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Martina Hølleland

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NTNU
Norwegian University of
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Faculty of Engineering
Department of Civil and Environmental Engineering

Martina Hølleland

Retrofitting combined sewer systems with nature-based solutions using long-term climate scenarios

A case study from Bergen, Norway

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Martina Hølleland

Civil and Environmental Engineering
Submission date: June 2020
Supervisor: Tone Merete Muthanna

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

Abstract

Urban combined sewer systems across the world face capacity constraints and adaptation requirements to prepare for a changing climate. In dense urban areas retrofitting by separation is often costly, and available space for green infrastructure is limited. Online nature-based solutions (NBS) can provide enhanced detention and retention to reduce combined sewer overflows (CSOs). This study explores the effect of retrofitting online NBS to reduce CSOs using the city of Bergen, Norway, as case study. A combined sewer system's response was modelled using long-term continuous simulations (LTS) with an extensive set of climate scenarios. The case study catchment drains into the fjord Puddefjorden where bathing water quality is of concern.

A Geographical Information System (GIS) software was used as a preliminary tool to identify potential locations based on a set of criteria, such as surface slope and distance to surrounding structures. In this case, existing drains were targeted for retrofitting online prefabricated bioretention cells. An existing Storm Water Management Model (SWMM) was used for catchment modelling and assessing the effect on CSOs. The assessment criteria were based on reduction in both CSO volume and frequency. In addition, minimum criteria for achieving sufficient performance was investigated.

The study revealed marginal differences in reducing both volume and frequency of CSOs, post implementing bioretention cells. The percent of area implemented with NBS together with the hydraulic load, were found to be critical for the bioretention performance. The performance investigation implied that the prefabricated bioretention cells did not represent enough area within the sub-catchments to achieve sufficient performance. An adjusted model setup with increased bioretention surface area and hydraulic load, but still below suggested guidelines, achieved some performance increase. However, the reductions were small considering the simulation time period. This study substantiates the importance of thorough investigation of placement and potential performance of NBS prior to implementation.

Sammendrag

Urbane fellessystemer verden rundt står overfor kapasitetsbegrensninger og tilpasningskrav for å kunne møte fremtidige klimaendringer. Separering av avløp og overvann i tette urbane strøk er ofte kostbart, samtidig som det er begrenset med tilgjengelig areal for grønn infrastruktur. Naturbaserte løsninger som er direkte påkoblet fellessystemet kan gi økt fordrøyning og infiltrering for å redusere mengden overløp. Dette studiet etterforsker effekten av å montere naturbaserte løsninger for å redusere overløp i et område i Bergen, Norge. Langsiktige kontinuerlige simuleringer av fellessystemet ble brukt sammen med et omfattende sett av klimaprojeksjoner, til å modellere responsen på overløp. Nedbørsfeltet drenerer til Puddefjorden hvor det er ønsket badevannskvalitet.

Et geografisk informasjonssystem (GIS) ble brukt som verktøy for å identifisere potensielle plasseringer basert på et sett med kriterier, som for eksempel overflatehelning og avstand til omkringliggende konstruksjoner. Eksisterende sluk ble i dette tilfelle brukt som utgangspunkt for montering av prefabrikkerte regnbed direkte påkoblet fellessystemet. En eksisterende Storm Water Management Model (SWMM) ble brukt til å modellere nedbørsfeltet og vurdere effekten av regnbedene. Ytelsen ble målt i reduksjon av både volum og aktiveringsfrekvens av overløpene. Minimumskriterier for å oppnå tilstrekkelig ytelse ble i tillegg undersøkt.

Simulering av regnbedene resulterte i kun marginale reduseringer i både overløpsvolum og aktiveringsfrekvens. Prosentandel av nedbørsfeltet med implementert regnbed sammen med den hydrauliske belastningen viste seg å være kritisk for effekten av regnbedene. Undersøkelsen av minimumskriteriene antydet at overflatearealet til de prefabrikkerte regnbedene ikke var tilstrekkelig i forhold til arealet av nedbørfeltet, for å kunne oppnå tilstrekkelig ytelse. Et justert modelloppsett med økt overflateareal på regnbedene og økt hydraulisk belastning, men fortsatt under anbefalte retningslinjer, oppnådde en viss ytelsesøkning. Ytelsen fordelt over hele simuleringsperioden var i midlertidig fortsatt svært lav. Studiet underbygger hvor viktig det er å utføre grundige undersøkelser av både potensielle plasseringer og ytelse av naturbaserte løsninger, før de implementeres i et nedbørsfelt.

Preface

This thesis is submitted as the final product for the course *TVM4905 Water and wastewater engineering, Master's thesis* at the Norwegian University of Science and Technology (NTNU), Department of Civil and Environmental Engineering.

The purpose of the thesis was to investigate spatial allocation and performance of retrofitting online bioretention cells to a combined sewer system, for a case study in Bergen. The performance was assess through the reduction in frequency and volume of targeted CSOs. The structure of this thesis follows the structure of a research article, presented as a manuscript with the intent of future publication. I would like to express my full gratitude to my supervisor Associate Professor Tone Merete Muthanna, for giving me support and guidance throughout this process. Thank you for the great conversations and feedback, which I have truly appreciated. I addition, I would like to thank PhD candidate Elhadi Mohsen Hassan Abdalla for the support with programming in RStudio.

This master thesis was conducted as a part of the Klima2050 project – Risk reduction through climate adaptation of buildings and infrastructure (klima2050.no). The previous BINGO project – Bringing innovation to ongoing water management – a better future under climate change (projectbingo.eu), has been a foundation for information and data used for this study. This thesis has been a collaboration with Bergen municipality.

In addition, I would like to thank:

- Erle Kristvik for providing me with data from the BINGO project and the support regarding the existing SWMM model.
- Marit Aase at Bergen Municipality for proving me with data regarding the Damsgård catchment area and the combined sewer system.
- Nazia Zia at Bergen Municipality for providing me with the flow paths for the Damsgård catchment area.

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Martina Hølleland

Martina Hølleland

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CSO	Combined Sewer Overflow
DTM	Digital Terrain Model
GIS	Geographical Information System
LID	Low Impact Development
LTS	Long-Term continuous Simulation
NBS	Nature-Based Solution
NTNU	The Norwegian University of Science and Technology
SUDS	Sustainable Urban Drainage System
SWMM	Storm Water Management Model
WSUD	Water Sensitive Urban Design
USEPA	United States Environmental Protection Agency

1 Introduction

Climate change combined with increasing urbanization is requiring adaptation measures within stormwater management worldwide. Urban combined sewer systems face capacity constraints due to increased stormwater volume and rapid runoff response, resulting in combined sewer overflows (CSOs). CSOs divert untreated wastewater mixed with stormwater and other pollutants to nearby water bodies, deteriorating the water quality of the recipients (USEPA, 2004). In line with the UN Sustainable Development Goals of clean water and sanitation (#6) and sustainable cities and communities (#11) (United Nations, 2015), increased frequency and volume of CSOs is of great concern. In dense urban areas full sewer separation is often costly due to the necessary excavation and pipe dimensions, while available space is limited. Accordingly, there is a need for alternative adaptation measures such as the implementation of nature-based solutions (NBS), also known as Sustainable Urban Drainage Systems (SUDS) in the UK, Water Sensitive Urban Design (WSUD) in Australia and Low Impact Development (LID) in the United States (Fletcher et al., 2014). NBS are actions inspired by, supported by or copied from nature with the aim of enhancing the resilience of societies in a sustainable way (European Union, 2015). Green roofs, swales, bioretention cells and rain gardens are some NBS with the goal of bringing the runoff hydrograph back to pre-development state (Eckart et al., 2017). NBS offers a more sustainable and adaptable alternative to the traditional grey stormwater management.

