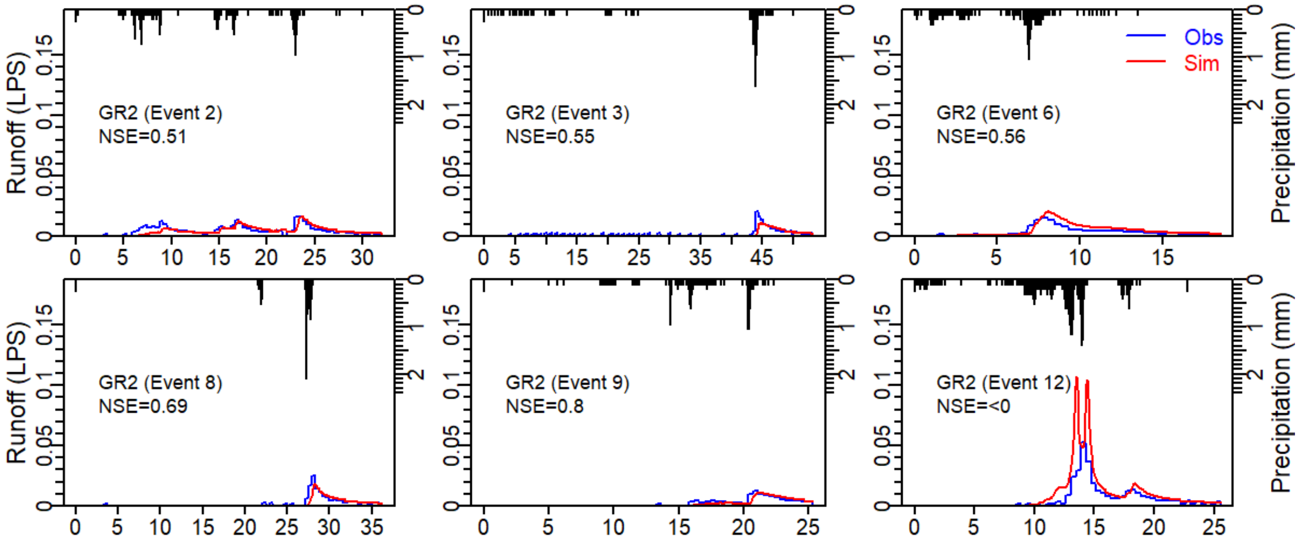

Figure 2 Hyeto-hydrographs of 6 validation events based on parameter sets from calibration event 5^C. Observed (blue), simulated (red) runoff and corresponding NSE values are shown.

4.4 Model parameter sensitivity

All events were calibrated on GR2 and all parameter sets obtained by calibration iterations with NSE > 0.5 were analysed. Event 5^C, event 7 (see section 4.3) and event 12 were unable to receive NSE > 0.5 and are therefore not part of the analysis. Table 5 show the parameter values gained from the calibration procedure.

Porosity and field capacity are calibrated to have realistic values and are similar for all calibration assessments with a mean of 70% ± 4% and 30% ± 8%, respectively (Table 5). The parameters' stability implies that the model succeeds at assessing these parameters.

Table 5 Parameter sets obtained from the calibration procedure of all events where NSE > 0.5. Average and standard deviations are also shown.

	Event #										
Parameter	1	2	3	4	6	8	9	10	11	Av.	Std.dev
Porosity	0.74	0.67	0.74	0.73	0.68	0.71	0.75	0.62	0.75	0.71	0.04
Field capacity	0.42	0.31	0.26	0.23	0.23	0.44	0.28	0.30	0.21	0.30	0.08
Conductivity	1341	1223	2334	1723	1115	576	239	363	37	995	756
Cond. slope	27.0	23.8	32.7	25.1	33.2	23.5	18.1	20.5	60.0	29	13
Void fraction	0.09	0.21	0.32	0.31	0.80	0.96	0.67	0.06	0.86	0.48	0.35
Manning's n	0.16	0.02	0.01	0.01	0.01	0.01	0.01	0.09	0.36	0.08	0.12

Conductivity slope is defined as the rate of which the substrates hydraulic conductivity decreases as soil water content decreases (Rossman, 2015). This parameter, together with Manning's n in the drainage layer, were found to correlate with maximum intensity ($R^2 = 0.70$ and 0.75) (Figure 3). The parameters increase as the maximum intensity of an event increases. Manning's n was also found to correlate with minorly with precipitation volume ($R^2 = 0.50$).

For events 6, 8 and 9, the void fraction is calibrated to be high, while Manning's n is low. A larger void fraction will decrease the contribution of the roughness, implying nearly free water passage through this layer. Furthermore, conductivity values (K_{sat}) are relatively low for these events. This suggests that for these events, substrate parameters determine the flow rate meaning that detention processes occur in the module's substrate layer. For precipitation characteristics as initial saturation and duration, no clear correlations with the optimal parameters were observed.

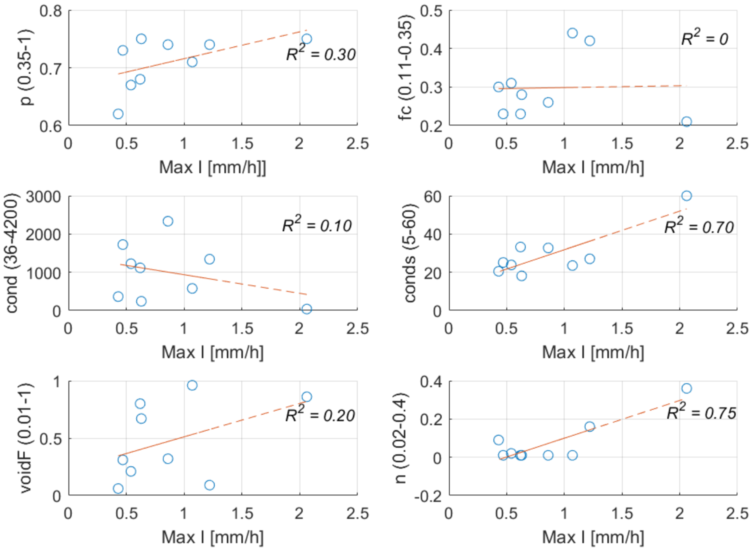

Figure 3 Correlations between parameters obtained in the calibration procedure and maximum intensity (Max I) of events.

