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Evaluating Hydrological Performance of LID-Modules in Mike Urban

A Case Study of CSO Reduction in Grefsen, Oslo

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Description

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Subject: LID modules in Mike Urban/Reduction of combined sewer overflows

Title: Evaluating Hydrological Performance of LID-Modules in Mike Urban ; A Case Study of CSO Reduction in Grefsen, Oslo

Background

Low Impact Development (LID) can be a cost-effective approach to manage water quantity, improve water quality and help communities stretch their infrastructure investments further by providing multiple environmental, economic, and community benefits. Blue green stormwater measures can be divided into two main categories; (1) detention performance during precipitation events and in the time immediate following the event; (2) retention (consumption) of water through storage and subsequent evapotranspiration. This master thesis will evaluate the modules for green roofs and bioretention cells in the urban water collection model, Mike Urban. It is expected that the detention performance will be a function of antecedent moisture content, precipitation intensity and duration, as well as substrate/soil specific properties. The evaluated LID modules will be applied to a case study to assess the impact on the reduction of combined sewer overflows (CSOs). This will be completed by testing different scenarios with synthetic precipitation events and use flow duration curves to evaluate the long term effect.

Objectives

1. Evaluate the suitability of the green roof and bioretention cell module in Mike Urban with specific focus on:
    a. Evaluation of the transfer of green roof model parameters from SWMM to Mike Urban
    b. Evaluation of the bioretention cell module through calibration of parameters using the Nash Sutcliffe Efficiency index as evaluation criteria
    c. Mike Urban as a transwatershed design tool – is it possible to find calibration

    parameters that span watershed boundaries?

2. Evaluation of the CSO reduction with implementation of the green roof and the bioretention cell module in Mike Urban
    a. To what extent do the implementation of LID-modules reduce the CSOs in volume and peak flow for different design events?
    b. Can application of flow duration curves work as a design strategy in evaluating CSO reduction?

Collaboration partners: Klima 2050, Vann- og Avløpsetaten, DHI

Location: Department of Civil and Environmental Engineering.

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Preface

This thesis is the final product of the course TVM4905 Water and Wastewater Engineering, Master's Thesis. It is submitted to the Norwegian University of Science and Technology (NTNU). The topic of the thesis is evaluation of the hydrological performance of LID-modules in Mike Urban and implementation of LID controls in urban areas for reduction of combined sewer overflows.

I would like to express my gratefulness to my supervisor Tone Merete Muthanna. Muthanna has given me feedback and advices, especially on topics related to the green roof and bioretention cell assessments together with model use and uncertainties. Thank you for inspiration and guidance during the writing process as well as great support throughout the master´s thesis semester. I will also thank Ashenafi Seifu Gragne for support with Mike Urban and the calibration processes. Thank you for informative discussions and for better understanding of urban drainage modelling.

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- Odd Adler-Gjerde and Kristina Tvedalen (DHI) for the Mike Urban model license and support with the modelling
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- Ingrid Lindberg Russwurm for providing data of the green roof calibration and better understanding of the SWMM model
- My supporting friends and family

Trondheim, June 11, 2018

Ragni Rønneberg Hernes

Sammendrag

Hyppigere og mer intense nedbørshendelser i tillegg til flere tette flater og en aldrende infrastruktur har ført til større risiko for kombinert overløpsdrift i byer. Regnvann som naturlig ble infiltrert og fordøyd i terrenget blir i dag ført til avløpsnettet som ikke har kapasitet til å håndtere det endrede nedbørsmønsteret. Overløpet «AK52» på Grefsen i Oslo slipper ut overvann og avløpsvann ut i den kritiske resipienten Akerselva. Det er ønsket å redusere dette overløpet med blant annet å implementere åpne overvannsløsninger.

Mike Urban har blitt brukt for å evaluere effekten av grønne tak og regnbed for reduksjon av overløpsdriften på Grefsen. Første steg i metoden er å evaluere den hydrologiske ytelsesevnen til de nylig lanserte overvannsmodulene (LID-modulene) i Mike Urban. Dette er gjennomført ved bruk av observerte avrenningsdata fra et grønt pilottak i Oslo sammen med 3 kalibrerte parametersett fra SWMM. For regnbedet er det blitt brukt observerte avrenningsdata fra et tidligere eksperiment samt relevante parametere fra litteraturen. Regnbedet er kalibrert i Mike Urban og evaluert med Nash-Sutcliffe Efficiency (NSE) koeffisienten. De evaluerte og kalibrerte modulene har deretter blitt implementert i modellen for Grefsen. Fire ulike scenarier med forskjellig prosentandel implementerte grønne tak og regnbed har blitt utviklet. Dette gir en prosentvis reduksjon av de impermeable arealene. Et siste scenario består av fullstendig reduksjon av de impermeable arealene med både grønne tak og regnbed. Alle scenarioene ble simulert med fire syntetiske nedbørshendelser og en langtidsserie med observert nedbørsdata fra 1993.

I evalueringen av grønne tak ble det observert gode resultater for to av simuleringene i Mike Urban. Disse hendelsene viste gode korrelasjoner med observerte data og også en tydelig likhet med avrenningskurven i SWMM. Likevel, for en tredje hendelse ble det observert et avvikende resultat sammenliknet med resultatet fra SWMM. Noen modellparametere ble funnet sensitive i Mike Urban og ulikheter i bruk av infiltrasjonsmetoder og designforskjeller kan ha påvirket resultatet. Regnbedet økte fra 0.06 til 0.73 i NSE-verdi etter manuell kalibrering. Det ble observert en forsinkning i den simulerte avrenningskurven. Utgangssaturasjonen i mediet ble funnet sensitiv til denne forsinkningen samt den maksimale avrenningen. Andre sensitive parametere for kalibreringen av regnbedet var parametere knyttet til jordmediet samt utløpseksponenten. Begge LID-modulene responderte tilfredsstillende i Mike Urban. Likevel ble det funnet at en direkte overføring av parametere fra SWMM var en kompleks prosess og at kalibreringsusikkerheter gjør det vanskelig å finne parametere for universell bruk.

Implementering av LID-modulene til Grefsenområdet viste at en reduksjon av de impermeable arealene på 3,6 % resulterte i en reduksjon av overløpsvolumet på over 7 % for alle scenarier og

simulerte nedbørshendelser. Regnbed responderte bedre ved de store nedbørshendelsene, mens grønne tak hadde en god effekt under de mindre hendelsene. Den kombinerte løsningen gav 100 % reduksjon av overløpet for de to minste nedbørshendelsene. Resultatgrafene for simulering med syntetiske nedbørsserier gav avrenningskurver uten bemerkningsverdige haler. Dette kan tyde på at modellen ikke etterligner virkeligheten fullt ut da det er kjent at disse overvannstiltakene forsinker avrenningsvolumer i større grad. Det kan dermed diskuteres om simulering med syntetiske nedbørsserier er den best egnede metoden for å evaluere implementering av overvannstiltak.

Videre ble det laget en «flow-duration»-kurve for en simulering med nedbørdata for 325 dager fra 1993. Kurven viste at overløpet ble redusert fra 2 timer uten tiltak til 50 minutter med den kombinerte løsningen. Alle scenarier gav reduksjon i både volum, varighet og overløpshendelser. Kurven viste også at totalvolumet gjennom året ble redusert i større grad ved implementering av regnbed, men at grønne tak viste seg å fungere godt ved mindre hendelser, spesielt for hendelser der overløpet ikke ble aktivert. «Flow-duration»-kurven har vist seg å være et nyttig verktøy for å forstå helheten og langtidseffekten av å implementere overvannstiltak. Den kan også brukes til å måle suksess av å oppnå spesifikke krav til overløpsdrift. Det er videre anbefalt å kjøre lengre tidsserier og tidsserier med våtere og mer intense nedbørshendelser for å kunne oppnå en robust evaluering av overløpsreduksjon på Grefsen.

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Thesis Structure

This thesis has been written in paper format. This is an untraditional format for the master's thesis. The manuscript presented in this thesis is the enlarged version of the paper ("Evaluating Hydrological Performance of LID-Modules in Mike Urban; A Case Study of CSO Reduction in Grefsen, Oslo"). The paper has been accepted for presentation at The Nordic Hydrological Conference which will take place in Bergen 13th to 15th of August 2018. Further information about the framework of the scientific journal is seen in Appendix A. Complementary information and results not included in the paper, are found in Appendices B – J.

Abbreviations

AK52	Overflow weir in case area Grefsen
BRC	Bioretention Cell
CF	Climate Factor
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
DHI	Danish Hydraulic Institute
EIA	Effective Imperviousness Area
FDC	Flow Duration Curve
GR	Green Roof
IDF	Intensity - Duration – Frequency
ImpKW	Calculated impervious area for the kinematic wave surface runoff model
ImpPhys	Physical impervious area
KW	Kinematic Wave surface runoff model
LID	Low Impact Development
MIKE 1D	Modelling engine in Mike Urban
MOUSE	Model for Urban Sewers
MU	MIKE URBAN
NB21	Nils Bays vei 21 (Bioretention Cell)
NSE	Nash-Sutcliffe Efficiency Index
Oslo VAV	Oslo Municipality Water and Sewerage Administration
PE	Person Equivalents
Q_{mu}	Simulated runoff in the Mike Urban model
Q_o	Observed runoff
Q_s	Simulated runoff
Q_{swmm}	Simulated runoff in the SWMM model
SWMM	Storm Water Management Model
TA	Time-Area surface runoff model
y	Year of return period
2y	Precipitation event with 2 years of return period
5y	Precipitation event with 5 years of return period
5y(c)	Precipitation event with 5 years of return period and added climate factor of 1.5
30y(c)	Precipitation event with 30 years of return period and added climate factor of 1.5

Evaluating Hydrological Performance of LID-Modules in Mike Urban; A Case Study of CSO Reduction in Grefsen, Oslo

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Norwegian University of Science and Technology (NTNU), 2018

Abstract

Paved surfaces, increased precipitation amounts and intensities in addition to limited capacity in the sewer systems, cause a higher risk of combined sewer overflows (CSOs). Low impact development (LID) is a possible solution to mitigate some of the consequences by managing the stormwater locally. To evaluate the effect of LID controls, the hydrological performance of the green roof (GR) and the bioretention cell (BRC) modules in the Mike Urban (MU) model have been evaluated and applied to the Grefsen catchment in Oslo. Observed data from a pilot GR and a previously tested BRC were used in the evaluation of the modules in addition to three GR parameter sets from a study using the SWMM model. The NSE index showed respectable results for 2/3 GR events compared to the results in SWMM. The BRC reached an NSE value of 0.73 post calibration. The hydrological performance of the LID modules in MU was satisfactory, but some inaccuracies in the transfer of the SWMM parameters were detected. The CSO reduction in the Grefsen catchment simulated with synthetic precipitation events presented superior results for BRCs during larger precipitation events, while GRs were proven to have beneficial outcomes during smaller events. The flow duration curve was furthermore confirmed a satisfactory analysis tool in evaluating the overall importance of LID controls. The case study approach has been valuable to test the real life complexity typically faced in modelling urban combined systems.

Keywords:
CSO, Flow duration curves, Hydrological modelling, LID, Mike Urban, Urban drainage

1 Introduction

Increased use of impervious surface due to urbanization has led to challenges in facing the consequences of climate change with increased precipitation volumes and intensities (Jacobson, 2011, Shuster et al., 2007). Limited natural infiltration and evaporation processes in urban areas are some of the outcomes causing increased runoff rates and flooding. Alongside with population growth and aging infrastructure, the capacity of the combined sewer systems (CSSs) is pressed to the limit (Nilsen et al., 2011). Another aspect of the problem is combined sewer overflows (CSOs) polluting the receiving waters. CSOs are significant contributors of wastewater and an unfortunate mixture of waste, toxic materials, pollutants and plastics which are routed to the oceans (EPA, 2011). In light of the recent focus on the ever increasing plastic pollution to the oceans there is projected to be more plastic than fish in the world Oceans by 2050 (Lykketoft et al., 2016). In a case study in Norway by Nie et al. (2009), the total amount of CSOs was predicted to increase with 36 % with a correspondingly 20 % increase in precipitation due to climate changes. Moreover, Nilsen et al. (2011) looked at future climate scenarios and predicted an total CSO increase of 82.9 % when using years with maximal annual precipitation as a base for the projections. Yet, a number of green solutions have been proven valuable in reduction of CSOs along with other environmental and economic benefits (Eckart et al., 2017, Fenner, 2017, Liu et al., 2015, Liao et al., 2015).

A large number of studies have investigated the implementation of LID controls to reduce CSOs. Lucas and Sample (2015) investigated the reduction of CSOs and found that a solution with green infrastructure gave the most resilient system with lowest peak flows and smallest outflowing volumes compared to traditional grey infrastructure. Moreover, Liao et al. (2015) discovered in their study of CSOs that the combination of grey solutions and LID controls resulted in a superior reduction in volume and peak flow compared to the grey solution isolated. One of the methods to model LID practices is to look at the reduction of the Effective Impervious Area (EIA), used in the study by Palla and Gnecco (2015) amongst others. EIA is the impervious area hydraulically connected to the drainage system contributing to increased stormwater runoff rates and volumes (Shuster et al., 2007). It has been discussed in literature that a reduction in EIA can have a positive impact on the efficiency in the urban drainage systems (Palla and Gnecco, 2015, Lucas and Sample, 2015).

MIKE URBAN (MU) is a system developed by the Danish Hydraulic Institute (DHI) for modelling water distributing networks and collection systems (DHI, 2017a). MOUSE (Modelling Urban Sewers) and MIKE 1D are two simulating engines that can be simulated with the time-area (TA) or the kinematic wave (KW) surface runoff model amongst others. The TA model is a simple surface runoff model based on minimal data input necessities. The

KW model is amongst others dependent on the length and slope of every sub-catchment alongside with the roughness of five characteristic contributing surfaces (DHI, 2017b). The program upgrade in 2017 released the LID implementation option with a catchment-based method built on the research published by US EPA (DHI, 2017a). Each of the LID-modules contain a set of layers and associated parameters. The LID-modules in MU can be simulated with the MIKE 1D engine and the KW surface runoff model, exclusively (DHI, 2017a). Several studies regarding the hydrological performance of LID-modules, both individually and on a catchment scale, have been done using the open source model "Storm Water Management Model" (SWMM) (Chui et al., 2016, Gülbaz and Kazezyılmaz-Alhan, 2017, Palla and Gnecco, 2015, Peng and Stovin, 2017). These studies have been used as references due to limited present material concerning the LID-modules in the MU model.

Calibration is a necessity in models used for technical systems (Tscheikner-Gratl et al., 2016). It is considered important in modelling of LID modules to achieve reliable model results (Krebs et al., 2016b). However, it has been proven that the calibrated parameters are not generic and that they can also variate for different precipitation events (Russwurm, 2018, Peng and Stovin, 2017). Rosa et al. (2015) calibrated measured and literature based parameters for a watershed using traditional runoff controls and a watershed using LID controls. It was found that the uncalibrated SWMM simulations for the LID watershed had less acceptable results compared to observed data then the traditional watershed. The predictions for the LID watershed improved significantly post calibration.