A case study from Fredrikstad, Norway, found that if precipitation would increase by 20%, 30% and 50%, then the total amount of CSOs would increase by 36%, 54% and 89% respectively (Nie et al., 2009). Consequently, with increased precipitation CSOs are expected to pose a greater impact on receiving waters. Semadeni-Davies et al. (2008) simulated climate change and urbanization scenarios to study the impact on the combined sewer network in a coastal city south in Sweden. The study revealed a worst case scenario with a 450% volume increase of CSOs, while the use of NBS could reduce the number of CSOs to very low or negligible levels for both present and future climate scenarios. Combining different stormwater controls as well as varying their implementation rate have shown promising results as stormwater adaptation measures (Chen et al., 2019; Eaton, 2018; Li et al., 2019), among others.

Available space for green solutions are often limited in urban areas, making it challenging to implement NBS. Large-scale stormwater control measures are not always suitable in densely developed communities (Chen et al., 2019). This creates a desire to investigate the performance of more adaptable and less space consuming solutions, such as bioretention cells. Bioretention cells are flexible measures as they can be implemented in either new development projects or retrofitted into developed areas (Clar et al., 2004; Chen et al., 2019). Retrofit designed solutions can increase resilience to climate change by reducing stress on existing urban stormwater infrastructure (Eckart et al., 2017). Heavily urbanized areas are suitable for bioretention implementation, including sidewalks, traffic islands, street median strips and other impervious areas (USEPA, 2004). Eaton (2018) found bioretention and rain gardens to be the most effective for runoff reduction by studying a largely residential catchment in New York City, United

States. The same study found the relative implementation rate of different stormwater controls (percent of land area implemented on) to be an important variable in controlling the runoff reductions. A number of catchment modelling tools are utilized to evaluate the performance of implementing NBS (Eckart et al., 2017), such as the Storm Water Management Model (SWMM) developed by the United States Environmental Protection Agency (USEPA). Zahmatkesh et al. (2015) evaluated a scenario consistent of several NBS using SWMM for the Bronx river catchment in New York City, United States. The study revealed a reduction in both annual runoff volume and peak flow rates post implementing NBS.

The ability to mitigate runoff through NBS is significantly affected by the geophysical location of the stormwater control as well as catchment characteristics (Zahmatkesh et al., 2015). Specific site conditions such as soil condition, rainfall patterns and land use will impact the effectiveness of NBS, and should be considered when designing stormwater strategies and controls (Eckart et al., 2017). In addition, the implementation of NBS is often intertwined with several hydro-environmental and socio-economic considerations and constraints (Zhang and Chui, 2018). Kuller et al. (2019) conceptualizes spatial suitability for NBS into two perspectives; opportunities and needs. Opportunities refers to NBS needing a place while needs represents an areas need of the benefits derived from NBS implementation (Kuller et al., 2019). The implementation of NBS may provide environmental, social and economic co-benefits which underline the importance of having a holistic approach to NBS placement and design (Raymond et al., 2017). Despite the numerous studies on the performance of bioretention, most guidelines refer to larger rain gardens intended for new development (Geosyntec Consultants, 2013; City of Edmonton, 2004).

In Norway, the three-step strategy is a widely accepted approach for adaptive stormwater management (Lindholm et al., 2008). It is considered a standard approach and applied through municipality guidelines. The strategy presents an approach that considers stormwater management while simultaneously accounting for climate change and increasing urbanization. The three stages are: (1) Capture runoff from an average everyday storm event and handle it through infiltration; (2) Detain and retain runoff from larger storm events; (3) Route excess stormwater from extreme events and which cannot be handled by the previous step to safe floodways (Bergen Kommune, 2019). This study focuses around the first two steps of the strategy, managing stormwater locally by infiltrating and detaining runoff followed by a controlled release (Bergen Kommune, 2019). Retrofit options can assist the traditional grey infrastructure by detaining and controlling the stormwater.

The present study aims to investigate potential locations for retrofitting prefabricated bioretention cells connected as an online solution to a combined sewer system, using an urban catchment on the west coast of Norway as case study. The bioretention cell would infiltrate small events, both infiltrate and detain medium events, while larger events would be routed into the combined sewer system after initial capacity is reached. A Geographical Information System (GIS) was used as a preliminary tool to identify potential retrofit locations based on a set of criteria, such as surface slope and distance to surrounding structures. In this case, existing drains were targeted as potential locations. The performance of the bioretention cells were assessed through reduction in frequency and volume of three targeted CSOs. The catchment modelling was performed using an existing SWMM model with long-term continuous simulations (LTS) of the combined sewer system’s response and an extensive set of climate scenarios (10x10 years of 5 minutes rainfall).

This study aims to answer the following research questions:

1. How to develop placement criteria for retrofitting nature-based solutions?
2. What is the effect of retrofitting combined sewer systems with small online nature-based solutions on combined sewer overflows?
3. What are the minimum implementation criteria to achieve sufficient performance?

2 Study area

The city of Bergen, Norway, was used as case study, focusing on the Damsgård catchment area (Figure 1). Bergen is a coastal city known for its wet and temperate climate (Köppen-Geiger). The surrounding mountainous topography along with the coastal climate causes frequent precipitation over the city, with a mean annual precipitation of 2250 mm (Jonassen et al., 2013).