5 Discussion

5.1 Accuracy of the LID-GR module

In this study, the accuracy of SWMMs LID-GR module was investigated. Runoff response from two GRs have been simulated. The results show that runoff can be simulated accurately, but with certain limitations. In general, peak flow simulations are delayed, and for large events with high precipitation peak volumes are overestimated.

The drainage mat in the LID-GR module only accounts for transportation and no storage. Laboratory tests conducted primary to this study show that this mat can retain 7-10 mm of water. Even though the extra storage was added to the substrate layer, this effect proved limited. Water flow through the substrate is quicker than through the drain mat, due to the high permeability of GR soils. This might explain the model's tendency to overestimate peak flows.

The only difference between the experimental green roofs, GR1 and GR2 in this study is the extra plastic drainage board in GR1. Despite the extra storage supplied by the drainage board, GR1 generates more runoff than GR2 (Table 1). Moreover, it has been observed that the cups are seldom filled, also after heavy watering of the roof (Braskerud, 2014). This indicates that water flows vertically through the felt, through the holes of the drainage board and then along the surface of the roof. As for today, the LID-GR module is unable to simulate this process. Assumingly, better simulation results would be achieved if the module allowed for storage capacity in the drain mat and flow along smoother surfaces, i.e. along roof surfaces, under plastic drainage boards.

5.2 LID-GR parameter sensitivity

Burszta-Adamiak and Mrowiec (2013) and Palla and Gnecco (2015), recognize initial saturation as influential to the model output, but this study shows no sensitivity to the model input, making initial saturation irrelevant. This may be reasoned with (i) uncertainties related to the soil moisture measurements, (ii) the preliminary burn-in simulation period of 1 hour, (iii) available storage is very small compared to precipitation volume in events used in this study, or (iv) the fact that initial saturation does not exclusively refer to the substrate, but also the drainage mat (Peng & Stovin, 2017).

Conductivity shows large variations, in our study as well as in literature, ranging from 38 mm/h (Krebs et al., 2016) to 1000 mm/h (Palla & Gnecco, 2015; Peng & Stovin, 2017). Here, it does not tend to vary with rainfall characteristics nor initial conditions. However, this parameters is closely related to conductivity slope which is more decisive at unsaturated soil moisture levels. Moreover, Peng and Stovin (2017) and Krebs et al. (2016) identify conductivity slope as sensitive to peak runoff, which is compatible with this parameter being correlated with peak precipitation intensity found in this study.

5.3 Implications

Consistent models can support implementation of GRs, as they become more relevant for filling gaps related to stormwater management. If a GR's function is to account for step 1 and step 2 in the stormwater 3-step approach, SWMM's LID-GR module is applicable. This is because of the model's satisfying performance when simulating events with return period of <2 years. If the module is applied for design purposes with design events as input, the following consideration will be important:

(1) The physical configurations of the roof should be as similar as possible or identical to the LID-GR module.

(2) In case of calibration, the calibration events should have similar characteristics as the design events considered.

5.4 Limitations to the study

The limitations to this study is the size of the experimental site. Distance to the gutter is short, and the GR built-up is very thin. This might affect (i) large variations in the optimal parameter sets and (ii) the fact that detention processes seem to take place in either the substrate layer or the drainage mat. Inconsistencies in the parameters related to the drainage mat causing more or less free water flow may explain the model's tendency to delay and overestimate peak flows for large precipitation events.

5.5 Proposals on further model refinements

To improve model performance two adjustments should be done. First, there should be one sole parameter that refers to the soil moisture content of the substrate. As pointed out by Peng and Stovin (2017), runoff should not be initiated when initial saturation does not exceed field capacity. Thus, the moisture content in the substrate and drainage layer should be separated. Secondly, vertical flow in the drainage layer should be made possible, so that the model also can represent GRs with plastic drainage boards.

6 Conclusion

GRs are in general mainly intended to mitigate stormwater runoff. Reliable modelling practices are needed to place confidence in the efficiency of GRs.

In this event-based study, the accuracy of SWMMs LID-GR module has been investigated through replication of observed runoff from a GR experimental site. The model was calibrated separately with four different events. All four parameter sets were applied to eight validation events. Model parameter sensitivity to the precipitation input has been examined.

The main conclusions of this study are:

- SWMM is applicable for modelling green roof detention performance. However, the model tends to delay and overestimate peak flows
- Validation procedures should be based on parameter sets derived from calibration events with similar characteristics
- Detention routines seem to be modelled in the LID-GRs substrate or drainage layer, but seldom in both layers at the same time
- Conductivity slope is sensitive to precipitation maximum intensity and thus important when modelling detention processes. This parameter is especially important when the substrate layer is unsaturated and needs to be seen in relation to conductivity which is more decisive as the GR soil is saturated

Furthermore, some refinements should be made to the LID-GR module, such as improvement of the drainage layer to better represent physical features of a GR.

Further research should examine the following:

- Apply the model to larger roofs
- Apply the model on different sites with identical manufactured GR to investigate climatic differences
- Apply wintertime generated model input to the module in order to investigate seasonal variations and GR winter performance.