Many studies have looked at the peak flow and volume reduction for LID implementation using single synthetic design events (Palla and Gnecco, 2015, Chui et al., 2016). This is a simple and effective way of assessing the effect of stormwater controls. However, a limited analysis of evaluating peak flow and volume reduction in synthetic design events may be a less robust method for LID design planning. A flow duration curve (FDC) present the amount of flow with increasing duration (Lucas and Sample, 2015). It can be a practical design tool to display the complete range of discharges and compare scenarios in hydrological modelling. Palhegyi (2010) focused on using FDCs when presenting results of modelling bioretention cells implementation in three watersheds. The study illustrated that the use of the FDC strategy provided a clever result analysis for long term surface hydrology in terms of meeting specific design criteria.

Limited references have been found of incorporate LID modules in MU. In order for this to be a transwatershed design tool, it is essential to find calibration parameters that span watershed boundaries. This is currently lacking in literature. Based on these research needs, the objectives for this paper is as follows;

1. Is the hydrological performance of the evaluated LID-modules in MU of acceptable range?
2. How is the effect of LID implementation on the overflow weir in the Grefsen catchment?
3. To what extent can flow duration curves work as a practical result analysis tool in LID design planning?

2 Study Area and Data

2.1 Site description

Grefsen is located in the northern part of Oslo and is a typical residential area with partly combined and partly separated sewers. Oslo has an annual rainfall of 755 mm, normally with the heaviest precipitation events during the summer months (Klimaservicesenter, 2017). This study will focus on the combined sewer systems (CSS) part of the Grefsen catchment. The area connected to the CSS is roughly 50 ha (≈37 % of total area) with 793 buildings and 2299 person equivalents (PE) (46 PE/ha). The area connected to the CSS is relatively flat and the impervious area is 27 %, with 18 % roof coverage and 9 % roads and parking lots. The area experiences frequent problems in terms of flooding of basements and repeated CSOs polluting the receiving river Akerselva due to underlying clay deposits and limited capacity in the CSS (NGU, 2018, Oslo Municipality and VAV, 2014). Total monitored time of CSOs over five years (2011, 2012, 2013, 2016 and 2017) is 1594 minutes based on calculations from Oslo Municipality Water and Sewerage Administration (Oslo VAV). Hence, the municipality of Oslo has established a goal to reduce the frequency of CSOs (Oslo Municipality, 2015, Oslo Municipality and VAV, 2014). To reach this goal several alternatives of low impact development (LID) systems may be a solution by focusing on step 1 and 2 in the strategy for stormwater management (Oslo Municipality, 2014). Site area is illustrated in Figure 1.

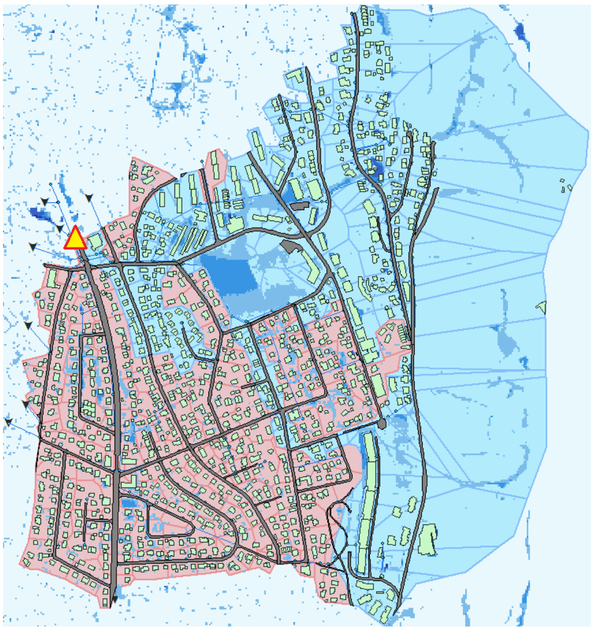


Figure 1 Grefsen area illustrated in the MU model. Red sub-catchments denote area connected to the CSS, blue areas refer to area connected to the separate system. Overflow weir, AK52, is marked with a hazard triangle.

2.2 LID-modules Input Data

The evaluation of the green roof (GR) module was based on observed discharge from a pilot GR in Oslo together with three parameter sets from a study using the SWMM model (Russwurm, 2018). Three precipitation events and corresponding parameter sets for the GR were applied in MU to evaluate the hydrological performance. The three events, fixed parameters and calibrated parameter sets for every event may be observed in Table 1.

Observed data from a previous experiment exploring the detention capacity of a bioretention cell (BRC) in Oslo, were used to assess the parameter set for the BRC module in MU (Saksæther and Kihlgren, 2012). The experiment produced a synthetic precipitation event by pouring water from a tank into the BRC with a known volume over time, which made it possible to estimate the approximate return period for the event. Two of these synthetic events for the BRC named “NB21” have been used to construct a suitable time series for the simulation of the BRC module in MU. The observed discharge (Q_o) from the experiment for event 1 was used as the reference for the calibration. Precipitation events and BRC characteristics for NB21 are listed in Table 1.

Table 1 Precipitation events and input parameters for a) the green roof and b) the bioretention cell.

a) Green Roof*

Precipitation events

Event #	Start time (YYYY/mm/dd HH:mm:ss)	Duration (h)	Total prec. (mm)	Max. intensity (mm/h)	Return period (Y)
1	2011/06/07 07:09:00	2.75	29.5	1.22	5
10	2011/08/28 21:05:00	20.50	56.4	0.43	20
11	2014/06/03 15:47:00	14.35	45.0	2.06	5

Fixed parameters for all events

Catchm. area (m^2)	Slope (%)	Store. h. (mm)	Veg. cov(%)	Surf. r. (M)	Thickn. soil(mm)	Wilt. p.(1/1)	Suct. h (mm)	Thickn. drain.mat (mm)
8	5.5	3	0.1	5.0	40	0.10	60	10

Parameter sets

Event #	Int.sat (%)	Width (m)	Por. (1/1)	Field cap. (1/1)	Cond. (mm/h)	Con. slope (-)	Void fract. (1/1)	Drain. mat roughm. (M)
1	18	2	0.736	0.417	1340.9	27	0.091	6.41
10	31	2	0.623	0.301	362.9	20.5	0.06	11.76
11	19	2	0.745	0.205	36.6	60	0.863	2.82

b) Bioretention Cell

Precipitation events

Event #	Start time (YYYY/mm /dd HH:mm:ss)	Duration (h)	Total prec. (mm)	Return period (Y)
1	2011/08/31 15:36:00	0.5	20.4	5 – 10
2	2011/09/01 08:03:00	0.33	24.1	25 – 30

General		
Catchment/Collection area (m^2)	149.3/139	Saksæther and Kihlgren (2012)
Surface area BRC (m^2)	10.3	Saksæther and Kihlgren (2012)
Volume capacity (m^3)	2.74	Saksæther and Kihlgren (2012)
Sand/Compost/Other (%)	50/ 45/ 5	Braskerud and Paus (2013)
Clay/Silt/Sand (%)	6/ 17/ 77	Saksæther and Kihlgren (2012)
Organic material (%)	8	Saksæther and Kihlgren (2012)
Initial saturation (%)	34	Saksæther and Kihlgren (2012)
Surface layer		
Height (mm)	200	Braskerud and Paus (2013)
Soil layer		
Thickness (mm)	600	Braskerud and Paus (2013)
Hydraulic conductivity (m/h)	0.37	Braskerud and Paus (2013)
Storage layer		
Height (mm)	200	Braskerud and Paus (2013)
Drain layer		
Drainage pipe diameter (mm)	100	Braskerud and Paus (2013)
Drain capacity flow (mm/h)	200(1)	Saksæther and Kihlgren (2012)
Offset height (mm)	50	Saksæther and Kihlgren (2012)

*All data from study by Russwurm (2018)

(1) Max flow of Q_o

2.3 Case study input data

A calibrated MU model from Oslo VAV has been used for the implementation of LID-modules at the Grefsen study site. The area connected to the CSS is divided into 136 sub-catchments and consists of 145 manholes, 158 pipes, and one overflow weir named AK52. The MU model was calibrated using the TA surface runoff model, while in this study it has been modified for use of the KW surface runoff model. The MU model has been run using the MOUSE and the MIKE 1D engine (DHI, 2017a).

Four synthetic precipitation events have been constructed from IDF-curves based on methods from Oslo VAV. A common practice in Norway for evaluating the future precipitation intensities is to use a climate factor (CF). In Oslo a CF is estimated to be 1.5 for events with 200 years return period (Paus et al., 2014). Thus, a CF of 1.5 has been used for two of the events for a conservative approach, both marked with the annotation (c). Event 1 refer to a return period of 2 years (2y), event 2 a return period of 5 years (5y), event 3 a return period of 5 years with CF (5(c)) and event 4 a return period of 30 years with CF (30y(c)). I order to analyze the time of exceedance for the overflow weir over a longer period of time, an input precipitation series from 1993 was used.

3 Methods

The method was divided into two main parts; (1) The hydrological performance of the green roof and the bioretention cell modules were evaluated; and (2) the evaluated LID controls were applied to the Grefsen catchment in Oslo to assess the effect on the CSO at AK52.

3.1 Hydrological Performance of the LID-modules

Simulated discharge was calculated using the kinematic wave model (KW) and the MIKE 1D engine for the GR and the BRC modules. Parameter sets for the three events in the SWMM study were used in MU to simulate the discharge from the GR with the associated precipitation time series, see section 2.2, Table 1. The model setup consisted of a catchment area and a connected GR with equal surface area. To be able to compare the observed discharge results from the pilot GR with the MU results, the Nash-Sutcliffe efficiency index (NSE), shown in Equation 1, was calculated for the three selected events. Furthermore, the NSE index was calculated for evaluation of the correspondence between the discharge curves in MU and SWMM.

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

The bioretention cell "NB21" was used for calibration in this study (Saksæther and Kihlgren, 2012). Similar area characteristics at the NB21 site and the study site at Grefsen made NB21 a suitable BRC to use as input parameters, supported with appropriate literature. The model setup consisted of a catchment area with the size of the collecting area (roof) and the BRC itself. The BRC setup was created with fixed input parameters from Table 1 in section 2.2, and parameters selected from literature shown in Table 2.

Table 2 Bioretention cell parameters.

Surface layer		
Vegetative cover (-)	0.10	Chui et al. (2016)
Surface roughness (M)	10	Chui et al. (2016)
Surface slope (%)	1	Chui et al. (2016)
Soil layer		
Porosity (1/1)	0.5*	Chui et al. (2016)
Field capacity (1/1)	0.2*	Chui et al. (2016)
Wilting point (1/1)	0.1*	Chui et al. (2016)
Conductivity slope (-)	10	Chui et al. (2016)
Suction head (mm)	87.5	Chui et al. (2016)
Storage layer		
Porosity (1/1)	0.40*	DHI (2017a)
Infiltration cap. of surrounding soil (mm/h)	0	Cipolla et al. (2016)
Clogging factor (-)	0	DHI (2017a)
Drain layer		
Exponent (-)	0.5*	Chui et al. (2016)
* Parameters for calibration		

Event 1 (from Table 1) was used for the calibration process. The aim of the calibration was to match the peak flow of the simulated and observed discharge curves. It was necessary to go through with manual calibration, changing selected parameters which are not based on physical geometry marked with a * in Table 2. An upper limit of 100 simulations were set for the manual calibration if not a predetermined NSE value of 0.8 was fulfilled earlier. Following calibration of event 1, the calibrated parameters were applied to event 2. This was done as a verification of goodness of fit, and it was not performed a direct calibration of parameters for event 2. Ultimately, a sensitivity analysis was executed for the initial saturation and the width parameter alongside with the calibration parameters.

3.2 Case: Grefsen

3.2.1 The MIKE URBAN Model

The calibrated MU model was constructed by using the time-area (TA) surface runoff model, while in implementation of LID modules the kinematic wave model (KW) must be applied.

Consequently, a calibration of the kinematic wave parameters has been necessary. The model was simulated with the TA model applying the input precipitation events (event 1, 2, 3 and 4). The weir discharge at AK52 for event 2, 5 years of return period, was used during the manual calibration. Event 1, 3 and 4 were applied for verification of the model.

First, the imperviousness of every sub-catchment in the KW model setup was estimated by using the imperviousness in the TA model as a reference. The physical imperviousness (ImpPhys) was calculated from the MU maps. The relation between the ImpPhys and a generated imperviousness for the KW model (ImpKW) has consequently been computed with a transfer function seen in equation 2. The transfer function has a linear parameter (a) and an exponential parameter (b) to be able to achieve the best possible relation. The calculated ImpKW for every sub-catchment was then allocated into steep imperviousness for roofs and flat imperviousness for roads in the KW setup section (DHI, 2017b). The permeable areas were set as low permeable.

$$ImpKW = a * ImpPhys^{b} \tag{2}$$

Secondly, the default slope in the KW parameter section of 10 ‰ was chosen to keep as a fixed parameter, while the characteristic length of each sub-catchment and the Manning´s number where used as parameters for the calibration. The parameters were kept uniform for every sub-catchment. During calibration, it was decided to keep the contribution of runoff from the permeable areas equivalent to zero due to overestimated magnitudes of discharge. Thus, the Manning´s number was set equivalent to zero for the permeable contributing areas. The NSE index was calculated to evaluate the success of the calibration. Ultimately, a sensitivity analysis was performed for the calibration parameters.

With calibrated KW parameters and a satisfactory NSE value (>0.9) for event 2, the remaining events were simulated. The weir discharge at AK52 for every event from the KW simulation was compared with the corresponding discharge from the TA simulation. With NSE values superior than a value of 0.9 for all events, the calibrated model was affirmed ready for use.

3.2.2 Implementation of LID-modules

The calibrated GR and BRC modules have been used for the LID implementation in the case study. From the calibration of the GR, the three parameter sets for the three events in Table 1 were evaluated. The parameters used in the SWMM model are not generic and there are many uncertainties in approximating the values (Peng and Stovin, 2017). Moreover, the parameters in the SWMM study (Russwurm, 2018) consisted of large variations in the parameter sets for the different events for the same pilot roof. Hence, it was decided to pick the median value from the three parameter sets. The calibrated parameter set for the BRC was used without any further modifications. It was not accounted for evaporation processes in the modelling of GRs or BRCs, which may underestimate the efficiency of the modules in implementation to the Grefsen catchment.