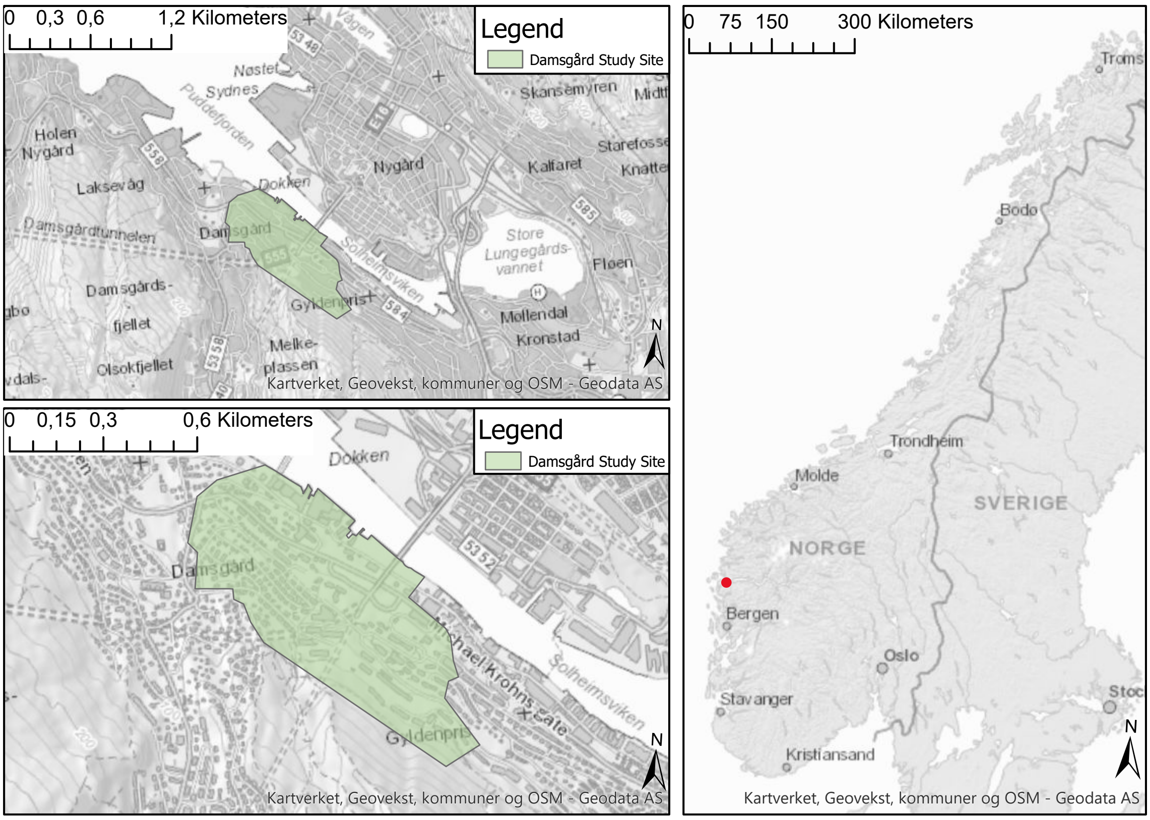


Figure 1: Damsgård study site, Bergen

Damsgård is situated between the mountain foot of Løvstakken and the city fjord Puddefjorden. The area is known for its steep residential hillside and an industrial area along the waterfront. The upper part of the drainage area is forested, while the Damsgård area is urbanized with high-density residential use. The area is currently under a larger transformation relocating the industry and creating a residential area with recreational activities along the waterfront. The municipality is therefore interested in keeping the fjord at bathing water quality.

The existing water and wastewater infrastructure consists of pipes purposed for water distribution, wastewater collection, stormwater collection and combined sewer. The residential hillside is dominated by combined sewer systems collecting and transporting both sewer and stormwater to wastewater treatment. The combined sewer system is equipped with several CSOs discharging to the fjord in cases when maximum capacity is reached during larger storm events. The combination of high urbanization and steep hillside results in rapid runoff response during storm events causing frequent activization of CSOs and deteriorating water quality in receiving fjord. The combined sewer system with the three targeted CSOs is shown in Figure 2.

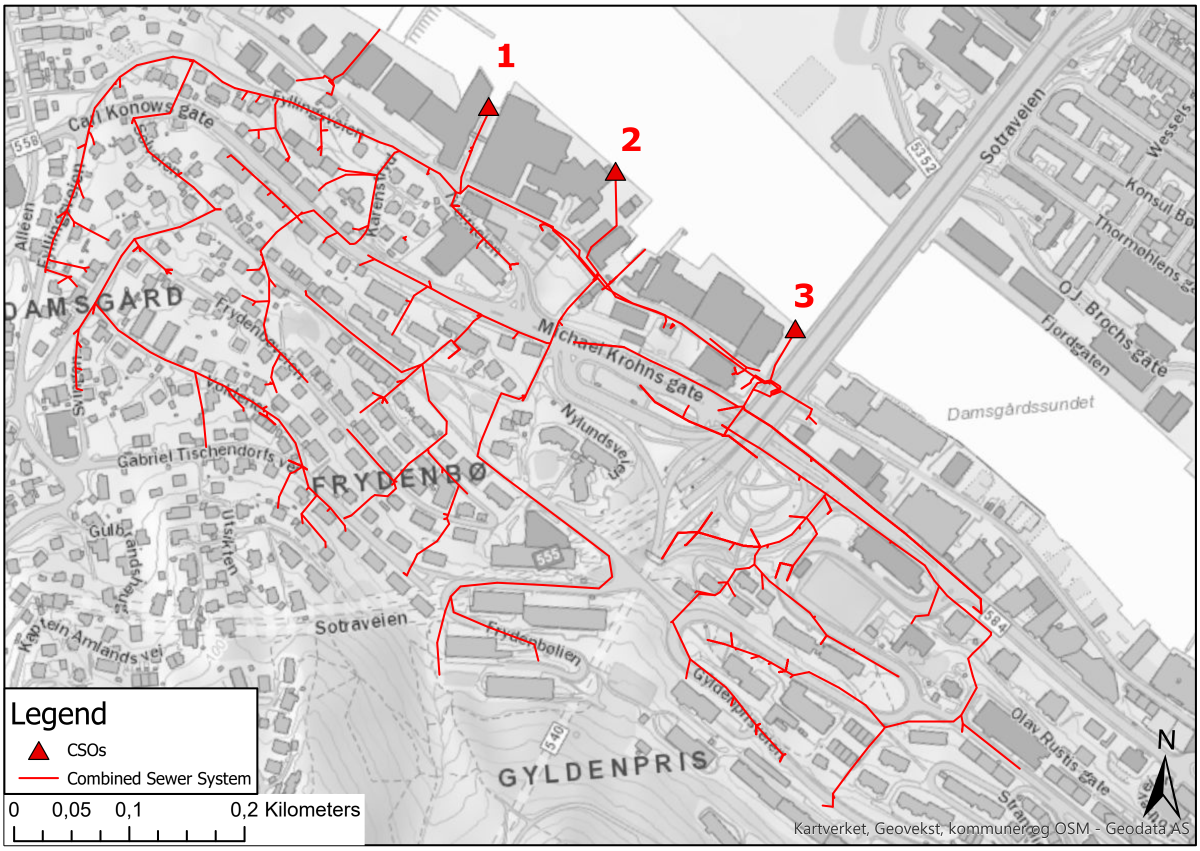


Figure 2: Combined sewer system with targeted CSOs

Increased frequency and volume of storm events with higher intensities are expected in the future due to climate change (Hanssen-Bauer, 2015). In Bergen, like many other central areas, the population is projected to grow (Iacovides et al., 2016), likely leading to more urbanization with paved surfaces and changed runoff patterns. Sustainable adaptation measures are therefore needed to manage todays and future stormwater challenges. The municipality of Bergen clearly states an overall desire of implementing NBS with the purpose of handling stormwater, in order to keep receiving water bodies clean (Bergen Kommune, 2019). Intercepting and detaining stormwater before it reaches the combined sewer system would reduce the risk of CSO activization.

3 Method and materials

3.1 Model setup

This study investigates spatial allocation and performance of smaller sized bioretention cells connected as an online solution to the combined sewer system. The purpose of the bioretention cells is to detain stormwater locally prior to entering the combined sewer system, causing a delayed runoff response. A pre-fabricated bioretention cell with an underdrain was used as basis for this analysis, targeting primarily road runoff. The runoff would first be diverted into a soil layer with limited infiltration capacity before being routed into a storage layer in a lower level of the unit. The storage layer would have a sealed bottom with a drain connected to the combined sewer system, resulting in no ground water recharge. The units were designed to infiltrate smaller rain events, partly infiltrate and detain medium events, while larger events would be routed into the combined sewer systems after initial infiltration and detention capacity is reached. Excess stormwater exceeding the surface storage would spill over the berms of the bioretention cells, and be collected by existing drains downstream. Existing drains connected to the combined sewer system were targeted as potential locations to limit the extensiveness of implementation. An overview of the process stages is given in the flow chart below (Figure 3).