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Appendix A – GR experimental site, Oslo

The study site in Oslo, Norway:

Figure A.1 GR1 (right), reference roof (RR) and GR2 (left). Photo taken when the roof was newly established in August 2009.
Photo: Bent Brakserud

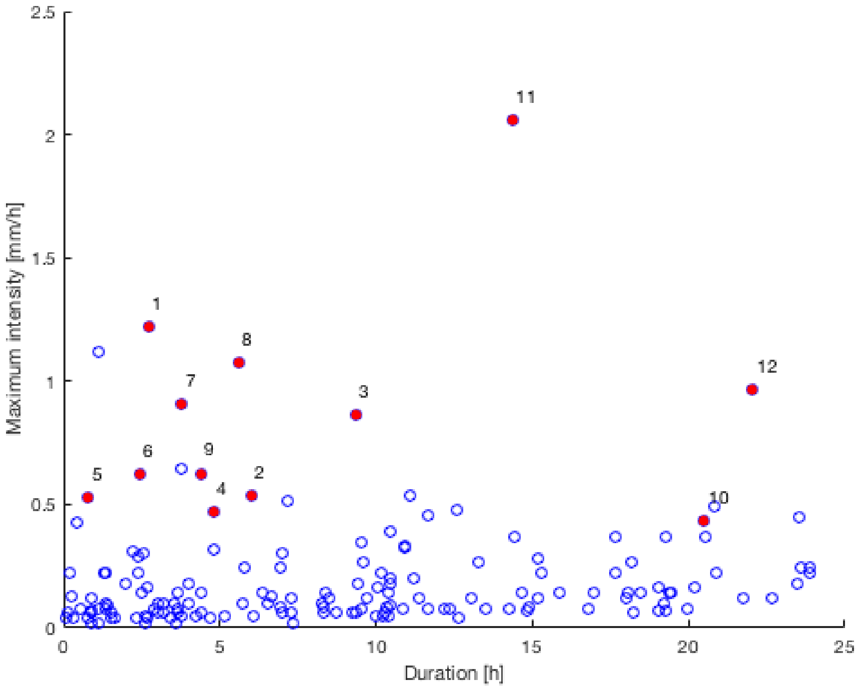
Figure A.2 Build-up of GR2 (left) and GR1 (right). Note that a VT-felt similar to GR1s was added to GR1 in August 2011.
Photo: Bent Braskerud

Appendix B – Scripts for event selection

B.1 Matlab script – Event selection with respect to maximum intensity

```
%This script identifies events with high maximum intensity

N =
xlsread('/Users/ingridrusswurm/Documents/MASTER/OneDrive_1_15/Events/OS
LEvents1.xls');
N(isnan(N)) = 0;
N(N(:,35)>1, :) = [];        %Remove events with more than 1 precip
N = N(logical(N(:,5)),:);    %Remove events with no runoff contribution
N = N(logical(N(:,30)),:);   %Remove events without moist measurements
N(N(:,4)/60 > 24, :) = [];   %Remove events with dur > 24h

durP = N(:,4)/60;            %[h]
MaxI = N(:,13);              %Maximum intensity (MaxI)
moistStart = N(:,30);        %Initial moisture content

%Scatter plot Duration - Maximum intensity
scatter(durP,MaxI, 'b')
ylabel('Maximum intensity [mm/h]')
xlabel('Duration [h]')

%Identify events with high intensity have duraitons < 10h
hold on
M = NaN(size(N));
for i = 1:size(M)
      if N(i,4)/60 < 10       %Dur < 10 h
      M(i,:) = N(i,:);
      end
end

%Construct matrix, M, of significant events
%with respect to MaxI
M(isnan(M)) = 0;
M = M(logical(M(:,1)),:);
M(M(:,13) < 0.4, :) = [];    %Remove ev with MaxI < 0.4 mm/h
x = size(M,1);               %x = 13
M = [NaN(x,12) M(1:x, 1:37)];
M(:,1:6) = datevec(M(:,13));
M(:,7:12) = datevec(M(:,14));
M(:,1) = M(:,1) - 100 + 2000;
M(:,7) = M(:,7) - 100 + 2000;
M(:,3) = M(:,3) -1;          %Datevec datenumber correction
%Column 1-6 indicates startP
%Column 7-12 indicates stopP

%M1 is matrix of 3 events with long durations and high returnperiod
%M1-events are independant of MaxI
%M1-events are identified in "Dur_Int"
M1 = NaN(3,size(N,2));
x1 = size(M1,1);
M1(1,:) = N(17,:);
M1(2,:) = N(103,:);
M1(3,:) = N(107,:);
M1 = [NaN(x1,12) M1(1:x1, 1:37)];
```