3.2.3 Scenarios

Table 3 Case scenarios

LID implementation	Scenarios				
	0	**I**	**II**	**III**	**IV**
GR (% of roofs)	0	20	50	100	-
EIA reduction (% of catchment area)	**0**	**3.6**	**9**	**18**	-
BRC (% of roofs)	0	20	50	100	-
EIA reduction (% of catchment area)	**0**	**3.6**	**9**	**18**	-
GR (% of roofs) + BRC (% of roads)	-	-	-	-	100
EIA reduction (% of catchment area)	-	-	-	-	**27**

Four scenarios with implementation of the calibrated GR and BRC were constructed for reducing the CSO at the overflow weir AK52. Scenario 0 refers to the “do-nothing”-scenario. Each scenario has been created with a certain percentage of LID implementation, which each result in an Effective Impervious Area (EIA) reduction of the catchment area. It is assumed that all the impervious area calculated for the KW model is hydraulically connected to the drainage system. Thus, all the calculated impervious area for the KW model is counted for as EIA ((Shuster et al., 2007, Krebs et al., 2016a). Ultimately, a combined solution (Scenario IV) with a complete EIA reduction (27 %) was created where the BRC was applied for reducing the EIA of the fraction of roads. Scenarios are listed in Table 3. All scenarios were simulated with the selected input precipitation events with return periods of 2, 5 and 30 years. For each scenario, the CSO volume and peak flow reduction and the hydrograph delay have been evaluated and compared. In order to evaluate the long term effect of the LID implementation in the Grefsen area, a flow duration curve (FDC) was created for the precipitation series from 1993.

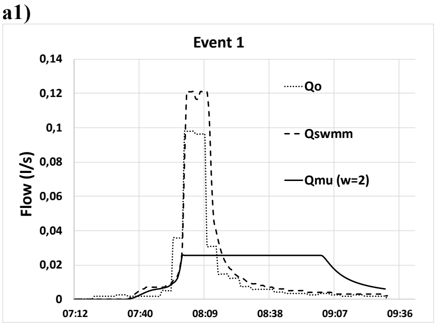
4 Results and Discussion

4.1 The Green Roof and Bioretention Cell modules

For the GR evaluation, event 10 and 11 reached reasonable NSE values compared to the SWMM results, while event 1 resulted in inferior NSE values. Results are listed in Figure 2. The physical width of the GR of 2 m was preserved in the SWMM model. However, it was observed that this parameter had an impact on the peak flow in MU. Consequently, the width was extended to a value of 12 m to test the sensitivity of the parameter. The NSE value for event 1 and 10 increased when applying a width of 12 m. Moreover, the match in peak flow and the match between the MU and SWMM discharge curves improved correspondingly. Nevertheless, event 11 did not follow the same pattern as the previous events and achieved the best match by maintaining the original width. This event had the highest registered maximum intensity, but no other noticeable pattern of the different responses for the events were detected. Other parameters may have affected the dissimilarities in SWMM and MU, but a full calibration procedure was not continued.

For event 1, it was observed that the drain outflow was initiated before the beginning of the precipitation event in the SWMM model, but for the MU model it was delaying until introduced precipitation. This may derive from the fact that the initial saturation in the soil and the drainage layer is considered the same in SWMM resulting in runoff before the initial saturation exceeds the field capacity (Peng and Stovin, 2017). Other observations illustrated generally softer discharge curves for all events in MU compared to SWMM. Some differences in the SWMM and MU models may have affected the results. The SWMM model was simulated with the Green-Ampt infiltration equations, while using the KW surface runoff model in MU, the Horton´s equations were automatically applied. Differences in how these infiltration models take the antecedent moisture conditions into account may lead to conflicting results (Mallari et al., 2015). Moreover, some design layout dissimilarities are found between the two models in creating sub-catchments and for the impervious parameters amongst others (Rossman, 2015, DHI, 2017a).

The parameters for the green roof module have proven to be dependent on every unique roof and include many uncertainties in estimating the values (Peng and Stovin, 2017). Moreover, the parameters from SWMM used in this study showed a large variation of calibrated parameters for the same pilot roof. This complicates the parameterization for widespread use and makes transfer of parameters between different hydrological models a complex routine.

a) Green Roof				
Event #	**NSE(Q_{swmm}/Q_o)**	**NSE (Q_{mu}/Q_o)**	**NSE (Q_{mu}/Q_{swmm})**	**a1)**
1	0.73	0.14 (0.78)	0.17 (0.95)	
10	0.88	0.85 (0.90)	0.98 (0.99)	
11	0.51	0.56 (0.51)	0.99 (0.72)	

b) Bioretention Cell				
Soil Layer			**Storage layer**	**Drain layer**
Porosity (1/1)	Field cap. (1/1)	Wilting point (-)	Porosity (1/1)	Exponent (-)
0.39	0.26	0.06	0.37	2.2

Calibration Results									
Event 1					**Event 2**				
NSE_{pre}	NSE_{post}	Hydrograph delay (min)	ΔPeak flow (%)	Time to peak (min)	NSE_{pre}	NSE_{post}	Hydrograph delay (min)	ΔPeak flow (%)	Time to peak (min)
0.06	0.73	+3	+0.48	+3	0.14	0.60	+2	-3.41	+3

Figure 2 LID-module results. ***a)*** *Green roof. NSE values associated to the three calibration events. NSE(Qswmm/Qo) refers to the original NSE value from the SWMM study. NSE(Qmu/Qo) refers to the NSE value calculated in this study with MU. NSE(Qmu/Qswmm) refers to the comparison between the SWMM and the MU discharge curves. Parenthesis indicate NSE values using the width of 12 m.* ***a1)*** *Event 1 simulated with the original width of 2 m.* ***b)*** *Bioretention cell. Calibrated parameters and calibration results for both events.* *NSE_{pre} and NSE_{post} represent the values before and after calibration, respectively.*

For the BRC evaluation event 1 was simulated with the input parameters from Table 2 before manual calibration was initiated. Satisfactory results for the peak flow were achieved. The calibrated parameter set of can be observed in Figure 2 together with the calibration results.

The input time series was made as a synthetic precipitation event in MU and will not represent the tank inflow in the experiment absolutely. This may complicate the complete mimicking of the BRC as exemplified with the hydrograph delay in the beginning of the events, seen in Figure 2. Finding the optimal parameters through manual calibration will affect other properties of the simulated curve depending on what criteria is set as objective. Increased initial saturation reduced the hydrograph delay, but correspondingly increased the peak flow and lowered the NSE value. The sensitivity analysis showed that a 90 % increase in initial saturation affected the peak flow with an increase of 13 %. Compared to a study in SWMM by Chui et al. (2016) it was found that the impact of the initial saturation on the peak flow for bioretention cells was minimal, questioning the correspondences of the SWMM and MU models. As the soil parameters are dependent on each other (DHI, 2017a), the three parameters were changed simultaneously for the sensitivity analysis. The soil parameters and the drain exponent appeared to have the greatest impact on the peak flow. Compared to other studies the hydraulic conductivity, berm height and size of the drain have been found as sensitive parameters (Sun et al., 2011, Chui et al., 2016). These were set as fixed parameters in this study and were not evaluated in the sensitivity analysis. Porosity in the storage layer was less sensitive and the width parameter had no detectable impact on the peak flow.

The calibrated parameters will not necessarily function for other similar BRCs with different design events. This complicates the transfer of parameters for widespread use. Besides the hydrograph delay, the MU model replicates the observed discharge curve satisfactory.

4.2 Case: Grefsen

4.2.1 Calibration

During the calibration process the calculated imperviousness for the KW model (ImpKW) was reduced additionally to match the discharge volume and peak flow from the TA model. Tscheikner-Gratl et al. (2016) argued that uncalibrated models may overestimate runoff volumes and that they are sensitive to the impervious parameter. This was comparable for the simulation of the uncalibrated kinematic wave model. The transfer function for the impervious area in the KW model was optimized in the calibration process and resulted in the linear parameter “a” of 1.1 and the exponential parameter “b” of 0.658. Associated with other studies the imperviousess is important in calculation of the surface runoff and use of different methods to calculate the impervious area may lead to different outcomes (AL-Amin and Abdul-Aziz, 2013). Manning´s n was calibrated to be 0.0125 and 0.0143 for the steep and flat imperviousness, respectively, and zero for the permeable surfaces. The characteristic length of every sub-catchment was set to a value of 10 m during calibration to match the initiation of the observed discharge curve. Manning´s n for the permeable surfaces was observed to be the most sensitive parameter followed by the Manning´s n for steep impervious and flat impervious areas. Slope and length were less sensitive parameters.

The calibration procedure has illustrated the complexity of assessing parameters that reproduce physical characteristics. Slope, length and Manning´s n were set equal to all sub-catchment which will not fully replicate the reality. Nor are all the optimized parameters physically meaningful. The uncertainty of calibration parameters is a well-known concept and discussed in several studies (Deletic et al., 2012, Krebs et al., 2016a). Also, a uniform characterization of the impervious area in hydrological modelling calls for improvement in the future (Shuster et al., 2007). Moreover, calibrated parameters based on single design events, may not function when applied to other events (Song et al., 2018). Nontheless, the calibrated parameters for the KW model showed reasonable NSE values for all applied event in this study.

4.2.2 Scenario Results

All scenario results are illustrated in Figure 3. The results are sorted for events 1 - 4 in figures a – d, respectively. The simulated scenarios demonstrated an overall greater reduction of peak flow with implementation of BRCs compared to GRs. In addition, BRCs responded better for the larger events (event 3 and 4) in both peak flow and volume reduction. These results are comparable to other related studies (Liu et al., 2015, Chui et al., 2016). However, the GR responded as good as the BRCs in volume reduction for the smallest precipitation events (event 1 and 2). Especially for event 2 (5y), the volume reduction was superior for GRs compared to BRCs in implementation of scenario III. All scenarios resulted in a delay in time to peak, but no noticeable differences were discovered between the modules. Not surprisingly, the combined solution achieved the best results for all events and reduced CSOs with 100 % for event 1 and 2.

Palla and Gnecco (2015) argued that a 5 % reduction of EIA was necessary to achieve beneficial results in implementation of green roofs and permeable pavements. The impervious area was greater than in the Grefsen catchment and the study focused on the general surface runoff reduction. In this study, a reduction of 3.6 % has proven to give noticeable results in reducing the CSOs. All simulated events achieved volume reduction greater than 7 % when implementing scenario I (EIA red. 3.6 %), though differences in the reduction efficiency between the smaller and larger events were remarkable. Associated with other studies, LID controls are more effective for small events and other traditional “gray” controls or a combination of both are suitable for larger, more intense events (Damodaram et al., 2010, Liu et al., 2014).

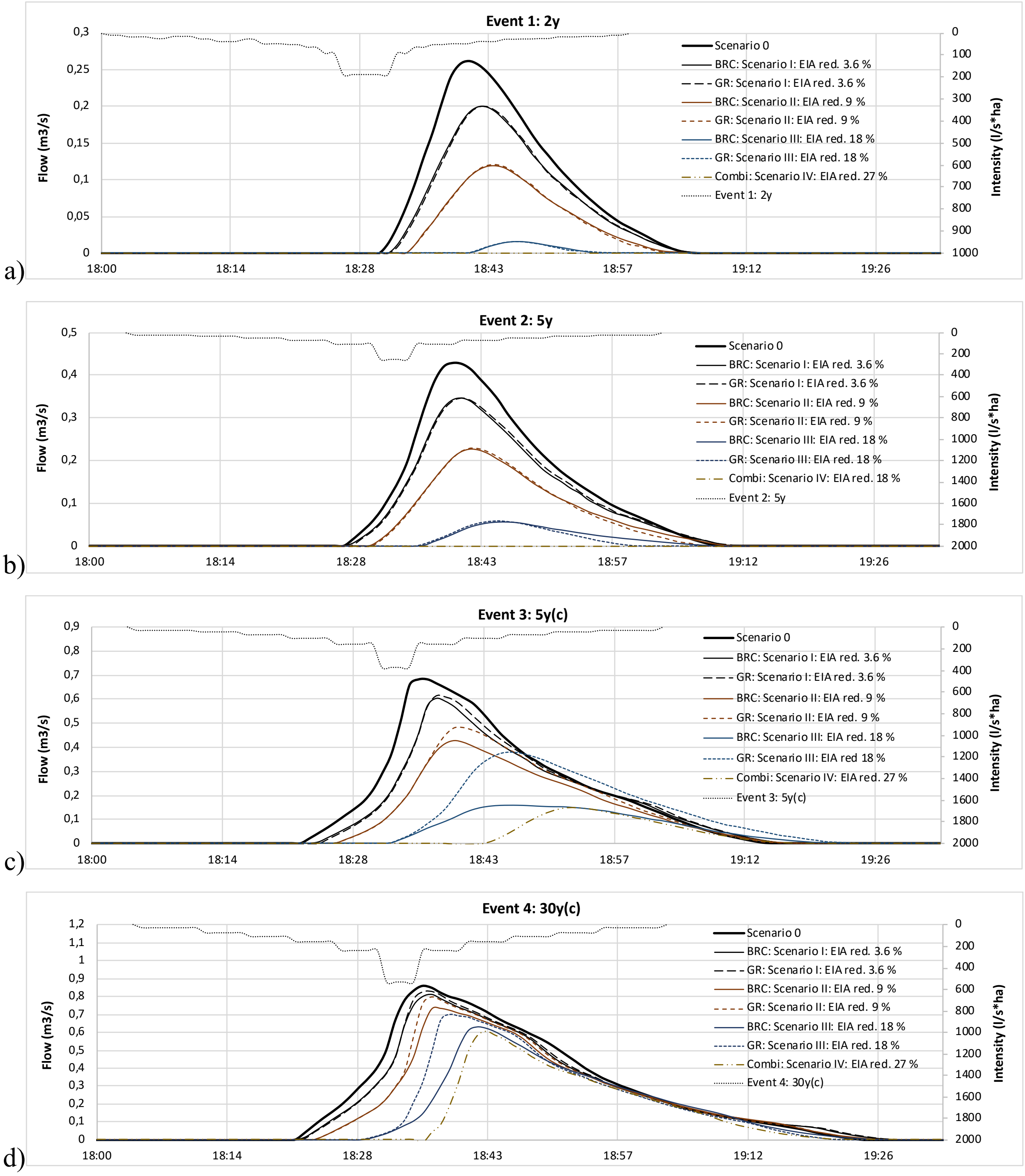


Figure 3 Scenario results. y indicates year of return period. (c) indicates added climate factor of 1.5. a) Results of the discharge at AK52 for event 1. b) Results of the discharge at AK52 for event 2. c) Results of the discharge at AK52 for event 3. d) Results of the discharge at AK52 for event 4.

The effect on the CSO discharge of the LID implementation is dependent on the efficiency of the BRC and GR, hence the calibrated parameters. The selection of the median value of the three parameter sets for the GRs will influence the efficiency of the green roof. This may give inaccurate results of the CSO discharge reduction. Similar to the study by Krebs et al. (2016a), the calibration of the BRC could have resulted in a different set of parameters and still have matched the observed discharge curve satisfactory or the calibrated parameters could have been further optimized with automatic calibration. Such parameter uncertainties may affect the results and also give different outcomes when applying different precipitation time series (Peng and Stovin, 2017).