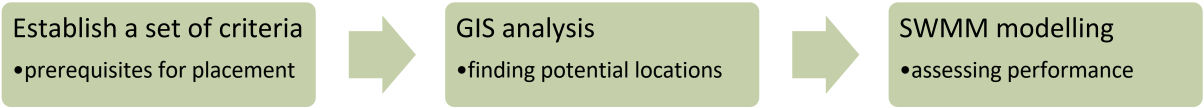


Figure 3: Flow chart of the process

3.2 Method for criteria selection

A set of criteria were established in order to narrow down potential locations for retrofitting bioretention cells. A literature review was conducted to acquire information about previously used or suggested criteria. The literature revealed several guidelines for larger rain gardens, but appeared to be limited concerning smaller retrofitted solutions. In addition, there was limited references for online solutions as opposed to offline infiltrating solutions. Consequently, the selected criteria were mostly found through trial and error during the GIS analysis within the physical constraints such as publicly owned land and allowable distance to buildings. The literature was used to support and guide decision making while trying out different actions, reviewing the potential placements and adjusting the actions accordingly. This strategy allowed for finding actions and the corresponding criteria that would remove areas unfit for retrofitting. The criteria used are presented in the results as well as described through the method for GIS analysis.

3.3 Area characteristics and hydro-meteorological data

The surface elevation model used for the GIS analysis was obtained from the Norwegian Mapping Authority through their publicly accessible online database (Statens Kartverk). With a resolution of 0.25 meters, a digital terrain model (DTM) of the catchment area was obtained using elevation points from 2017. The coordinate system WGS1984 UTM Zone 32N was used and the file format GeoTIFF. Information about the infrastructure in Damsgård was supplied in two shape files by the municipality of Bergen, along with a third shape file of the modelled flow paths.

Existing data on sewer production and climate predictions developed during the BINGO project was used as input in SWMM to assess the response of retrofitting NBS. A calibrated time series of sewer production representing the period from 2004 to 2005 was used (Alves et al., 2016). An existing ensemble of decadal climate projections was used as precipitation input for the catchment model in SWMM. The BINGO project developed 10 realizations of long-term climate projections with 5-minute precipitation interval, representing the decade from 2015 to 2024 (Alves et al., 2018; Kpogo-Nuwoklo, 2017). Decadal predictions account for both internal climate variability and external anthropogenic forcing (Kpogo-Nuwoklo, 2017). These projections were used together with observed precipitation from Florida weather station (2004-2014), making the precipitation data a total of 21 years.

3.4 Identifying potential locations through GIS analysis

A Geographical Information System (GIS) software was used as a preliminary tool to identify potential locations for retrofitting bioretention cells based on the previously set criteria, while targeting existing drains. GIS software is an efficient way to analyze elevation models and to supply information about the drainage area (Muthanna et al., 2018). The DTM and infrastructure data were imported into the chosen GIS software, ArcGIS Pro version 2.4.3, and clipped to a matching geographical size, making the model less computational. The functions used during the analysis are summarized in Table 1. The infrastructure data contained layers with several different attributes gathered within. *Select Layer By Attribute* was used to extract and create new layers for specific attributes that were desired in separate layers, such as the different purposed pipes. A new polygon was created using *Create Feature Class*, to narrow down the area of interest within Damsgård, including the targeted CSOs as well as their associated upstream water and wastewater system.

To locate drains connected to the combined sewer system, the relevant pipe network first had to be identified. Stormwater pipes connected to combined sewer pipes could be located using *Select Layer By Location* with the relationship *boundary touches*. The function was repeated, creating a new layer each time and locating the pipes connected to the newest created layer. The process was repeated until no more features were selected, in this case a total of twelve times. The new pipe layers were merged together creating one layer containing the extended combined sewer system. Combined sewer tunnels and pressurized pipes were removed from the layer due to being unsuited for retrofitting. *Select Layer By Attribute* was used to select drains, street drains and gullies, before creating a new layer of the selection representing the drains of interest. As for the pipes, the same method was used to locate the drains connected to the combined sewer system. The relationship *within a distance* of 0.1m to the combined sewer system layer was used to extract the connected drains.

The potential drains for retrofitting were clipped to the predefined sub-catchments imported from the existing SWMM model. Areas close to the recipient were not considered suitable due to the desire of intercepting surface runoff locally. A buffer of 100 meters (Shoemaker et al., 2009) was created around the fjord and the *Erase* function was used to remove the drains overlapping this area. Another two buffers were created to avoid implementation conflicts with existing features. A buffer of 1.5 meters around structures such as houses (Prince George's County, 2007), and a buffer of 1 meter around fences and brick walls. Drains within any of these buffers were erased from the layer. To ensure placement in close proximity of a road, the drains were clipped to be within a buffer of 3 meters around roads. Through *Select Layer by Attribute*, highways and county roads were singled out and separated into individual layers. Using *Select Layer by Location* and *within a distance* of 0.1 meter, ticking the invert spatial relationship box, drains outside highways were selected. The function was repeated for county roads only this time changing it to *removing from the selection*, removing the drains within the county roads. A new layer was created with the new selection of potential drains. In this particular catchment there is a bridge going over the fjord, where the GIS model basis was insufficient. A drain under the bridge was therefore manually removed from the potential drain selection.

Bioretention cells are best suited for low sloped areas, preferable around 5% but under 20% (Paus and Braskerud, 2013). The DTM files were imported into the GIS model to investigate the terrain slopes. The multiple files were merged together using the *Mosaic To New Raster* function, creating one new raster file. The spatial analyst tool *Slope* was used to carry out a slope analysis. A buffer of 0.5 meter was created around the drains to assess the surrounding surface slope. This buffer was used as an input in the function *Zonal Statistics as Table*, using the slope raster as values. The resulting table contained slope statistics within the 0.5 meter perimeter around the drains. Sorting the mean slopes in descending order, higher sloped areas could be located. Drains with a mean slope >10% were removed under the assumption of being too steep sloped for retrofitting. The *Zonal Statistics as Table* was run again with the remaining drains, and the distribution of the mean slopes was generated. The distributed mean value was used as the surface slope parameter in SWMM for the implemented bioretention units.

The percent of impervious area treated by the bioretention cells within each sub-catchment is required in the SWMM model. For this case, the bioretention cells aim to mainly capture road runoff. However, the impervious area within the catchment contain additional impervious areas such as roof tops. The GIS model was therefore used to estimate the percent of road surface within the impervious area, for each of the sub-catchments. *Tabulate Intersections* was used to compute the intersection between the sub-catchments and the roads, while cross-tabulating the areas. Zone fields that were kept for the sub-catchments were the identification number, the sub-catchments name and the percent imperviousness. The resulting table contained a column with the percent of road area within each sub-catchment. The percent of road area within the percent imperviousness for each sub-catchment was calculated by dividing the percentage of road with the percent of imperviousness, using the calculate tool in a new column.

Table 1: GIS functions used with their definitions from ArcGIS Pro

Function	Definition
Clip	Extracts input features that overlay the clip features.
Select Layer By Attribute	Adds, updates or removes a selection based on an attribute query.
Create Feature Class - polygon	Creates an empty feature class in an enterprise or file geodatabase; in a folder, it creates a shapefile.
Select Layer by location - boundary touches - within a distance - within * invert spatial relationship	Select features based on a spatial relationship to features in another dataset.
Buffer	Creates buffer polygons around input features to a specified distance.
Erase	Creates a feature class by overlaying the input features with the polygons of the erase features. Only those portions of the input features falling outside the erase feature boundaries are copied to the output feature class.
Mosaic To New Raster	Merges multiple raster datasets into a new raster dataset.
Slope	Identifies the slope (gradient or steepness) from each cell of a raster.
Zonal Statistics as Table	Geoprocessing tool that summarizes the values of a raster within zones of another dataset and reports the results to a table.
Tabulate Intersections	Computes the intersection between two feature classes and cross-tabulates the area, length, or count of the intersecting features.