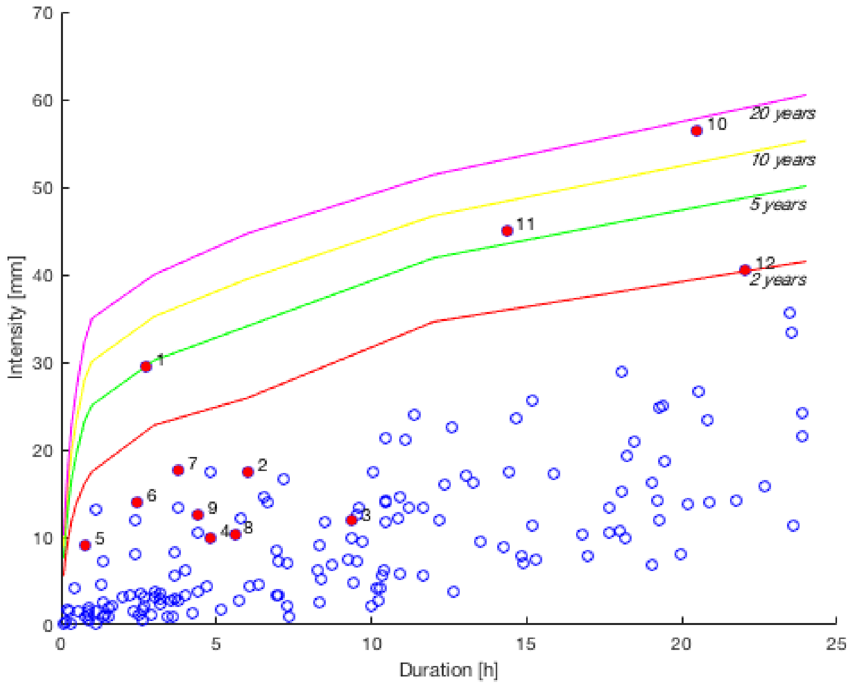
```
M1(:,1:6) = datevec(M1(:,13));
M1(:,7:12) = datevec(M1(:,14));
M1(:,1) = M1(:,1) - 100 + 2000;
M1(:,7) = M1(:,7) - 100 + 2000;
M1(:,3) = M1(:,3) -1;       %Datevec datenumber correction

%Highlight M events
%Remove nr 5, 8 and 12 in M -> obs runoff close to 0
scatter(M([1:4 6:7 9 11 13],16)/60, M([1:4 6:7 9 11 13],25), 'r',
'filled')
x = M([1:4 6:7 9 11 13],16)/60; y = M([1:4 6:7 9 11 13],25);
a = [1:9]'; b = num2str(a); c = cellstr(b);
dx = 0.1; dy =0.1;
text(x+dx, y+dy, c);

%Highlight M1 events
scatter(M1(:,16)/60,M1(:,25), 'r', 'filled');
x1 = M1(:,16)/60; y1 = M1(:,25);
a1 = [10:12]'; b1 = num2str(a1); c1 = cellstr(b1);
text(x1+dx, y1+dy, c1);
```



B.2 Matlab script – Event selection with respect to local IDF curves (Blindern 18701)

```
%This script compares events to local IDF curves

%N is matrix of events
N =
xlsread('/Users/ingridrusswurm/Documents/MASTER/OneDrive_1_15/Events/OS
LEvents1.xls');
N(isnan(N)) = 0;
N(N(:,35)>1, :) = [];       %Remove events with more than 1 precip
N = N(logical(N(:,5)),:);   %Remove events with no runoff contribution
N = N(logical(N(:,30)),:);  %Remove events without moist measurements
N(N(:,4)/60 > 24, :) = [];  %Remove events with dur > 24h

durP = N(:,4)/60;          %[h]
sumP = N(:,12);            %[mm]

%Adress local IDF storms (Blindern 18701)
IDF = xlsread('/Users/ingridrusswurm/Documents/MATLAB/IVF-kurve
Blindern.xlsx');
two = IDF(2,2:12)';
five = IDF(3,2:12)';
ten = IDF(4,2:12)';
twenty = IDF(5,2:12)';
twenty5 = IDF(6,2:12)';
fifty = IDF(7,2:12)';
hundred = IDF(8,2:12)';
two100 = IDF(9,2:12)';
durIDF = IDF(1,2:12)'/60;

%Plot N events
scatter(durP,sumP, 'b')
ylabel('Intensity [mm]')
xlabel('Duration [h]')

%Plot IDF curves
hold on
plot(durIDF,two,'r')
text(durIDF(end)-2,two(end)-2,'\it 2 years')
hold on
plot(durIDF,five,'g')
text(durIDF(end)-2,five(end)-2,'\it 5 years')
hold on
plot(durIDF,ten,'y')
text(durIDF(end)-2,ten(end)-2,'\it 10 years')
hold on
plot(durIDF,twenty,'m')
text(durIDF(end)-2,twenty(end)-2,'\it 20 years')

%Highlight M events
load('Events_MaxI.mat')
scatter(M([1:4 6:7 9 11 13],16)/60,M([1:4 6:7 9 11 13],24), 'r',
'filled')
x = M([1:4 6:7 9 11 13],16)/60; y = M([1:4 6:7 9 11 13],24);
a = [1:9]'; b = num2str(a); c = cellstr(b);
dx = 0.3; dy =0.9;
text(x+dx, y+dy, c);
```

```
%Highlight M1 events
load('Events_MaxI_Extra.mat')
scatter(M1(:,16)/60,M1(:,24), 'r', 'filled')
x1 = M1(:,16)/60; y1 = M1(:,24);
a1 = [10:12]'; b1 = num2str(a1); c1 = cellstr(b1);
text(x1+dx, y1+dy, c1);
```