Observations of the scenario discharge curves show a more or less simultaneous end time for all events with no noticeable tail for the hydrograph. As the applied LID controls are known to have longer detention time and correspondingly delay the hydrograph, these results question the hydrological performance. In the study performed by Gülbaz and Kazezyılmaz-Alhan (2017), such discharge hydrographs were discovered for the SWMM simulation of bioretention cells. Here, the observed discharge curve had a more natural shape with a longer tale, while the simulated curves were square formed and missed the tail of the hydrograph. Furthermore, the simulation with synthetic precipitation events show an almost linear reduction of peak flow and volume from the smaller to the larger events with applied scenarios. This way of assessing the effect of LID controls may give a simplified evaluation and exclude other aspects. Furthermore, Lucas and Sample (2015) argued that longer timeseries are necessary to evaluate performance of LID controls during different scenarios. Hence, assessing the CSO reduction effect by only using synthetic precipitation events may be a limited tool for LID design planning.

A flow duration curve (FDC) was created with precipitation data from 1993 to evaluate the long-term effect of LID-controls and to test the applicability of the FDC analysis strategy. The results in Figure 4 show that the overflow weir in the Grefsen catchment will be active approximately 2 hours without LID controls and 4 CSOs are registered. Implementation of scenario I for BRC and GR both reduced the CSO occurrences to 3 events and CSO duration to 81 and 80 minutes, respectively. This was furthermore reduced to 2 occurrences and 70 minutes with BRC and 66 minutes with GR in implementation of scenario II. Scenario III reduced the CSO occurrences to 2 events and durations of 65 and 59 for the BRC and GR implementation, respectively. The combined solution had the overall best effect with 2 occurrences and 48 min of activated CSOs.

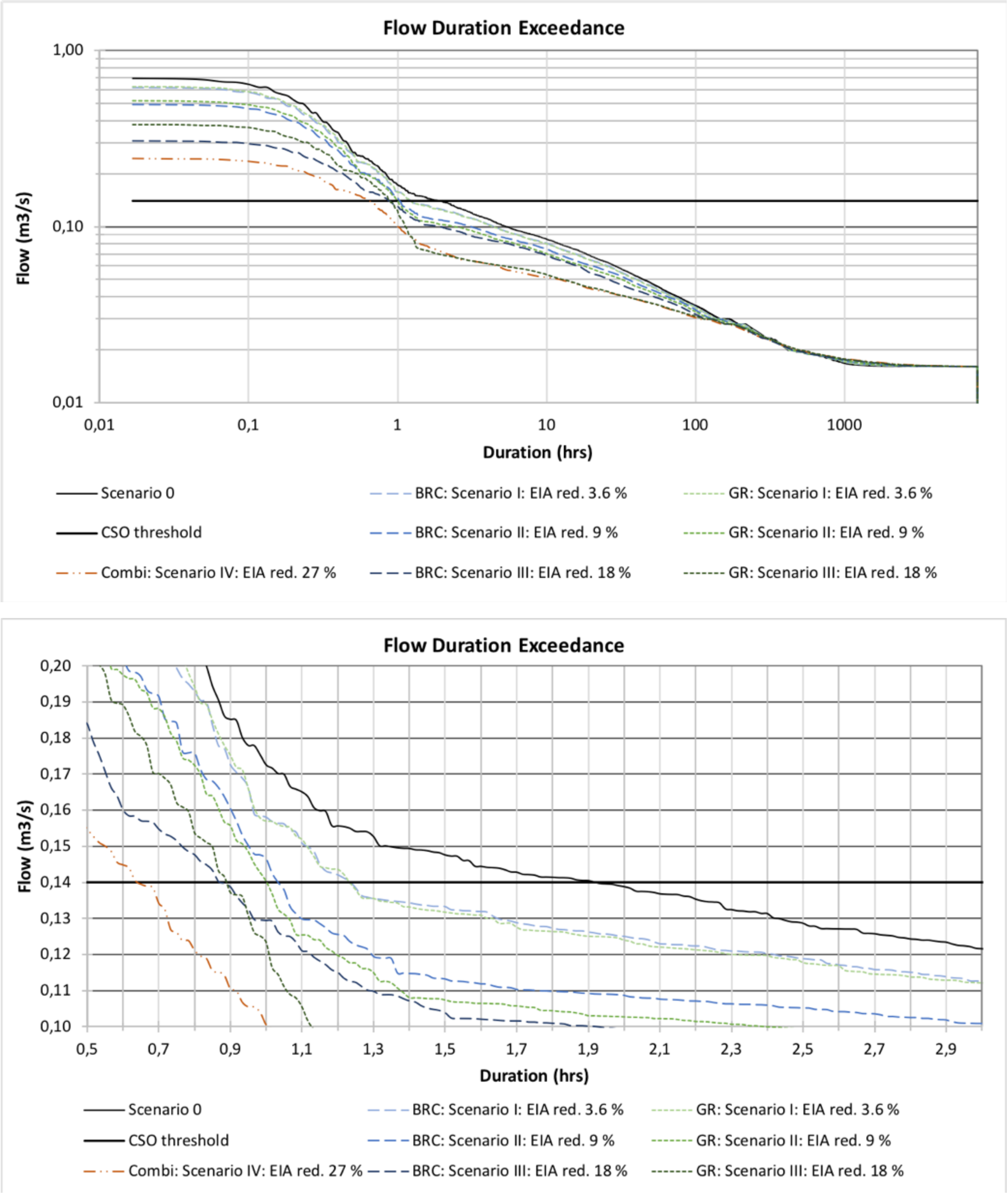


Figure 4 Flow duration curve for the long term discharge inflow to AK52 with scenario 0, scenarios I, II and III for BRC and GR, and combined scenario IV. CSO threshold is 0.14 m^3/s.

Besides the reduction of CSO duration and occurrences, the observations above and below the CSO threshold line are of interest. Following the curves exceeding the threshold, it can be noticed that the magnitude of the highest flows is clearly larger for scenario 0 compared to implementation of LID controls. Lucas and Sample (2015) argued that the volume of CSOs is strongly associated with negative impacts on the environment while the number of occurrences are not. Thus, the importance of LID implementation is illustrated in the FDC where the max flows are 0.70, 0.38, 0.31 and 0.24 m^3/s for scenario 0, scenario III with GR, scenario III with BRC and scenario IV, respectively. For the combined scenario this resulted in a total volume of 48 m^3 compared to 476 m^3 in scenario 0. From these results it can be concluded that BRCs respond superiorly for larger, more intense events, with correspondence with the results from the simulation with synthetic precipitation events. On the lower side of the CSO threshold line, it is observed that the GRs have a significant importance for smaller precipitation events. This corresponds to the recommendations in the strategy for stormwater management of implementing GRs in step 1 (Oslo Municipality, 2014).

FDCs have in this study been found to be a suitable tool to evaluate the impacts of LID implementation and developing long-term sustainable solutions. Besides the effect on the CSO volume and duration, the FDC supplements with understanding of the effects of the LID controls for smaller events below the CSO threshold. This will not be illustrated for the synthetic precipitation simulations only observing the CSO discharge. Nilsen et al. (2011) described advantages such as accessing a broader picture of the system performance, possibilities of performing statistical analysis and opportunity for the model to track the state of storages over time in simulations with longer timeseries. In decision-making processes and when establishing measures in municipalities to meet specific criteria in for example reducing CSOs, the FDC can be a practical tool. A limitation for the FDC was the time series of registered precipitation from 1993. Barely 2 hours of activated CSO was simulated with scenario 0 compared to the average monitored duration of 5.31 hours/year. The times series used in the simulation may therefore underestimate the discharges compared to precipitation series from wetter and more recent years and the effect of the implementation of LID controls may deviate. A recommended action for further works is to apply suitable time series for both dry and wet years and also longer time series to assess the most realistic results of the long-term evaluation.

5 Conclusion

In this study the hydrological performance of the BRC and the GR modules in Mike Urban were evaluated and implemented to reduce CSOs in a typical residential area in Oslo, Norway. The continuation of the parameters for the GR module from SWMM showed a relatively good correspondence for 2/3 tested precipitation events in Mike Urban. However, for event 1 the peak flow did not reach the expected value, nor did the drain outflow start simultaneously as in SWMM. Differences between the SWMM and MU models such as the applied infiltration methods and the model setup may have influenced the results. The BRC reached an NSE value of 0.73 for event 1 post calibration compared to the pre calibration value of 0.06. The module responded satisfactory in peak flow, but it was observed a delay in the beginning of the simulated discharge curve. Increasing the initial saturation reduced the delay, but sensitivity analysis illustrated a corresponding increase in peak flow. Sensitive parameters during calibration were soil parameters and the drain exponent. The overall hydrological performance of the GR and the BRC modules were found to be of acceptable range in Mike Urban. However, transfer of parameters between different hydrological models was proven complex and finding calibration parameters for widespread use was a difficult process. Hence, model parameters that span watershed boundaries need to be further investigated in the future.

The implementation of the calibrated LID modules to the Grefsen catchment showed that an EIA reduction of 3.6 % resulted in CSO volume reductions greater than 7 % for all applied scenarios. BRCs had the overall best response in reduction of peak flow and volume reductions for the larger events. GRs responded equally good as the BRCs during smaller events. The combined scenario reduced the CSO by 100 % for event 1 and 2. The observation of the discharge hydrographs illustrated an almost non-existing tail for all scenarios. This may question the hydrological performance of the model to fully replicate the physical reality. The flow duration curve provided better understanding of the long-term efficiency of implementing LID controls and other properties that could not be analyzed in simulations with synthetic precipitation series. All scenarios reduced CSO discharges in duration and occurrences. BRCs had a generally superior response for larger events and reduced the volume of CSOs to a larger extent than GRs, which is expected. However, the FDC showed that the GRs had remarkable impacts during smaller events when the overflow weir was not activated. In decision-making processes and when establishing measures in municipalities to meet specific criteria in for example reducing CSOs, the FDC can be a practical tool. For further works, it is recommended to test longer time series including wetter and more intense precipitation years to fully assess the response in implementation of LID controls.

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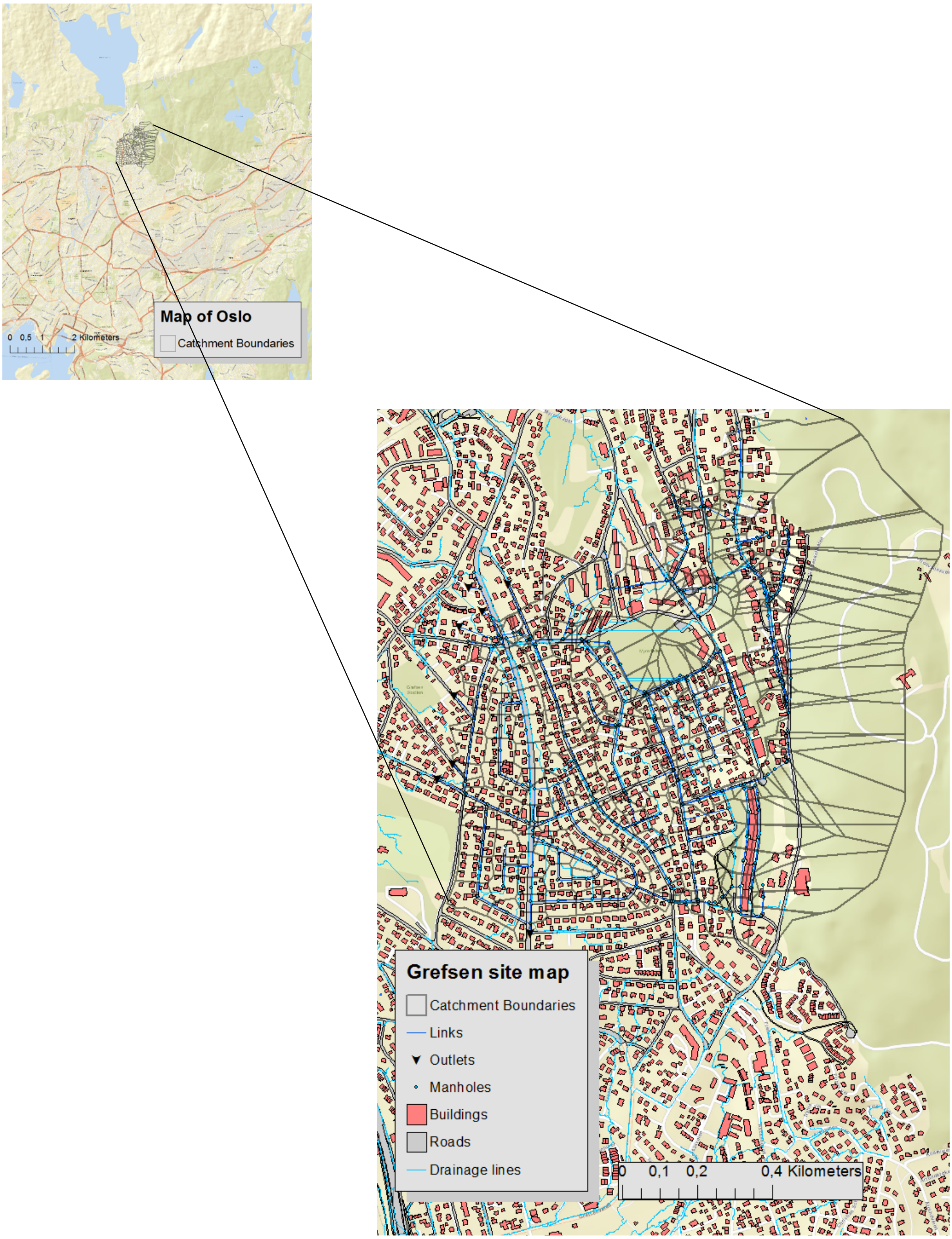
Appendix A Article Structure

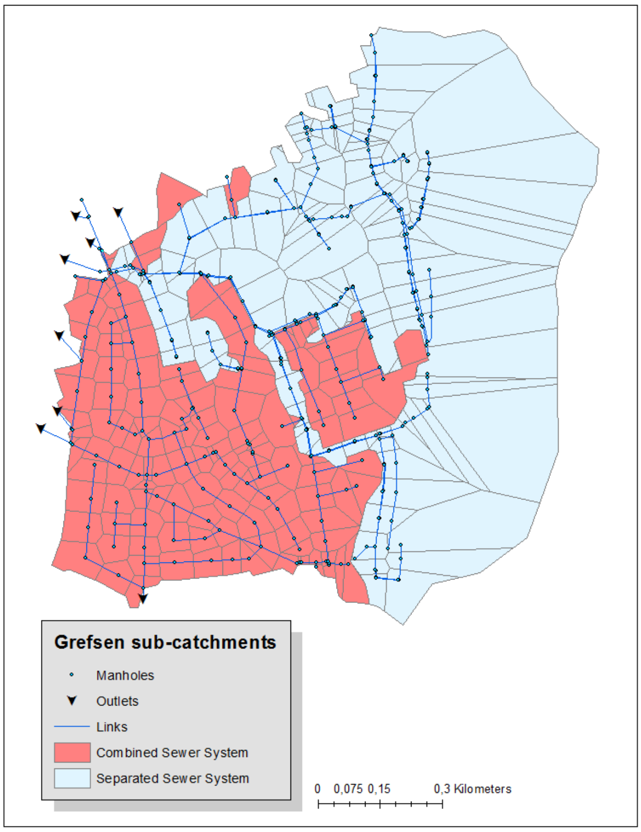
Hydrology Research Journal for the Nordic Water Conference 2018

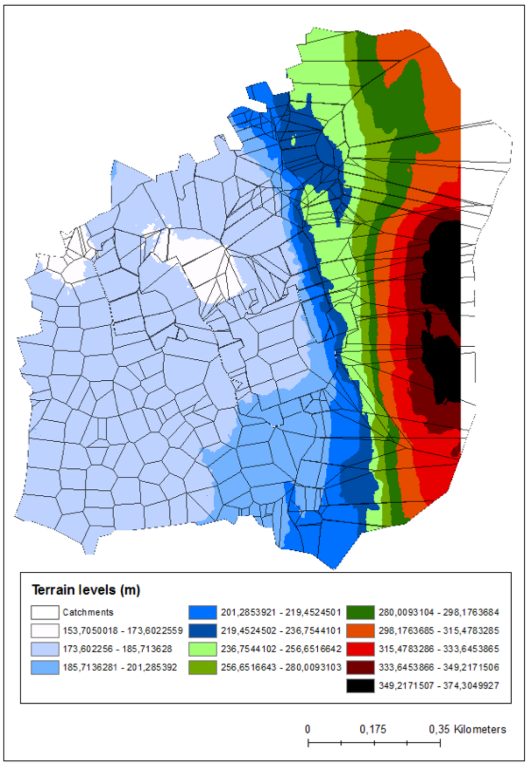
The research papers are fully documented, interpreted accounts of significant findings of original research. The maximum acceptable length of a Research Paper is 7500 words (less 350 words for each normal-sized figure or table you include).