3.5 Catchment modelling through SWMM

Catchment modelling was performed through a Storm Water Management Model (SWMM) to assess the effect of retrofitting NBS on targeted CSOs. The software used for this project was PCSWMM version 7.2 which utilizes SWMM version 5.1. PCSWMM supports GIS integration such that layers from the GIS analysis could be imported into the SWMM model (CHI Water). An existing hydrodynamic SWMM model was used for this case study. The full model was developed as part of the BINGO project, containing the entire drainage system in the Damsgård area (Alves et al., 2016). The subsystem used in this study covers the targeted CSOs and their associated drainage area. It consists of 88 sub-catchments draining to each their inlet and five outfalls. One outfall is located by a pumping station and represents the sewer transported to wastewater treatment. The remaining four outfalls discharge to the fjord, where three of them are CSOs while the fourth is a stormwater outfall. The three CSOs are the targeted outfalls for this project.

SWMM uses the term LID in their software and will therefore be used when referring to the SWMM bioretention modelling process. A LID was created using the LID Control Editor panel. By choosing bioretention cell as LID type, the given process layers are: Surface, Soil, Storage and Underdrain. The properties for each of the layers were filled in according to the table below (Table 2), with corresponding references to substantiate the values. The inside diameter of the drain was set to 100 mm, following the recommendations (Paus and Braskerud, 2013).

Table 2: Properties for the bioretention cell

	Property	Value	Reference/explanation
Surface			
	Berm height (mm)	100	Presumed
	Vegetation volume (fraction)	0	
	Surface roughness (Manning's n)	0.15	(Rossmann, 2015) Overland flow – grass
	Surface slope (%)	5.9	GIS analysis results
Soil			
	Thickness (mm)	500	Presumed
	Porosity (volume fraction)	0.437	(Rossmann, 2015) Loamy sand
	Field capacity (volume fraction)	0.105	(Rossmann, 2015)
	Wilting point (volume fraction)	0.047	(Rossmann, 2015)
	Conductivity (mm/hr)	100	(Paus and Braskerud, 2013)
	Conductivity slope	10	(Chui et al., 2016)
	Suction head	3.5	Presumed
Storage			
	Thickness (mm)	300	Presumed
	Void ratio (mm)	0.99	Empty space (only values <1 accepted)
	Seepage rate (mm/hr)	0	No groundwater infiltration
	Clogging factor	0	
Underdrain			
	Drain coefficient (mm/hr)	112	Calculated, Appendix 1
	Drain exponent	0.5	(Rossmann, 2015)
	Drain offset height (mm)	6	Standard value in SWMM
	Open level (mm)	0	
	Closed level (mm)	0	
	Control curve	-	

The drain coefficient and drain exponent determines the flow rate through the drain as a function of the stored water height above the drain (Rossmann, 2015). The exponent was chosen to be 0.5, making the drain act like an orifice (Rossmann, 2015). The drain coefficient value depends on the design of the drain and bioretention cell. Literature review revealed few studies listing their drain coefficients and in some cases with unclear units. The flow rate equation together with the standard orifice equation was used to find the drain coefficient. However, to avoid the assumption of the drain being completely filled, a filling degree was calculated. The flow was found by assuming K_{sat} as the limiting factor for maximal flow rate entering the drain. The Colebrook-White equation was used to find the flow capacity of the pipe, through PipeLife's tool for calculating velocity and flow for filled pipes (PipeLife). The flow fraction was used with a partial filling degree diagram (Ødegaard and Norheim, 2014) to find the filling degree of the drain (Appendix 1). The final value is given in Table 2 and the detailed calculations can be found in the appendix (Appendix 1).

The potential drains found through the GIS analysis were imported into the SWMM model, revealing which sub-catchments the bioretention cells should be placed within. The LIDs were implemented into each sub-catchment manually through the attribute list, using the LID Usage Editor. Some additional properties of the specific LID unit was required such as the surface area of each bioretention cell and the number of units within each sub-catchment. The size of the bioretention cell was assumed to be 1480 x 1480 x 1500 mm (width x depth x height) (Skjæveland). The percent of initial saturation was set to 50% for all sub-catchments, while the percent impervious area treated for each individual area was found during the previous GIS analysis.

When placing LIDs within an existing sub-catchment in SWMM, an equal amount of non-LID area is then displaced from the sub-catchment (Rossmann, 2015). According to the SWMM manual, the existing values for percent impervious area and width may need adjustments for the sub-catchments affected by the LID implementation, according to the area that was displaced (Rossmann, 2015). In this case, the percent impervious was adjusted accordingly while the width was assumed unchanged due to the small size of the bioretention cells. The new percent impervious area for each sub-catchment was calculated by dividing the impervious area remaining on the percent non-LID area remaining (Rossmann, 2015).

The calibrated sewer production time series covered only two years (2004-2005) of the 21 years with precipitation data. In order to have data on sewer production during the desired simulation period, the time series was repeated such that it would be reoccurring every two years. The Plan or Scenario manager in PCSWMM was used to create new projects for each of the desired scenarios. All 10 climate scenarios with and without LIDs were created, resulting in a total of 20 project scenarios. The precipitation data was added as a rain gauge file, while the sewer production was added as a time series. The original model setup (A) was run for all 20 project scenarios. The reduction in volume was assessed through the outfall nodes by the recipient, while the activization frequency was found using the flow diving nodes.

Minimum implementation criteria to achieve sufficient performance was investigated due to the first obtained results. Different LID parameters and sub-catchment conditions were changed in order to investigate how the model responded and bioretention cell performance. Two to three bioretention cells with the corresponding sub-catchments were used for this process. To avoid time consumption, the performance was assessed by simulating one year and observing changes in runoff for a selected event. The different scenarios tested are listed in the results (Table 4).

Following the event-based testing, another model setup was simulated over the full time period (21 years) with the 10 climate projections. This adjusted model setup (B) contained adjustments to the post LID implementation scenarios. In this setup, the surface area of all bioretention cells were increased to the size where it would occupy one percent of the corresponding sub-catchment. The impervious area of the sub-catchments were adjusted accordingly as previously mentioned. In addition, the impervious area treated by the LID was increased to 80 % for all bioretention cells.

3.6 Model output analysis

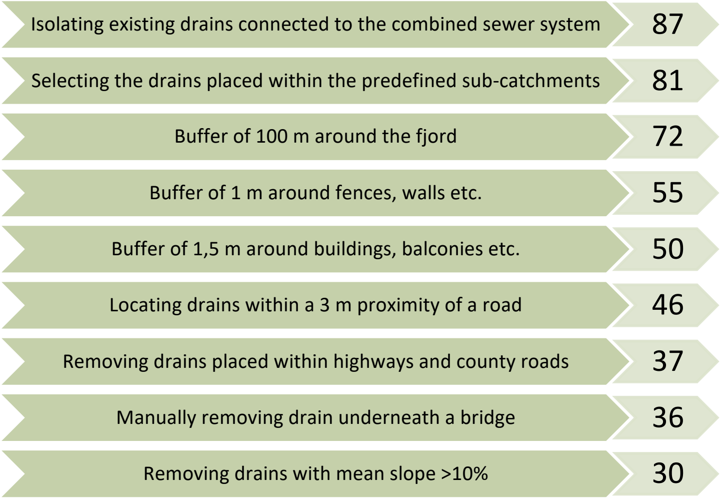
Flow duration curves were created to evaluate reduction in CSO activization frequency with the implemented bioretention cells. Curves were created for the two scenarios (A) and (B), and for each CSO. All climate projections are represented and the median projected scenario, with and without implemented bioretention. The open source software RStudio, version 1.2.5042, was used to create the flow duration curves. See appendix for RStudio scripts (Appendix 6).