Appendix C – Simulation results from GR2

C.1 Calibration events post calibration

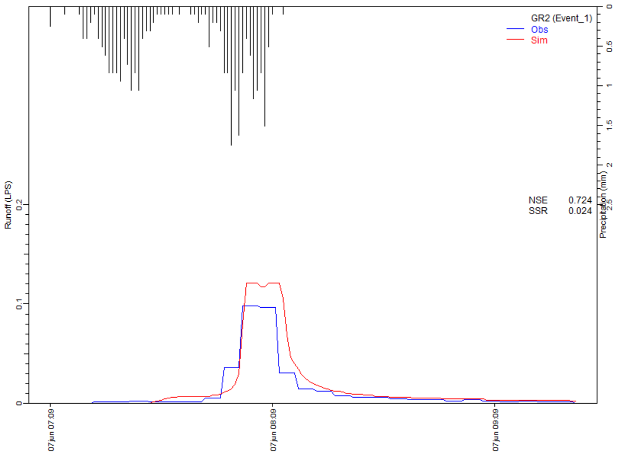


Figure C.1.1 Event 1^{C}

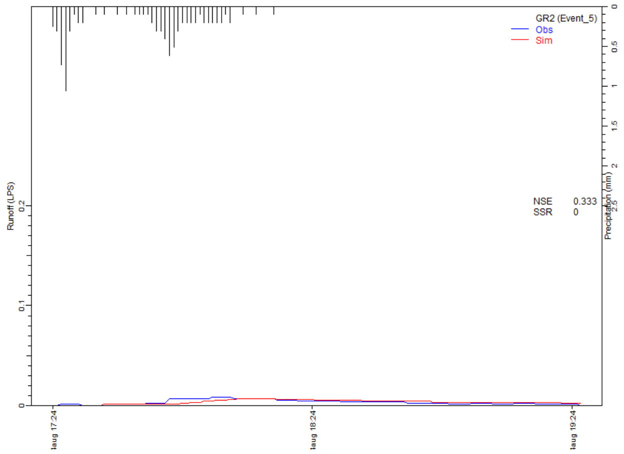


Figure C.1.2 Event 5^{C}

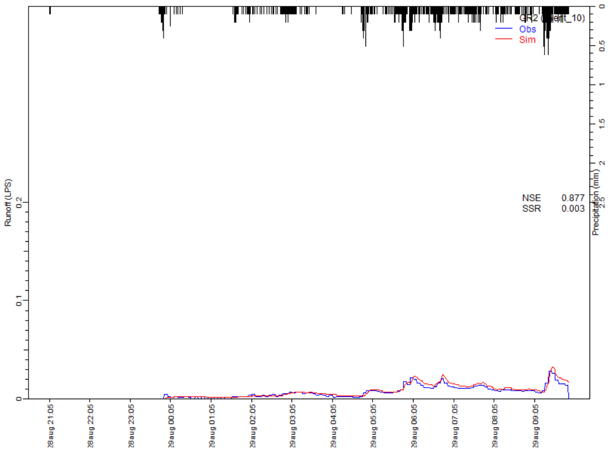


Figure C.1.3 Event 10^{C}

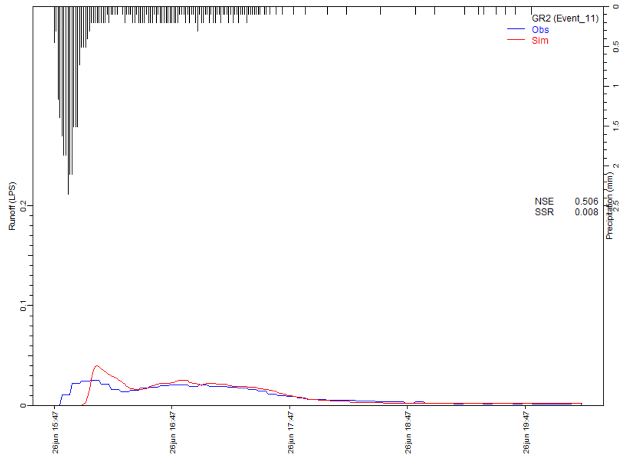


Figure C.1.4 Event 11^{C}

C.2 Validation events

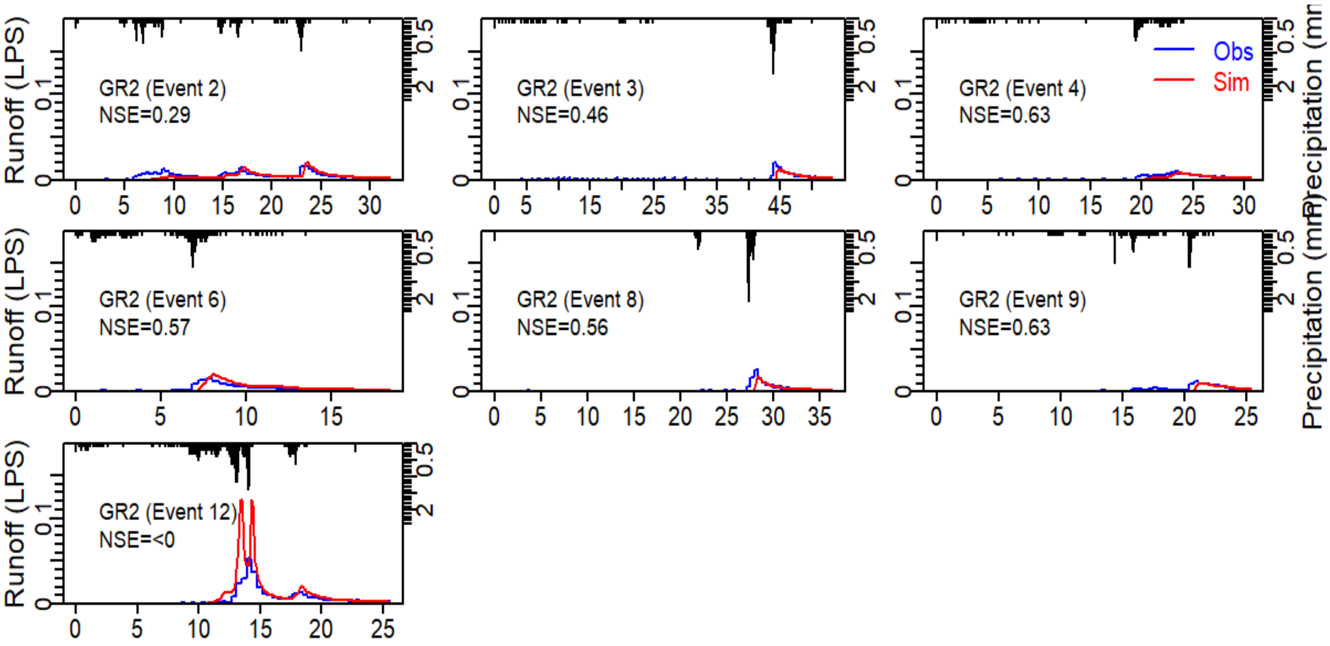


Figure C.2.1 Validation events with parameter set from event 1^C

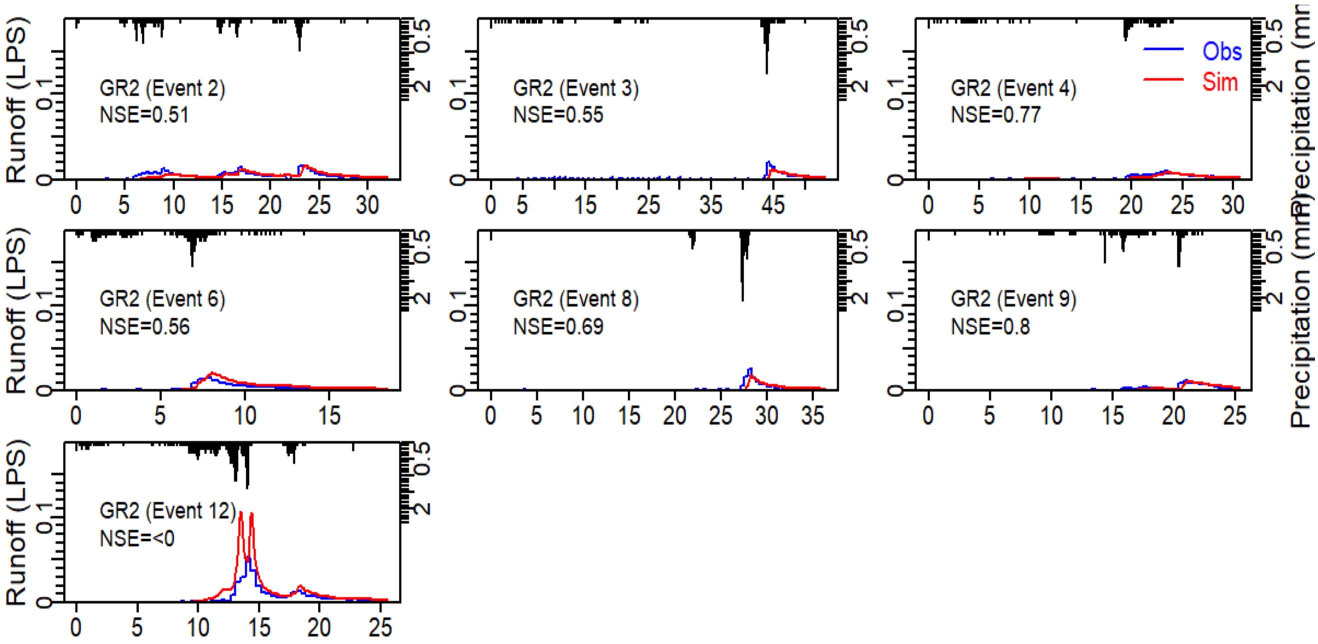


Figure C.2.2 Validation events with parameter set from event 5^C

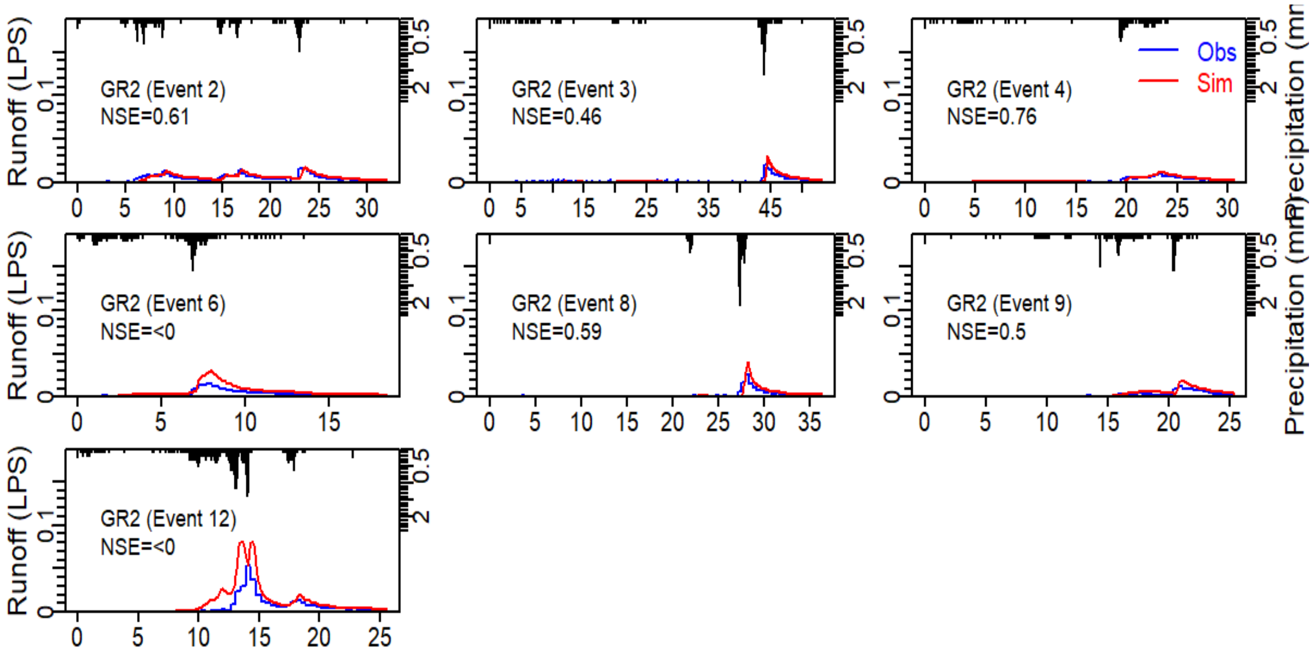


Figure C.2.3 Validation events with parameter set from event 10^C

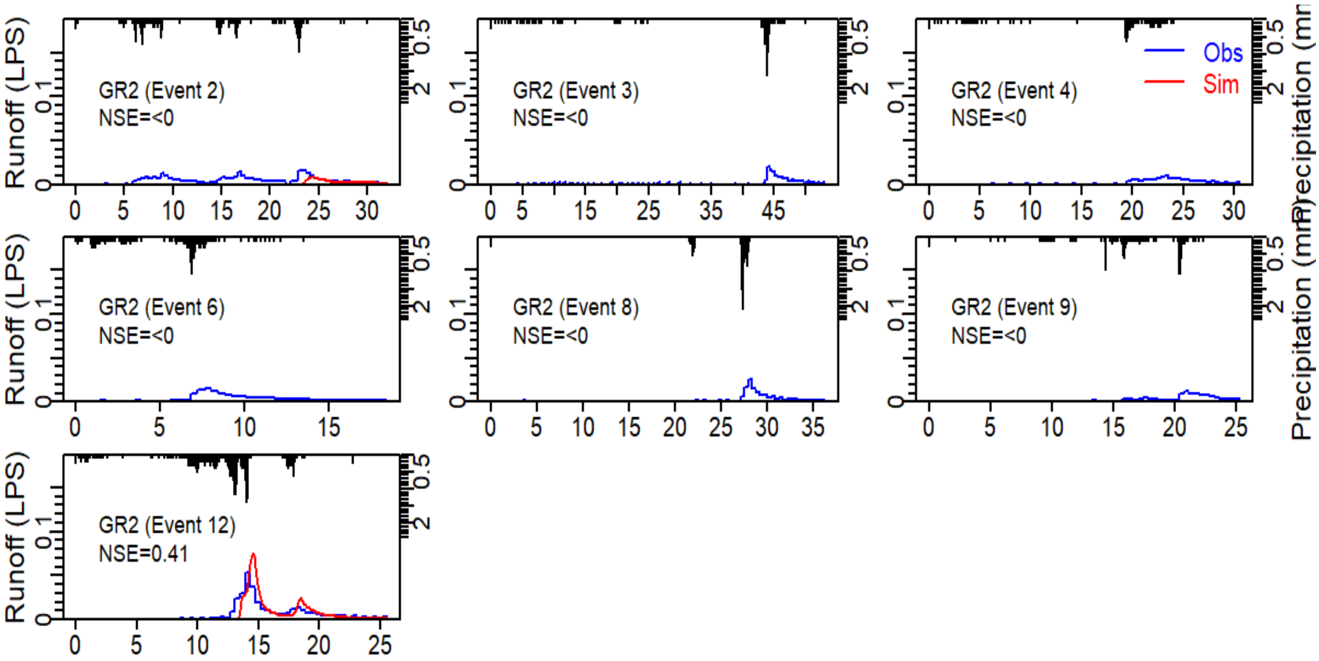


Figure C.2.4 Validation events with parameter set from event 11^C

Appendix D – R script

D.1 R script – Autocalibration of GR model

```
rm(list=ls())
graphics.off()

library(zoo)
library(geosphere)
require(rgdal)
library(hydroGOF)
library(hydromad)
require(raster)
# install.packages("hydromad", repos="http://hydromad.catchment.org")

setwd("C:/Users/ingridlr/Documents/GR_SWMM")
#setwd("M:/WD/Student/Projects/Ingrid/GR_SWMM")

load("Precip_all.RDat")                        ## Load precipitation data: all events
load("Runoff_all.RDat")                        ## Load Runoff data: all events
ppdt <- read.table("Data/Precip/P_Events.dat",header=F,skip=2)
source("GRSWMM_functions.R")

## Function for calibrating the GR model (SWMM)
GRModel <- function(thet) {
  ec <- ifelse(v==0, ev, vs)             # event
  thet <- round(thet, 3)
  write.table(thet, "par.txt", col.names = F, row.names = F)

  ## 1. Assign variables: parameter values
  por <- round(thet[1], 3)                       # Soil layers