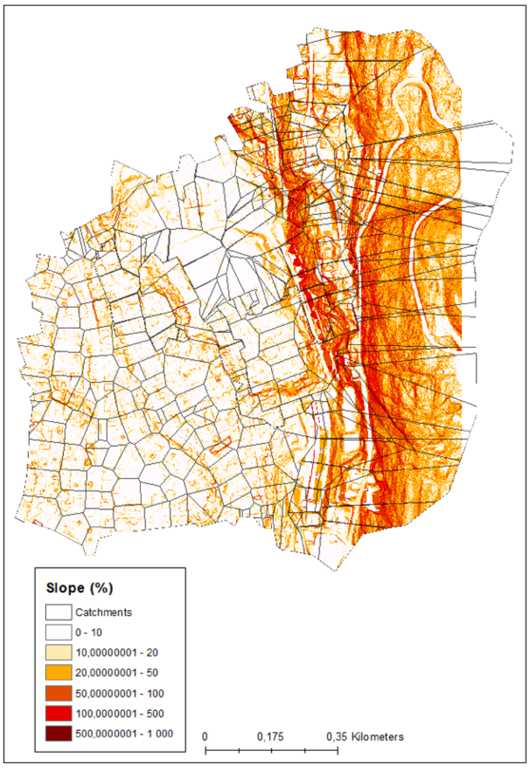
Title
Short title of no more than 80 characters (including spaces)
Author name(s), full postal addresses for each author. Include the e-mail address for the corresponding author only.
Abstract:
No more than 200 words briefly specifying the aims of the work, the main results obtained, and the conclusions drawn. Citations must not be included in the Abstract.
Keywords:
Up to 6 keywords (in alphabetical order) which will enable subsequent abstracting or information retrieval systems to locate the paper.
Main text: For clarity this should be subdivided into:
Introduction:
Should include a brief description of the background context for the work including research rationale/context, clearly identifying the scientific question(s) and their international (or regional) significance. It should include a succinct review/state-of-the-art synthesis of the directly relevant published international literature. The research aims and objectives should be clearly stated.
Study area and data:
Should describe the location, size, geographical and relevant climatic and other conditions of the region. It should clearly describe all the data used and their sources, including data periods, temporal resolution, limitations, quality, etc. Use of tables is encouraged where appropriate.
Methods:
A brief description of the methods/techniques used (the principles of these methods should not be described if readers can be directed to easily accessible references or standard texts).
Results and Discussion:
A clear presentation of experimental results obtained, highlighting any trends or points of interest. In the Discussion, a brief explanation of the significance and implications of the work reported, focusing on the novel contributions or new insights offered to the science and practice of hydrology.
Conclusions:
A brief statement of what was undertaken in the study (one or two sentences) followed by what was established relative to the stated aims and objectives. Where relevant this should include a brief summary of your argument. Where appropriate, clearly identified recommendations for action and/or research needs should follow.
References:
These should be to accessible sources. Please ensure that all work cited in the text is included in the reference list, and that the dates and authors given in the text match those in the reference list. References must always be given in sufficient detail for the reader to locate the work cited (see below for formats). Note that your paper is at risk of rejection if there are too few (<10) or too many (>25) references, or if a disproportionate share of the references cited are your own.
Supplementary Material:
Appendices and other Supplementary Material are permitted, and will be published online only.

Appendix B Grefsen Study Site

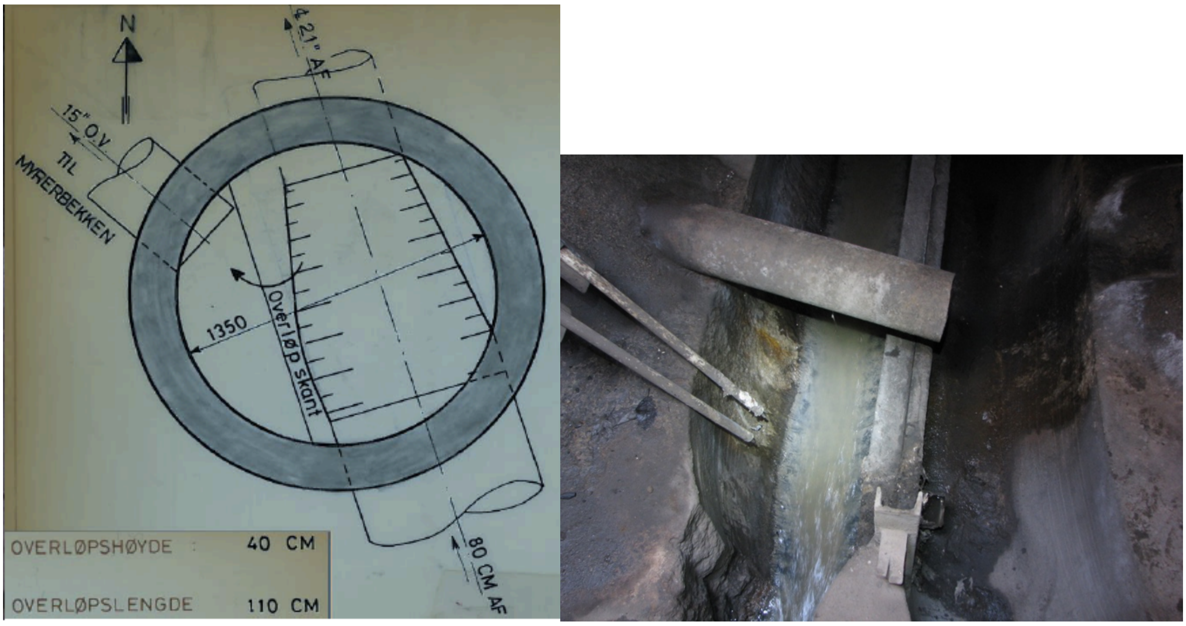



Grefsen sub-catchments
Manholes
Outlets
Links
Combined Sewer System
Separated Sewer System
0 0,075 0,15 0,3 Kilometers


Terrain levels (m)
Catchments
153,7050018 - 173,6022559
173,602256 - 185,713628
185,7136281 - 201,285392
201,2853921 - 219,4524501
219,4524502 - 236,7544101
236,7544102 - 256,6516642
256,6516643 - 280,0093103
280,0093104 - 298,1763684
298,1763685 - 315,4783285
315,4783286 - 333,6453865
333,6453866 - 349,2171506
349,2171507 - 374,3049927
0 0,175 0,35 Kilometers


Slope (%)
Catchments
0 - 10
10,00000001 - 20
20,00000001 - 50
50,00000001 - 100
100,0000001 - 500
500,0000001 - 1 000
0 0,175 0,35 Kilometers

Appendix C Overflow Weir AK52



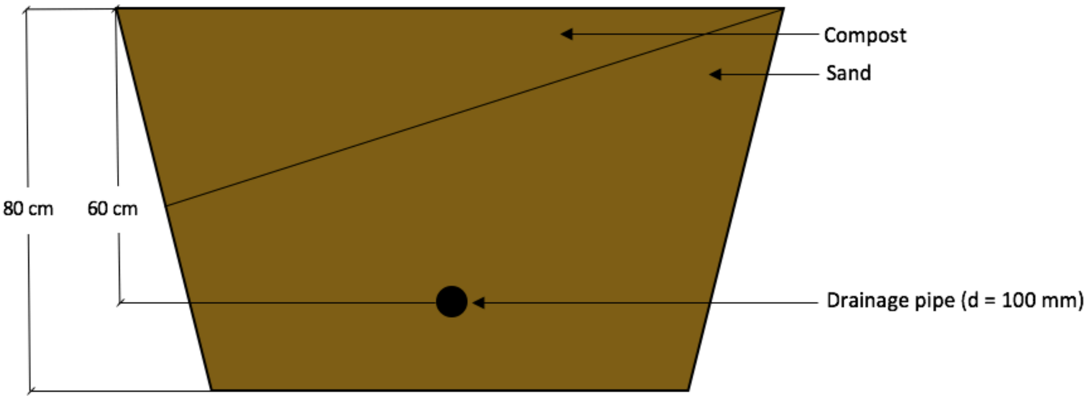
AK52 dimensions (in Norwegian) and illustration of a similar overflow weir. Source: Alexander Pham, Bent Braskerud, VAV

Appendix D The Green Roof and The Bioretention Cell

D.1 Pilot Green Roof

GR used in this study to the left with a substrate layer and a filt mat. Source: Bent Braskerud, VAV

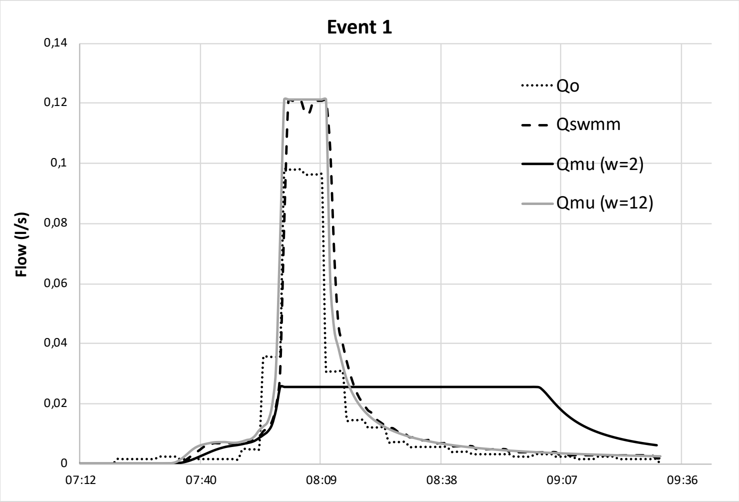
D.2 Bioretention Cell NB21



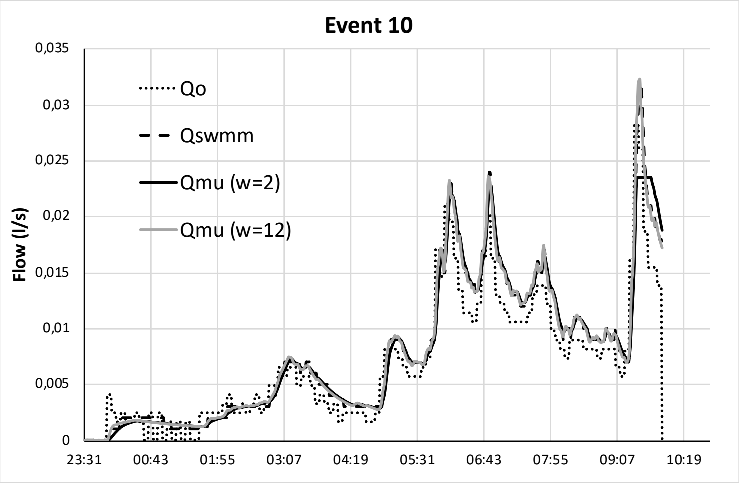
Bioretention Cell NB21 with dimensions and layer composition.