The flow representing the CSO activization threshold was implemented into the flow duration curves. These threshold values were found using the number of hours with outfall loadings for 2018, supplied by the municipality of Bergen. Using the online database for observations and weather statistics by the Norwegian climate service center (Norsk Klimaservicesenter), observed rainfall for 2018 was collected for the Florida weather station in Bergen. A simulation for 2018 was run and flow duration curves were created for each of the CSOs. The number of active hours were applied, revealing the CSO activization flow.

4 Results

The literature review along with the GIS trial and error process, resulted in a set of criteria used to narrow down potential locations for retrofitting. First, prerequisites for placing the bioretention cells were considered. In this case it was locating existing drains connected to the combined sewer system within existing sub-catchments. Further, different distances to various features were set as criteria such as a distance of 100 meters to the recipient (Shoemaker et al., 2009) and 1.5 meters distance to structures (Prince George's County, 2007). Additional criteria were applied along the way such as targeting only locations in immediate proximity of a road, where 3 meters was set as the criteria. Drains placed within highways or county roads were removed due to their high traffic load and the potential increased implementation conflicts. Drains covered in any way, in this case by a bridge, were considered unsuited for bioretention retrofits. The slope threshold was set to <10% due to the steep hillside of the catchment.

The GIS analysis revealed 81 existing drains within the predefined sub-catchments. By applying a distance of 100 meters to the waterfront, 72 drains remained. Additional buffers around structures such as houses and fences, narrowed the selection down to 50 drains. After removing drains with slopes >10%, the number of drains fit for retrofitting changed from 36 to a total of 30 drains. The applied criteria with the number of potential drains remaining after application, is shown in Figure 4.



Isolating existing drains connected to the combined sewer system	87
Selecting the drains placed within the predefined sub-catchments	81
Buffer of 100 m around the fjord	72
Buffer of 1 m around fences, walls etc.	55
Buffer of 1,5 m around buildings, balconies etc.	50
Locating drains within a 3 m proximity of a road	46
Removing drains placed within highways and county roads	37
Manually removing drain underneath a bridge	36
Removing drains with mean slope >10%	30

Figure 4: Criteria applied with the number of potential drains remaining

Importing the drains into the existing SWMM model revealed a drain placed within a sub-catchment not draining into the combined sewer network, resulting in a final number of 29 drains. These were unevenly distributed with two CSOs having seven bioretention cells retrofitted each, while the third had 15. The distribution of the drains can be seen in Figure 5.

Figure 5: The SWMM model with the potential drains represented as red points

The mean percent volume reduction achieved with the different climate scenarios are given in the table below (Table 3). The table shows the original model setup (A) and the adjusted model setup with increased bioretention surface area and hydraulic load (B), for each of the three targeted CSOs. In addition, the contributing drainage area is listed for each of the CSOs with the number of connected bioretention cells. Results for each climate scenario for both model setups is given in the appendix (Appendix 2).

Table 3: Mean percent volume reduction and contributing drainage area for the CSOs

	% Volume reduction		Drainage area (ha)	Number of LIDs
CSO	A	B		
1	2	49	9.3	7
2	3	36	8.0	7
3	4	46	12.4	15

An overview of the adjustments applied to investigate minimum criteria for sufficient performance, is given in Table 4. There were marginal changes in performance for most adjusted scenarios. However, increasing the surface area of the bioretention cells to represent one percent of the sub-catchment area in addition to increasing the hydraulic load to 80%, resulted in evident peak reduction. Detailed results from the criteria investigation are given in the appendix (Appendix 5).

Table 4: Adjustments applied with the corresponding performance increase

Adjustments applied	Performance increase
Increase % impervious area treated to	
• 50%	Marginal
• 80%	Small
Adjusting the drain coefficient	
• 40	Marginal
Decreasing K_{sat} to	
• 3cm/hr	Marginal
Adjusting conductivity slope to	
• 5	None
• 30	Marginal
Increase surface area of LID to	
• 5 m^2	Marginal
• 20 m^2	Small
• Until 1% of sub-catchment was occupied by LID	None
- With K_{sat} =3cm/hr	Marginal
- With 50% impervious area treated	Small
- With 80% impervious area treated	Evident
Changing drainage area to only include road surface (100% impervious)	
• With 90% impervious area treated	Marginal
Using rainfall from a different city	
• Trondheim (Risvollan weather station)	None

The flow activization thresholds that were found for each of the CSOs are given in Table 5, with the corresponding number of overflow hours supplied by the municipality for 2018. The flow duration curves created to find the thresholds can be found in the appendix (Appendix 3).

Table 5: Hours overflow in 2018 and flow thresholds

	Overflow for 2018 (hrs)	Threshold flow (m3/s)
CSO1	261.4	0.495
CSO2	50.2	1.622
CSO3	119.7	1.069

Flow duration curves for all CSOs for both model setups (A) and (B) are found in Appendix 4. The curves for CSO1 are given below, both with all climate scenarios represented and with the median scenarios.

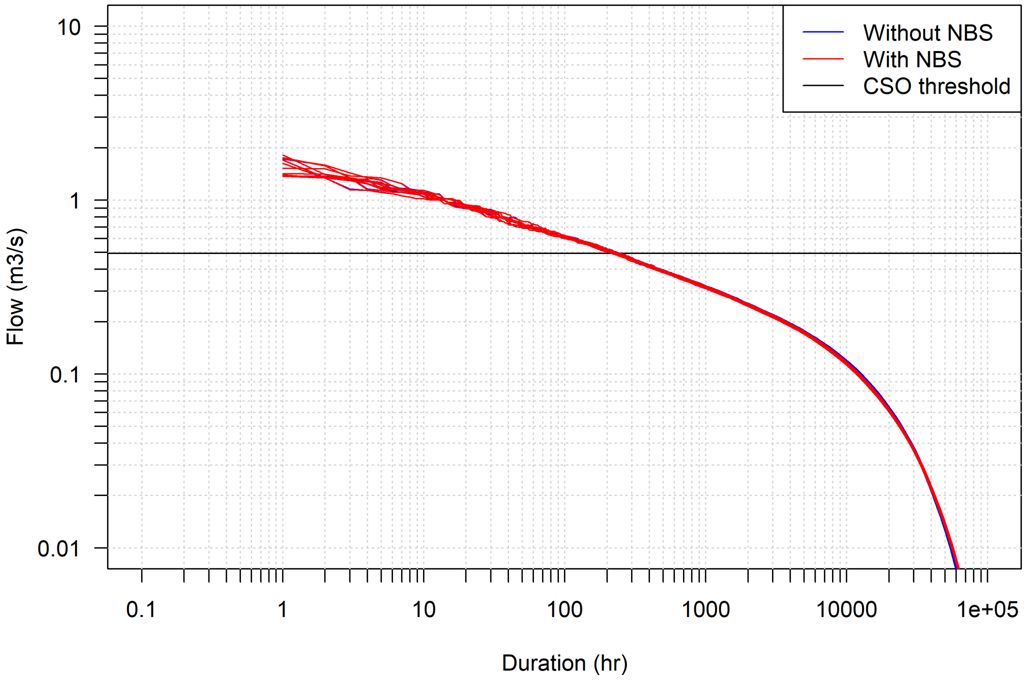


Figure 6: CSO 1, all climate scenarios for original model setup (A)