  FC <- round(thet[2], 3)                        # Soil layers
  Ksat <- round(thet[3], 1)                      # Soil layers
  Kcoeff <- round(thet[4], 1)                    # Soil layers
  Vratio <- round(thet[5], 3)                    # Drainage Mats
  Rough <- round(thet[6], 3)                     # Drainage Mats
  InitSat <- SI_sat[ec]                          #LID_USAGE

  ## 2. Edit the input file
  # a) "[LID_CONTROLS]"
  i.LCN <- indexEXT(entry="[LID_CONTROLS]")
  t.LCN  <- CovTable2(i.L_=i.LCN[3])               # a.1) SOIL
  t.LCN[[1]][4:5] <- c(por, FC)                    # a.1) SOIL
  t.LCN[[1]][7:8] <- c(Ksat, Kcoeff)               # a.1) SOIL
  ot.swm[i.LCN[3]] <- FillLine(r=1, t.dat=t.LCN)   # a.1) SOIL
  t.LCN  <- CovTable2(i.L_=i.LCN[4])               # a.2) DRAINAGE MAT
  t.LCN[[1]][4:5] <- c(Vratio, Rough)              # a.2) DRAINAGE MAT
  ot.swm[i.LCN[4]] <- FillLine(r=1, t.dat=t.LCN)   # a.2) DRAINAGE MAT
  # b) "[LID_USAGE]"
  i.LUS <- indexEXT(entry="[LID_USAGE]")
  t.LUS  <- CovTable2(i.L_=i.LUS)
```

```
  t.LUS[[1]][6] <- InitSat
  ot.swm[i.LUS] <- FillLine(r=1, t.dat=t.LUS)
  # c) "[SUBCATCHMENTS]"
  i.SCA <- indexEXT(entry="[SUBCATCHMENTS]")
  t.SCA <- CovTable2(i.L_=i.SCA)
  t.SCA[[1]][2] <- F_evt[ec]
  ot.swm[[i.SCA[1]]] <- FillLine(r=1, t.dat=t.SCA)
  # d) "[RAINGAGES]"
  i.RNG <- indexEXT(entry="[RAINGAGES]")
  t.RNG <- CovTable2(i.L_=i.RNG)
  t.RNG[[1]][1] <- t.RNG[[1]][7] <- F_evt[ec]
  ot.swm[[i.RNG[1]]] <- FillLine(r=1, t.dat=t.RNG)
  H_rec <- HistRec(Pdat=P_dat[[ec]], Qdat=Q_dat[[s]][[ec]])  ## Historic records
  #(head(P_dat[[ec]]))
  #(head(Q_dat[[s]][[ec]]))

  ################################################################################