Appendix E Green Roof Evaluation

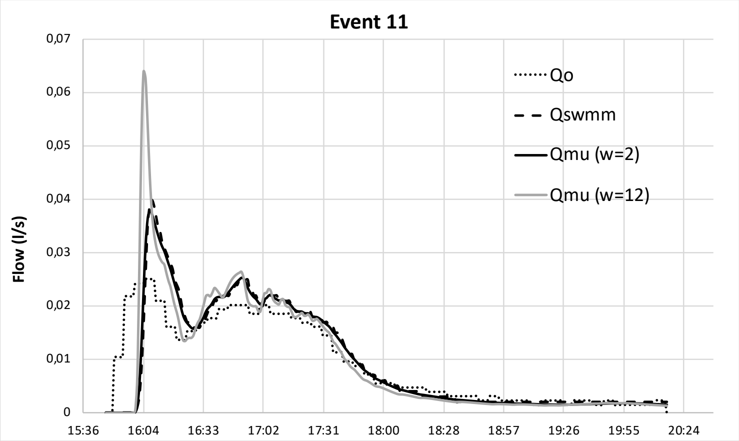
E.1 Results for Event 1



E.2 Results for Event 10

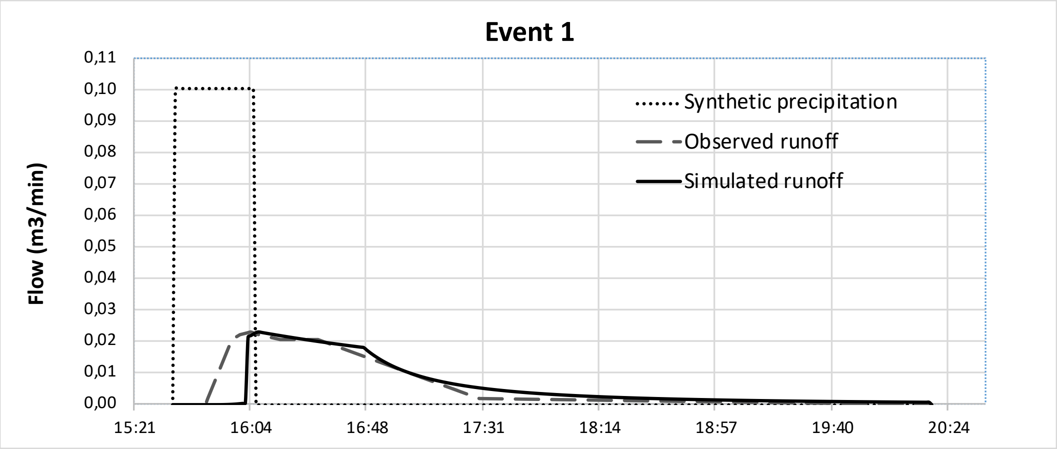


E.3 Results for Event 11



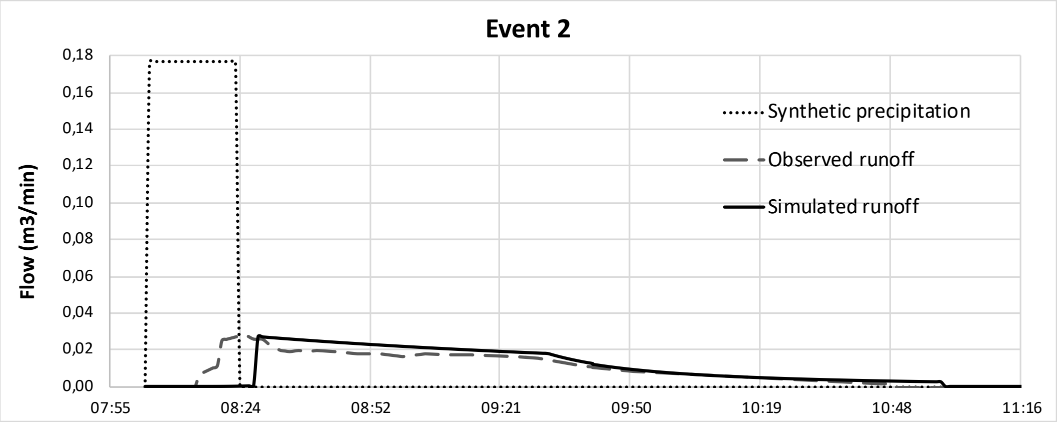
Appendix F Bioretention Cell Evaluation

F.1 Calibration Results for Event 1



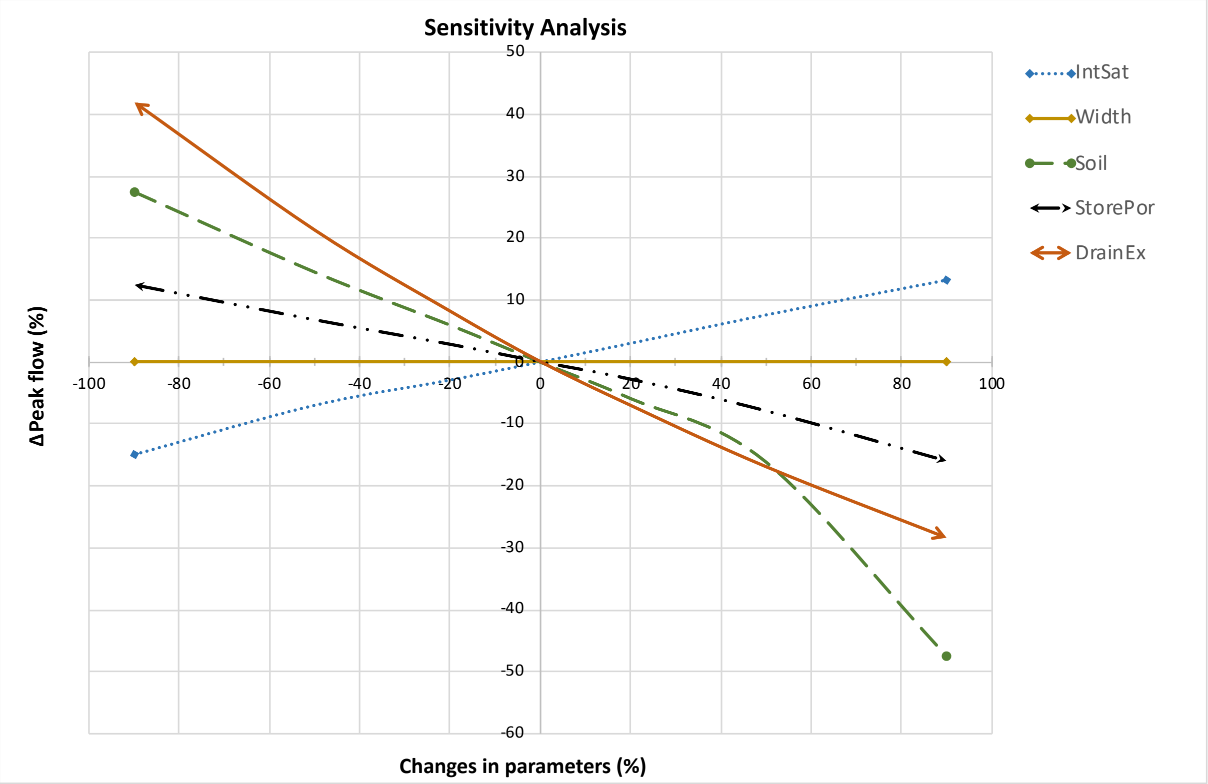
	Value	Description
NSE_{pre}	0.06	NSE value pre calibration
NSE_{post}	0.73	NSE value post calibration
ΔPeak flow (%)	+ 0.48	Percentage difference in peak flow for observed and simulated discharge
Time to peak (min)	+ 3	Time to peak flow for simulated discharge compared to observed discharge
Hydrograph delay (min)	+ 3	Time to initiated simulated discharge curve compared to initiated observed discharge curve

F.2 Calibration Results for Event 2



	Value	Description
NSE_{pre}	0.14	NSE value pre calibration
NSE_{post}	0.60	NSE value post calibration
ΔPeak flow (%)	- 3.41	Percentage difference in peak flow for observed and simulated discharge
Time to peak (min)	+ 3	Time to peak flow for simulated discharge compared to observed discharge
Hydrograph delay (min)	+ 2	Time to initiated simulated discharge curve compared to initiated observed discharge curve

F.3 Sensitivity Analysis



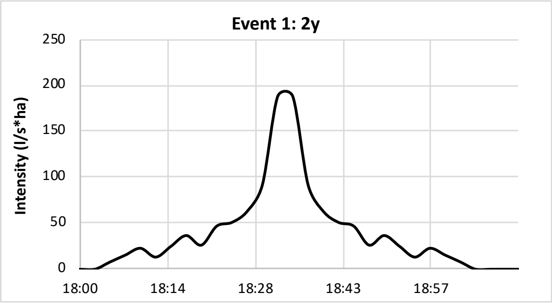
Sensitivity analysis results. Y axis illustrates changes in peak flow when changing different parameters represented on the x axis. The soil parameter includes changing both porosity, field capacity and wilting point equally as they depend on each other.

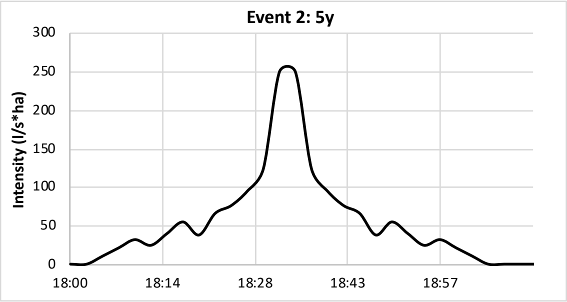
Appendix G Precipitation Input Data: Case Grefsen

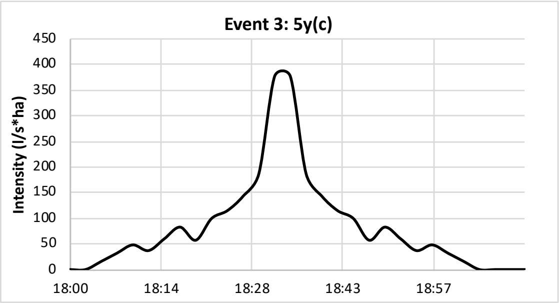
G.1 Synthetic Precipitation Events

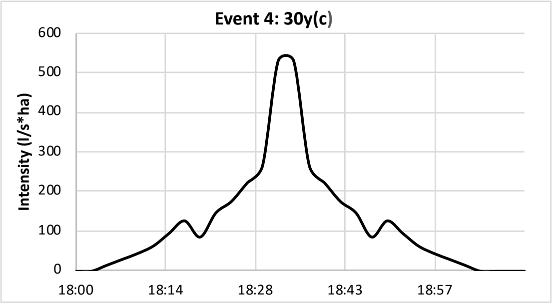
“y” indicates year for return period.

“(c)” indicates events with climate factor of 1.5

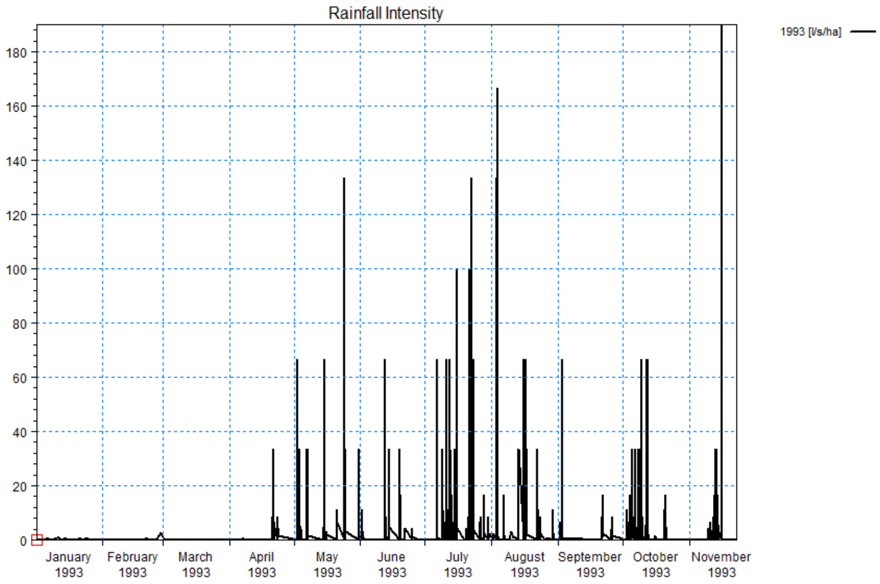








G.2 Precipitation Series 1993

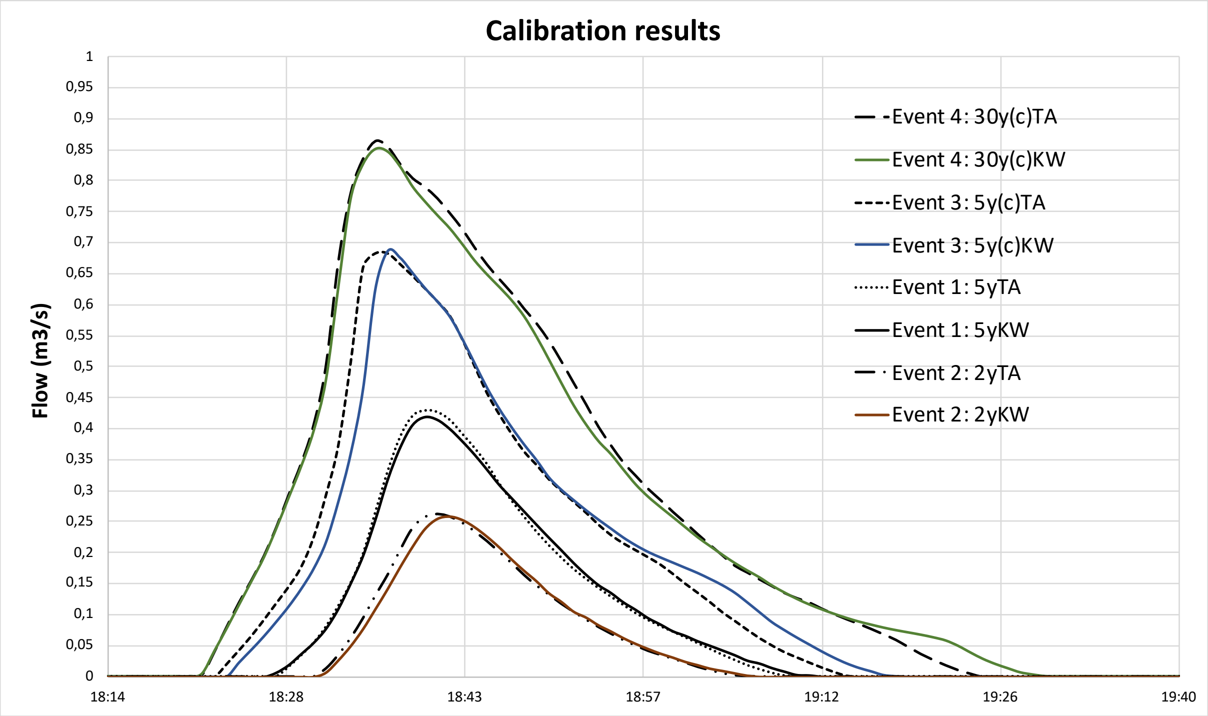


Appendix H Kinematic Wave Model calibration

H.1 Calibration Results

Calibrated parameters for the kinematic wave surface runoff model. Equal values for all sub-catchments. Manning´s n is divided into five contributing surfaces for steep and flat impervious areas and low, medium and high permeable areas.