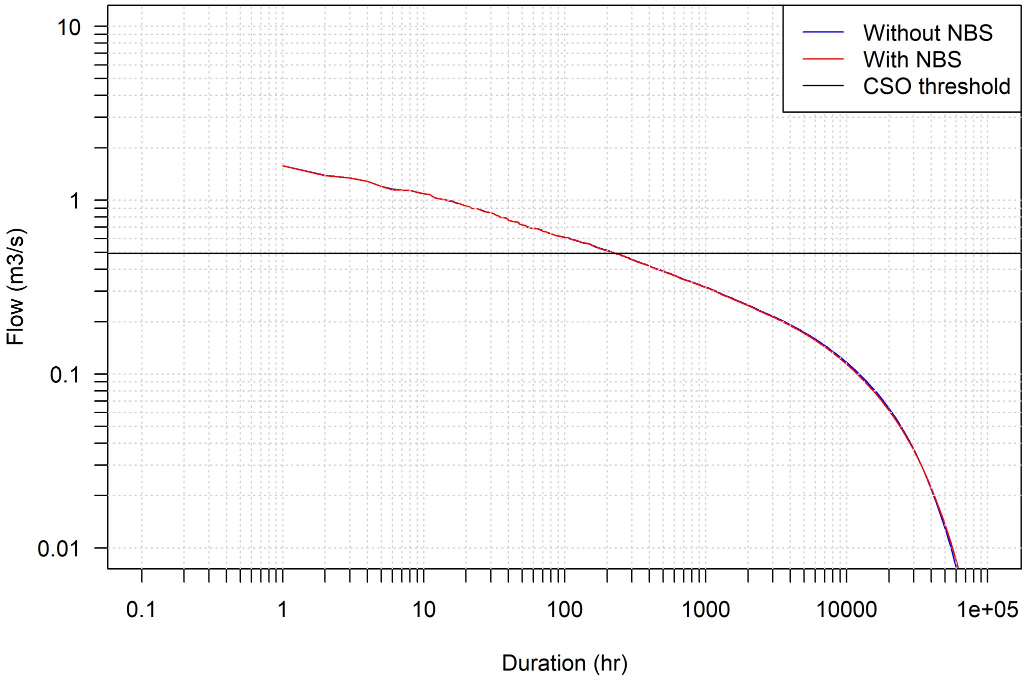


Figure 7: CSO 1, median scenario for original climate setup (A)

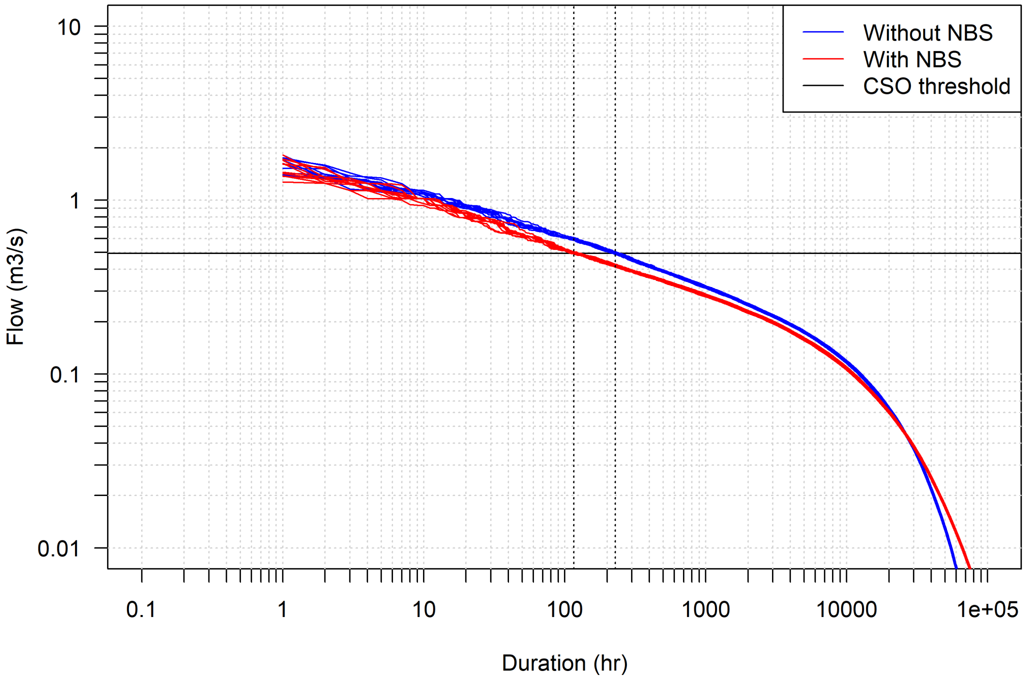


Figure 8: CSO 1, all climate scenarios for adjusted model setup (B)

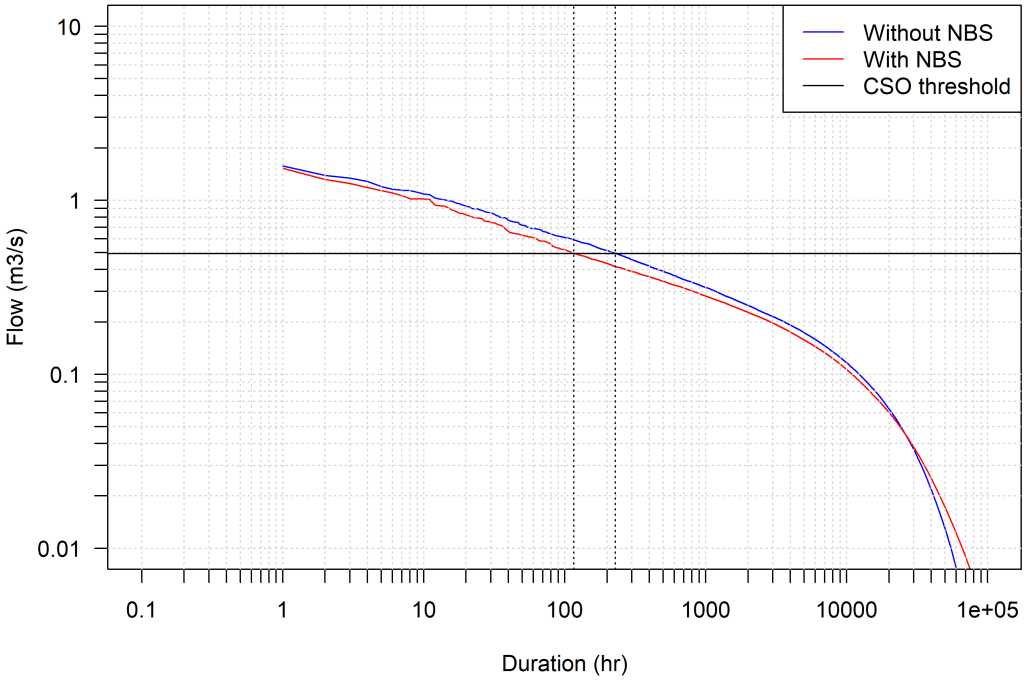


Figure 9: CSO 1, median scenario for adjusted model setup (B)

Using model setup (A), the resulting curves for CSO1 were on top of each other, revealing no difference in the climate scenarios with or without implemented bioretention cells (Figure 6). The reduction in activization frequency after implementing bioretention cells was found to be marginal for all three CSOs using the original model setup (A). Some increased performance was found for CSO1 with the adjusted model setup (B) where the curves for with and without bioretention cells are clearly separated (Figure 8). Both CSO1 and CSO2 har increased performance with the adjusted model setup (B), with a reduction of approximately 100 and 10 hours respectively.