  ## Start and End time specifications
  BAnly <- as.POSIXct(paste(H_rec[[3]][1], H_rec[[3]][2]), format="%m/%d/%Y %H:%M:
%S", tz="UTC")
  BAnly <- BAnly-(1*60*60)
  BAnly <- as.character(c(format(BAnly, format="%m/%d/%Y"), format(BAnly, format="
%H:%M:%S")))
  #print(BAnly)
  ot.swm[15] <- replaceINP(Ln=15, new_dta=BAnly[1]) #change from 3 to 4 if want to
start reporting from runoff
  ot.swm[16] <- replaceINP(Ln=16, new_dta=BAnly[2])
  ot.swm[17] <- replaceINP(Ln=17, new_dta=unlist(strsplit(H_rec[[4]][1]," "))[1])
  ot.swm[18] <- replaceINP(Ln=18, new_dta=unlist(strsplit(H_rec[[4]][1]," "))[2])
  ot.swm[19] <- replaceINP(Ln=19, new_dta=unlist(strsplit(H_rec[[4]][length(H_rec[
[4]])]," "))[1])
  dmy <- unlist(strsplit(unlist(strsplit(H_rec[[4]][length(H_rec[[4]])]," "))[2],"
:"))
  ot.swm[20] <- replaceINP(Ln=20, new_dta=paste(dmy[1],as.character(I(as.numeric(d
my[2])+1)),dmy[3], sep=":"))

  ################################################################################

  writeLines(ot.swm, con=paste("Temp/L34b_", stn,".inp", sep=""))

  ## 3. Run the SWMM model: excute the .bat file
  system(paste("swmm_",stn,".bat", sep=""))

  ## 4. Evaluation. Print to Files. Figures.
  return(EvalPlot(vrf=v, plt=pl, thet=thet, Hrec=H_rec))
}

F_evt <- paste("Event_", 1:12, sep="") ## List: names of precipitation event files
stns <- paste("GR",1:2,sep="")
n_stns <- paste(stns,"_out",sep="")
#SI_sat <- c(18,32,27,32,28,27,26,32,22,31,19,24) #GR2 SWMM corrections
```

```r
SI_sat <- c(22,35,35,35,26,26,24,35,27,35,14,24) #GR1 SWMM corrections

s <- 2
#for(s in 1:length(stns)) {
  stn <- stns[s]
  for(ev in c(1:6,8,9,12)) {
    pl <- v <- 0
    f_name <- paste("Cal_L34b_",stn,"_model_6P_Event_",ev,".txt",sep="")