	$ImpKW = a * ImpReal^{b}$		Manning´s n					Length (m)
Parameter	a	b	MSteep	Mflat	MLow	MMed	MHigh	
Value	1.100	0.658	0.0125	0.0143	0	0	0	10

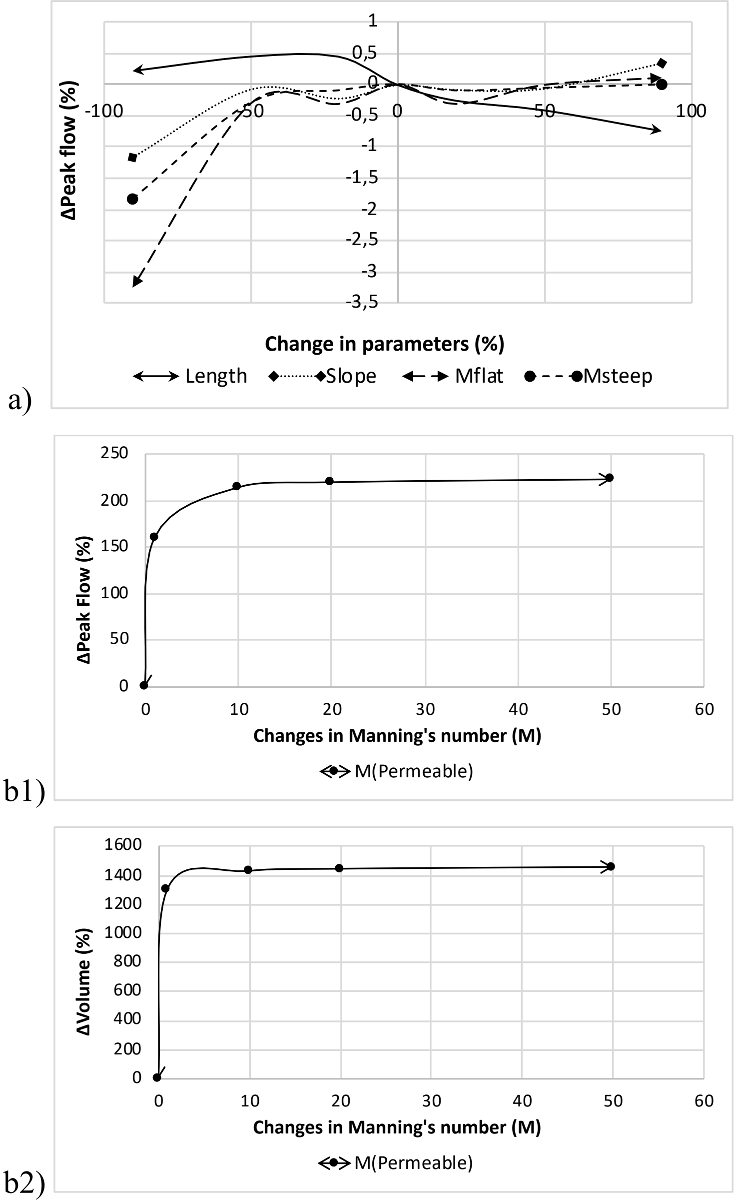


Calibration results for all simulated events. Stippled lines refer to the simulated events with the time-area model. Solid lines refer to the simulated events with the kinematic wave model.

Calibration results of the simulations with the kinematic wave model compared to the results from simulations with the time area model.

Event	NSE	Δvolume (%)	Δpeak (%)	Δpeak (min)	Δt_{start} (min)	Δt_{end} (min)
1: 2y	0.994	-1.85	-1.59	+1	0	+2
2: 5y	0.998	+0.48	-2.65	0	0	+119
3: 5y(c)	0.980	-1.29	0.41	+1	+1	+114
4: 30y(c)	0.998	-1.51	-1.48	0	0	+98

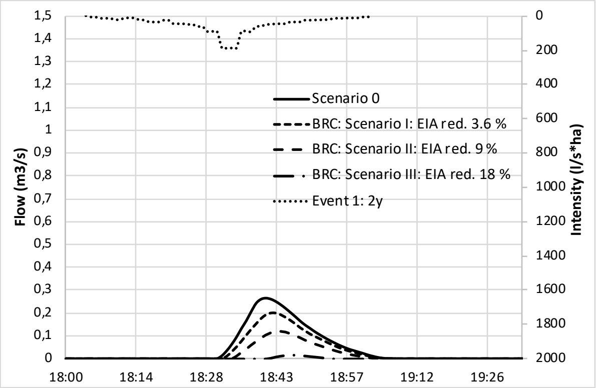
H.2 Sensitivity Analysis



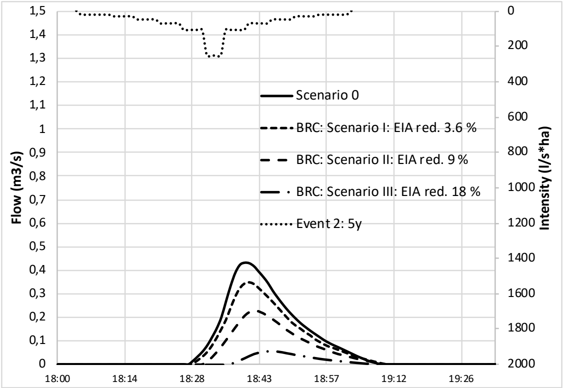
a) Sensitivity analysis of the calibration parameters in light of changes of the peak flow. Msteep and Mflat refer to the Manning´s number (M) for the impervious areas. b1) Sensitivity analysis of the Manning´s number (M) for the permeable areas in light of the percental change in peak flow. b2) Sensitivity analysis of the Manning´s number (M) for the permeable areas in light of the percental change in volume. Manning´s number (M) of 0 (reference parameter), 1, 10, 20 and 50 have been tested.

Appendix I Scenario Results

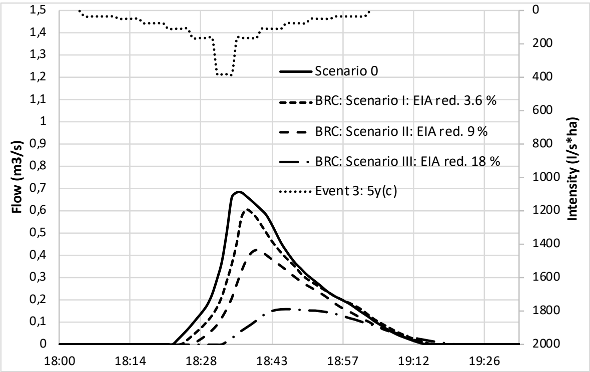
I.1 BRC Implementation



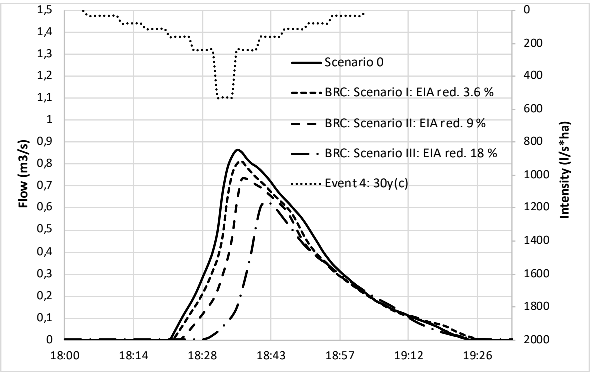
BRC implementation event 1: 2y



BRC implementation event 2: 5y



BRC implementation event 3: 5y(c)

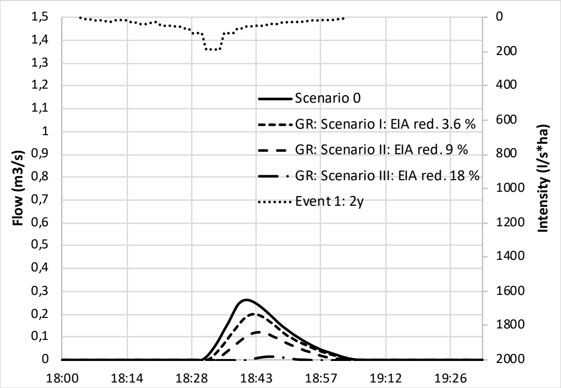


BRC implementation event 4: 30y(c)

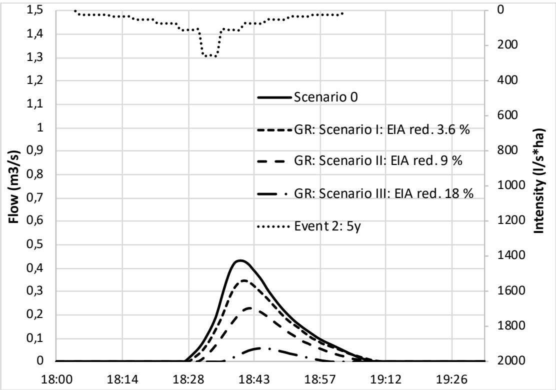
BRC implementation results

	Volume reduction (%)	**Peak flow reduction (%)**	**Peak lag (min)**
Event 1: 2y			
Scenario I: 20 % BRC: EIA red. 3.6 %	25	24	2
Scenario II: 50 % BRC: EIA red. 9 %	57	54	3
Scenario III: 100 % BRC: EIA red. 18 %	97	94	5
Event 2: 5y			
Scenario I: 20 % BRC: EIA red. 3.6 %	19	19	1
Scenario II: 50 % BRC: EIA red. 9 %	47	47	2
Scenario III: 100 % BRC: EIA red. 18 %	87	87	6
Event 3: 5y(c)			
Scenario I: 20 % BRC: EIA red. 3.6 %	15	11	2
Scenario II: 50 % BRC: EIA red. 9 %	36	38	4
Scenario III: 100 % BRC: EIA red. 18 %	69	77	10
Event 4: 30y(c)			
Scenario I: 20 % BRC: EIA red. 3.6 %	8	6	1
Scenario II: 50 % BRC: EIA red. 9 %	19	15	2
Scenario III: 100 % BRC: EIA red. 18 %	39	27	6

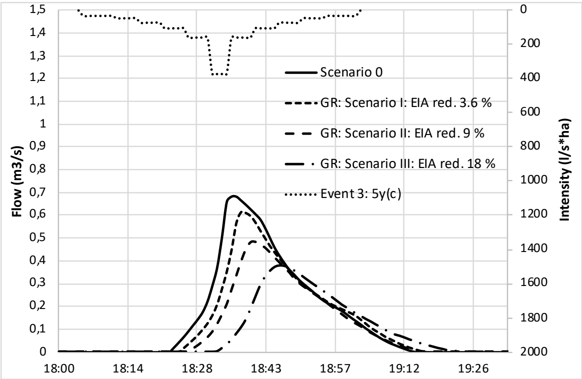
I.2 GR Implementation



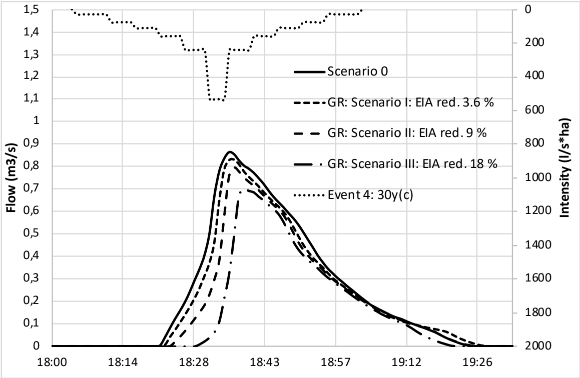
GR implementation event 1: 2y



GR implementation event 2: 5y



GR implementation event 3: 5y(c)

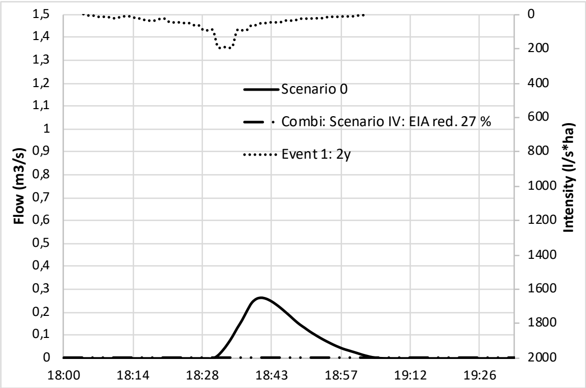


GR implementation event 4: 30y(c)

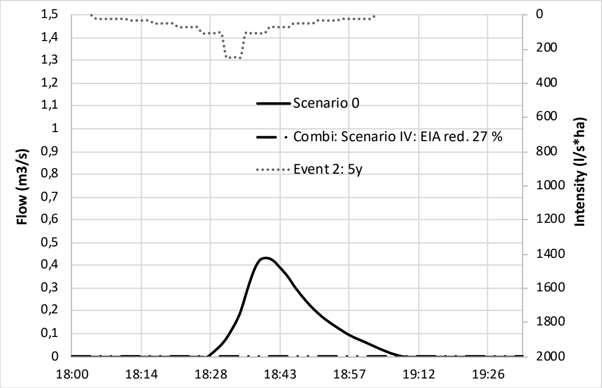
GR implementation results

	Volume reduction (%)	**Peak flow reduction (%)**	**Peak lag (min)**
Event 1: 2y			
Scenario I: 20 % GR: EIA red. 3.6 %	25	24	2
Scenario II: 50 % GR: EIA red. 9 %	58	54	3
Scenario III: 100 % GR: EIA red. 18 %	97	94	5
Event 2: 5y			
Scenario I: 20 % GR: EIA red. 3.6 %	18	19	1
Scenario II: 50 % GR: EIA red. 9 %	48	47	2
Scenario III: 100 % GR: EIA red. 18 %	90	86	5
Event 3: 5y(c)			
Scenario I: 20 % GR: EIA red. 3.6 %	12	10	1
Scenario II: 50 % GR: EIA red. 9 %	30	30	4
Scenario III: 100 % GR: EIA red. 18 %	39	44	9
Event 4: 30y(c)			
Scenario I: 20 % GR: EIA red. 3.6 %	7	4	1
Scenario II: 50 % GR: EIA red. 9 %	17	8	1
Scenario III: 100 % GR: EIA red. 18 %	33	19	3

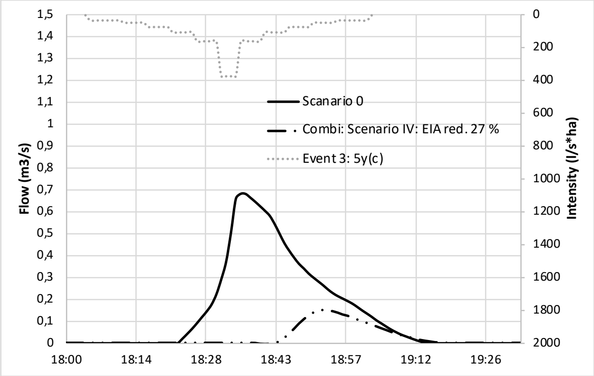
I.3 Combined Solution



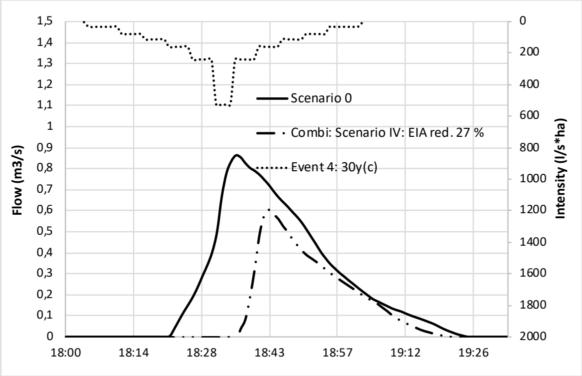
Combined solution event 1: 2y



Combined solution event 2: 5y



Combined solution event 3: 5y(c)

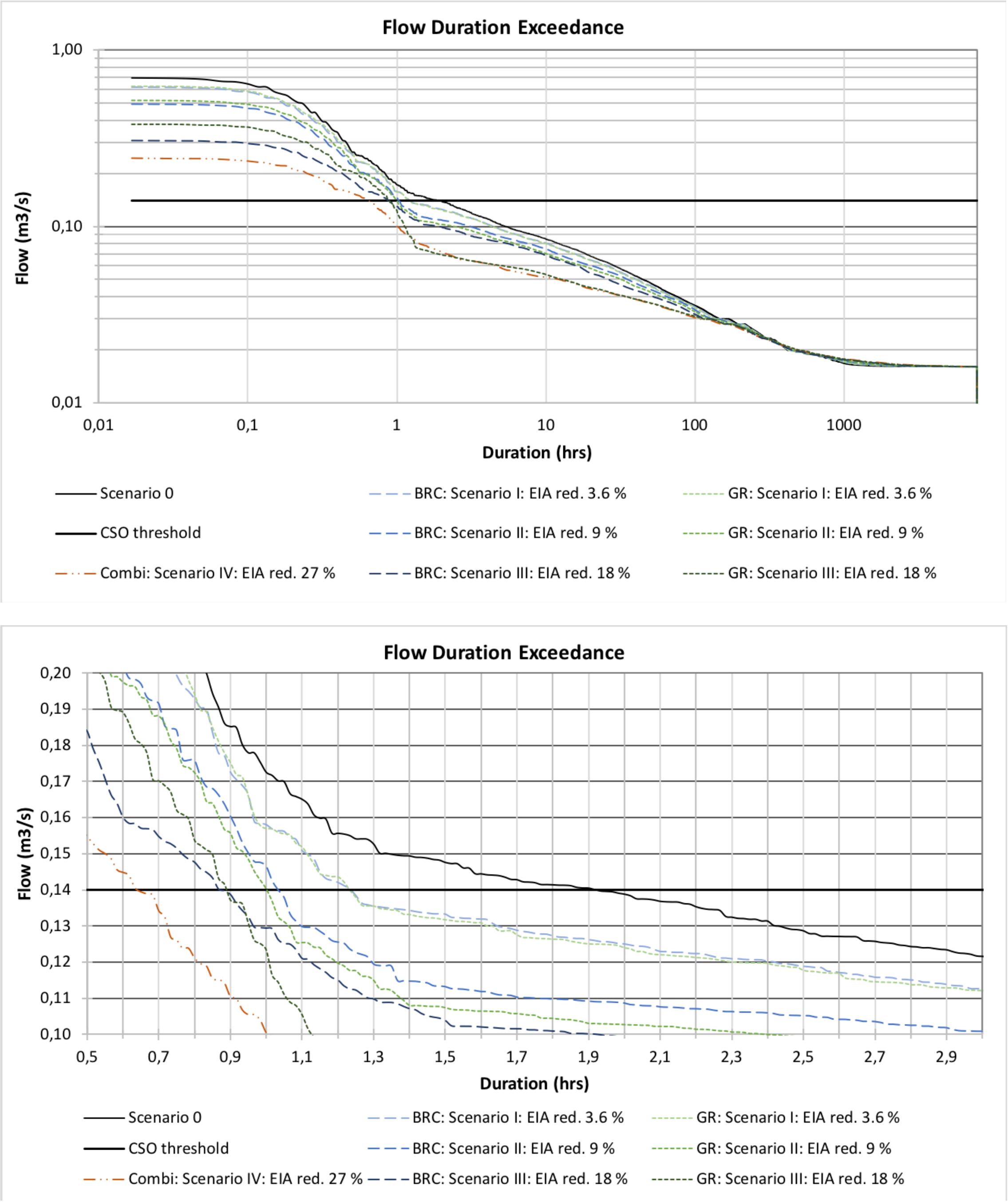


Combined solution event 4: 30y(c)

BRC+GR implementation results

	Volume reduction (%)	Peak flow reduction (%)	Peak lag (min)
Event 1: 2y			
Scenario IV: 100 % BRC+GR: EIA red. 27 %	100	100	-
Event 1: 5y			
Scenario IV: 100 % BRC+GR: EIA red. 27 %	100	100	-
Event 2: 5y(c)			
Scenario IV: 100 % BRC+GR: EIA red. 27 %	82	78	17
Event 3: 30y(c)			
Scenario IV: 100 % BRC+GR: EIA red. 27 %	50	30	7

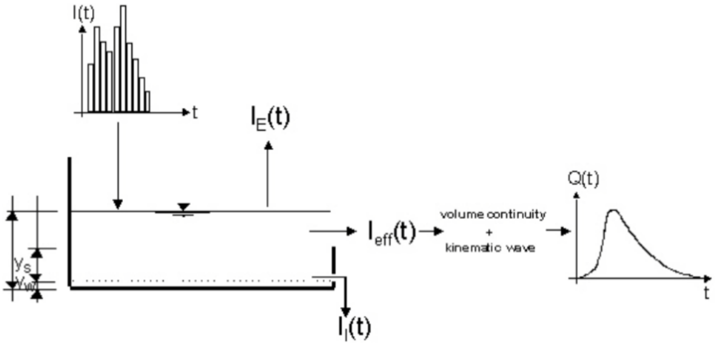
I.4 Flow Duration Exceedance



Flow duration curve for the simulation with precipitation data from 1993 and all simulated scenarios. a) The entire flow duration curve for 7800 hours (325 days) in logarithmic scale. b) Flow duration curve zoomed in to assess the duration of CSO exceedance for every scenario.

Appendix J Surface Runoff Calculations and LID-Module Model Setup

J.1 Kinematic Wave Model Concept



Kinematic wave model process with associated equations below. Illustration and all equations collected from DHI (2017b).

Equation 1: Effective Precipitation

$$I_{eff}(t) = I(t) - I_E(t) - I_W(t) - I_I(t) - I_S(t)$$

$$I_{eff} \geq 0$$

$I_{eff}(t)$ = Effective precipitation

$I(t)$ = Actual precipitation at time t, uniformly distributed over the individual catchments

$I_E(t)$ = Evaporation loss at time t. Evaporation loss is accounted only with RDI runoff computation

$I_W(t)$ = Wetting loss at time t

$I_I(t)$ = Infiltration loss at time t

$I_S(t)$ = Surface Storage loss at time t

Equation 2: Evaporation

$$I_E(t) = \begin{cases} I_{PE}(t)\ for\ \left(I(t) \geq I_{PE}(t)\right)\ or\ (y(t) > 0) \\ I(t) for\ \left(I(t) < I_{PE}(t)\right)\ and\ (y(t) = 0) \end{cases}$$

$I_E(t)$ = Evaporation loss at time t

$I(t)$ = Actual precipitation at time t

$I_{PE}(t)$ = Potential evaporation at time t

$y(t)$ = Accumulated depth at time t

Equation 3: Wetting Loss

$$I_W(t) = \begin{cases} I(t) - I_E(t) \; for \; y(t) < y_W \\ 0 \; for \; \left(I(t) \leq I_E(t)\right) \; or \; (y(t) \geq y_W) \end{cases}$$

$I_W(t)$ = Wetting loss at time t

I(t) = Actual precipitation at time t

$I_E(t)$ = Evaporation loss at time t

y_W = Wetting depth

y(t) = Accumulated depth at time t.

Equation 4: Infiltration

$$I_I(t) = \begin{cases} I_H(t) \; for \; (y(t) \geq y_W) \; and \; \left(I(t) - I_E(t) - I_W(t) \geq I_H(t)\right) \\ I(t) - I_E(t) - I_W(t) \; for \; \left(I(t) - I_E(t) - I_W(t) < I_H(t)\right) \\ 0 \; \; for \; y(t) < \; y_W \end{cases}$$

$I_I(t)$ = Infiltration loss at time t

$I_W(t)$ = Wetting loss at time t

y_W = Wetting depth

y(t) = Accumulated depth at time t

$I_H(t)$ = Infiltration loss calculated according to Horton

$$I_H(t) = I_{Imin} + (I_{Imax} - I_{Imin}) * e^{-k_a * t}$$

I_{Imax} = Maximum infiltration capacity (after a long dry period)

I_{Imin} = Minimum infiltration capacity (at full saturation)

t = Time since the start of the storm

k_a = Time factor (characteristic soil parameter) for wetting conditions

$$I_{Icum}(t_p) = \int_0^{t_p} I_H dt = \; I_{Imin} * t_p + \frac{I_{Imax} - I_{Imin}}{k_a} * \left(I - e^{-k_a * t_p}\right)$$

$I_{Icum}(t_p)$ = Cumulative infiltration (m) at time tp

Actual infiltration is equal to the infiltration capacity at any time within the period 0 → t. This is only the case for rainfall intensities higher than the infiltration capacity. Hence the equation follows as:

$$I_{Icum}(t_p) = \int_0^t I_I \; dt$$

For dry periods the infiltration capacity is slowly turning to the initial value. The inverse form of the Horton's equation:

$$I_H(t) = \; I_{IT} + (I_{Imax} - Q_{IT}) * e^{-1/(k_h * t)}$$

$I_H(t)$ = Infiltration loss capacity calculated according to Horton

I_{Imax} = Maximum infiltration capacity (after a long dry period)

I_{IT} = Infiltration capacity at the threshold between the wetting and drying period

t = Time since the start of the recovery process

k_h = Time factor (characteristic soil parameter) for drying conditions.

Equation 5: Surface Storage

$$I_s(t) = \begin{cases} I(t) - I_E(t) - I_W(t) - I_I(t) \ for \ y(t) \leq (y_w + y_s) \\ 0 \ \ for \ y(t) > (y_w + y_s) \end{cases}$$

I(t) = Precipitation intensity at time t

$I_S(t)$ = Surface storage loss at time t

$I_I(t)$ = Infiltration loss at time t

$I_W(t)$ = Wetting loss at time t

$I_E(t)$ = Evaporation loss at time t

y_W = Wetting depth

y_S = Surface storage depth

y(t) = Accumulated depth at time t.

Equation 6: Surface Runoff

$$If \ I_{eff}(t) > 0 \ \Rightarrow Surface \ runoff$$

$$Q(t) = M * B * I^{\frac{1}{2}} * y_R(t)^{\frac{5}{3}}$$

Q(t) = surface runoff

M = Manning's number

B = Flow channel width, computed as: B (m) = A (m^2) / L (m)

I = Surface slope

$y_R(t)$ = Runoff depth at time t

$$I_{eff}(t) * A - Q(t) = \frac{dy_R}{dt} * A$$

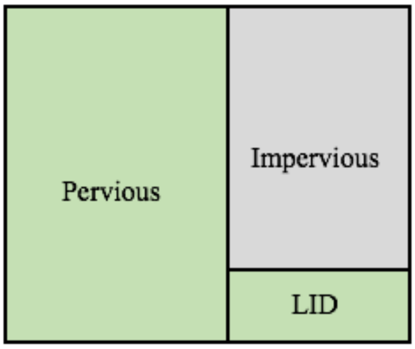
I_{eff} = Effective precipitation

A = Contributing catchment surface area

dt = Time step

dy_R = Change in runoff depth

J.2 Catchment Methodology for the LID Module in MIKE 1D



Pervious area: infiltration by Horton and runoff routed with kinematic wave model. Impervious area: Runoff routed with kinematic wave model. LID area: Subtracted from impervious area, runoff routed with kinematic wave model. Source: (DHI, 2017a).

Required (x) and optional (o) layers for the different LID types. Source: (DHI, 2017a)

LID type	Surface	Pavement	Soil	Storage	Underdrain	Drainage mat
Bioretention Cell	x		x	x	o	
Rain Garden	x		x			
Vegetative Swale	x					
Infiltration Trench	x			x	o	
Permeable Pavement	x	x		x	o	
Green Roof	x		x			x
Rain Barrel				x	x	

Surface layer

Receives direct rainfall and run-on. Stores some of the inflow in a depression storage. Surface outflow is generated and routed to the drainage system or to downstream land areas.

Pavement layer

Porous concrete or asphalt or paver blocks with filler material. Allows for full or partial inflow from stormwater into the lower layers.

Soil layer

Soil mixture in bioretention cells, rain gardens and green roofs.

Storage layer

Bed of gravel providing storage of water.

Underdrain

Conveying water from the storage layer to an outlet pipe.

Drainage mat

Special layer below the soil substrate in green roofs, routing the water to the drainage system.

J.3 Parameter List for the LID-Modules

Parameter	Explanation*
Surface layer	
Store.h (mm)	Height of surface depression storage.
Veg. cover (-)	The fraction of the storage area above the surface that is filled with vegetation (0 = no vegetation, 1 = no storage available).
Surf. roughn. (M)	Manning´s number, for routing of overflow from the surface.
Swale s.slope (1/1)	Slope of the sidewalls of a swale´s cross section. Calculation of the stored volume and wetted width. Ignored for other types of LID controls.
Surf. slope (%)	For routing of overflow from the surface. No routing of the overflow is applied if value equals zero.
Soil layer	
Thickness (mm)	Thickness of the soil layer.
Porosity (1/1)	Volume of pore space relative to total volume of soil.
Field cap. (1/1)	Volume of water in pores relative to the total volume in the soil, cannot be higher than the porosity. Percolation occurs when field capacity is exceeded.
Wilting point (1/1)	The moisture content of the soil cannot fall below this limit and wilting point cannot be higher than the field capacity level.
Infiltration (mm/h)	The rate of water flowing from surface into the soil (Horton´s).
Leakage (mm/h)	The rate of water going from the soil layer into storage. Leakage begins when soil storage exceeds field capacity.
Conductivity (m/h)	Hydraulic conductivity. Equivalent to leakage capacity.
Conduct. slope (-)	Slope of the curve of log (conductivity) versus soil moisture content (dimensionless).
Suction head (mm)	Value of soil capillary suction along the wetting front (Green-Ampt).
Pavement layer	
Thickness (mm)	Thickness of pavement layer
Porosity (-)	The ratio of the volume of the pores to the total volume of the pavement.
Imp. surface (-)	Ratio of impervious paver material to total area for modular systems, 0 for continuous porous pavement systems.
Perm. (mm/h)	Permeability of concrete or asphalt.
Clogging factor (-)	Voids that are clogged due to fine particles accumulation.
Storage layer	
Height (mm)	Height of storage layer.
Porosity (-)	The ratio of the volume of the pores to the total volume of the layer. Note that porosity = void ratio / (1 +void ratio).
Infil. cap. of surr. soil (mm/h)	Max rate at which water infiltrates to the surrounding soil through the bottom of the storage layer.
Clogging factor (-)	Volume of voids that are clogged due to fine particles accumulation. 0 to ignore clogging.
Drain layer	
Drain cap. (mm/h)	Coefficient C that determines the rate of flow through the underdrain as a function of height of stored water above the drain bottom. $Q = C*h^n$
Drain cap. (m^3/s)	Capacity of the drainage pipe.
Exponent (-)	Exponent n that determines the rate of flow through the underdrain as a function of height of stored water above the drain height. $Q=C*h^n$.
Offset height (mm)	Height of underdrain above the bottom of the storage layer
Delay (h)	The number of dry weather hours that must elapse before the drain in a rain barrel is activated.
Drainage mat layer	
Thickness (mm)	The thickness of the mat or plate.
Void fraction (-)	The ratio of void volume to total volume in the mat.
Roughness (M)	Manning´s number, used to compute the horizontal flow rate of drained water through the mat.
* All explanations are based on the DHI manual *(DHI, 2017a)*	