    n_stn <- n_stns[s]                    ## Node corresponding to gauging station
## Read the reference input file
    ot.swm <- readLines(con=paste("InpFiles/L34b_", stn,".inp", sep=""))

    ## Initial, lower and upper parameter values – (GR2)
    p.int <- c(0.65,    0.40,    2000,   40,    0.72,   0.2) #p fc cond conds vf n
    p.lwr <- c(0.55,    0.20,      36,    5,    0.05,  0.01)
    p.upr <- c(0.75,    0.54,    4200,   60,       1,   0.4)

    write.table(rbind(c("NSE","SSR","%Pdf", "d_cnY", "d_cnX", "T_lag", paste("P", 1:length(p.int), sep=""))), f_name,
                sep="\t", quote=F, append=F, col.names=F, row.names=F)
    m.opt <- SCEoptim(FUN=GRModel, par=p.int, lower=p.lwr, upper=p.upr, control=list(fnscale=-1))
    pl <- 1
    o.par <- m.opt$par
    # aaa__ <- as.numeric(unlist(read.table("par.txt", header=F)))
    # o.par <- thet <- aaa__
    P.sim <- GRModel(thet=o.par)
    ot.swm <- readLines(con=paste("Temp/L34b_", stn,".inp", sep=""))
    writeLines(ot.swm, con=paste("InpFiles/L34b_", stn, F_evt[ev],".inp", sep=""))

    ### Verification step
    f_nam2 <- paste("Verification_L34b_",stn,"_model_6P_","CalSet_", F_evt[ev],".txt",sep="")
    write.table(rbind(c("Event","NSE","SSR","%Pdf", "d_cnY", "d_cnX", "T_lag")), f_nam2, sep="\t", quote=F, append=F, col.names=F, row.names=F)
    for(vs in c(2:4,6:9,12)) {
      v <- 1

## Read the reference input file
      ot.swm <- readLines(con=paste("InpFiles/L34b_", stn,".inp", sep=""))
      P.sim <- GRModel(thet=o.par)
      ot.swm <- readLines(con=paste("Temp/L34b_", stn,".inp", sep=""))
      writeLines(ot.swm, con=paste("InpFiles/L34b_", stn, F_evt[ev],"_VerSet_", F_evt[vs],".inp", sep=""))
    }
  }
```