5 Discussion

This study aimed to develop placement criteria for retrofitting online bioretention cells and investigated what effect such solutions could have on CSOs. The performance was measured through reduction in CSO volume and frequency. In addition, the study set out to investigate minimum criteria for achieving sufficient performance. The performance of NBS retrofits can be affected by location, distribution, climate, design and maintenance among others. Finding suitable locations for retrofitting may be challenging due to space constraints in dense urban areas.

The potential locations for retrofitting bioretention cells are individual for each catchment. Consequently, placement criteria relevant to consider for a catchment might differ from the criteria used in this case. Applying additional criteria would increase the detailing of the location investigation. However, it would also be time consuming and perhaps lead to excessively detailing with unsure performance. Prioritizing which criteria to apply is important to effectively find realistic locations. A positive performance outcome would however push towards conducting a more detailed investigation during further planning processes. The criteria used for this case study are viewed as reasonable suggestions, and applicable to other catchments. A coarse recipe for finding criteria is to first investigate desired prerequisites for implementation, and then consider the surroundings to keep necessary distances as well as avoiding other potential implementation conflicts. Some of the applied criteria overlapped such that some drains would have be removed regardless of the applied criteria order.

A reasonable prerequisite could for example be placement along or in near proximity of a flow path. In this case an existing drain was used as a location basis, and the flow paths were assumed to be aligned with the drains. However, the GIS model revealed that some drains were not in immediate proximity of the modelled flow paths supplied by the municipality. During the implementation process it can be feasible to do smaller adjustments to the surrounding slopes. Constraining the drain selection to be along flow paths could therefore eliminate drains that could be of interest with just a few adjustments required. Additional criteria examples that might be relevant to consider is minimum width of roads and sidewalks, distance to telegraph poles, effect on road visibility around curbs, among others.

In order to locate the existing combined sewer system, including connected stormwater pipes, the placement of pipes in relation to each other in the GIS model were assessed. The *boundary touches* function used, excludes pipes where the boundaries are not completely overlapping. For the drains, a distance of 0.1 meter to the combined sewer network was used as the GIS analysis revealed several drains not touching boundaries with presumed connected pipes. Appropriate distances to buildings were accomplished by creating buffers. However, also structures such as bus stop shelters were included as it was not distinguished between different types of structures. These are smaller, public structures that could potentially be moved or made necessary adjustments to in order to implement the relevant bioretention cell.

The potential drains were constrained to being within 3 meters of a road, due to the target being road runoff. In addition, implementation within road classifications such as highways and county roads were assumed not feasible. The value of 0.1 meter buffer around these roads included all drains that were placed within the road, while drains placed on surrounding sidewalks were still kept as potential placements. A different approach would be to assume specific road classification as prerequisite for implementation, but this would require all roads to be classified in the GIS model.

The suggested slope for bioretention cells is around 5% and should not exceed 20% (Prince George's County, 2007). However, eliminating drains with >5% mean slope would drastically narrow down the number of potential drains due to the catchment topography. As some guidelines and studies advise using <10% as a maximum limit for drainage slope (Ariza et al., 2019; Geosyntec Consultants, 2010), this threshold was applied. An alternative solution to manage steep slopes, is to implement bioretention cells as a step solution. The excess stormwater spilling over the berms of one bioretention cell could then be routed as inflow into another.

The percent impervious area treated or percent road area within the impervious area found through the GIS analysis, varied a great deal. The sub-catchment with the lowest percent impervious area treated, was eight percent. This particular sub-catchment had two suitable drains and it could be argued that this would not be cost-efficient. Treating only eight percent of the impervious area will likely give insufficient performance, and would in all likelihood not be cost-efficient even with only one bioretention cell implemented. This substantiates how a thorough investigation of performance potential is important prior to implementation

The suitable locations found through the GIS analysis are theoretical (Li et al., 2019). Some existing roads, sidewalks or drains may not be suited for retrofitting due to practical constraints. The locations need to be explored further and adjusted accordingly, prior to implementation (Li et al., 2019). The placements found are limited to the information provided by the GIS model and the implemented criteria. In addition, the GIS model and SWMM model were not completely coinciding. By restricting the potential drains to be within the predefined sub-catchments, several drains were removed. From the GIS analysis these drains were connected to the targeted combined sewer systems, while they were outside of the contributing drainage area modeled in SWMM. In addition, some sub-catchments appeared to have either too high or too low percent impervious area compared to the observed road area within the sub-catchments. This is likely due to the calibration method used to calibrate the impervious area in the existing SWMM model. However, these differences were considered small, thus did not compromise our confidence in the two models.

For the simulations over the 21-year period, the sewer production time series was extended by repeating the two years of data collected. This assumes the sewer production pattern will stay the same without considering any future changes such as increased population. In cities such as Bergen, the population is expected to have a high growth (Iacovides et al., 2016). In addition, the current transformation of the Damsgård area could indicate a future increase in residential living, especially along the waterfront. Consequently, future sewer production should be projected to achieve a higher accuracy on the CSO response when simulating future climate scenarios.

Initial saturation of the bioretention cells were set to 50%. Antecedent conditions lead to varying runoff and causes uncertainty in expected runoff volumes (Davidsen et al., 2018). As this study simulated a longer time period, compared to looking at one specific event, the initial saturation would have an insignificant effect on the results. During the testing phase where multiple parameters were adjusted, the rain event used followed a couple of weeks with dry weather conditions.

The original model setup (A) resulted only in a slight volume reduction for all CSOs, while the adjusted scenario (B) gave an evidently larger reduction. CSO1 achieved nearly 50% volume reduction over a 21-year period. The large increase in volume reduction is likely due to the hydraulic load of the bioretention cells being adjusted as high as 80%, as well as the enlarged bioretention surface area. CSO1 and CSO2 have similar size of contributing drainage area, as well as each having seven bioretention cells implemented. CSO1 performed considerably better than CSO2 under the adjusted model setup (B). The difference is likely due to the lower threshold value for CSO1, as the bioretention cells are expected to have a higher effect on smaller rain events. In addition, the combined sewer not diverted into overflow by CSO1 is routed into CSO2. Consequently, CSO2 would experience a higher hydraulic load where the potential volume fraction reduced by the bioretention cells would be smaller. CSO3 had 15 bioretention cells implemented while having the largest contributing drainage area. Having the least amount of area per bioretention cell, the performance was expected to be high. However, the distribution and size of sub-catchments compared to the bioretention cells can influenced the performance. As with CSO2, the threshold for CSO3 is quite high and would influence the potential volume reduction.

The flow duration curves showed marginal difference after implementing bioretention cells for the original model setup (A). The three thresholds for activating the CSOs appeared to be relatively high, such that a potential reduction in frequency would require significant performance of the bioretention cells. As the bioretention cells in this case are prefabricated, the percentage of surface area occupied depends on the size of the drainage area and the number of units implemented per sub-catchment. Using the existing model setup (A), the bioretention cells constituted less than 0.1% of the existing sub-catchment area, for the sub-catchments containing one bioretention cell. A sub-catchment containing four bioretention cells, had 0.3% area occupied by bioretention. The suggested catchment area occupied by bioretention cells is 5-10% (Minnesota Pollution Control Agency, 2008), revealing that our prefabricated bioretention cells appear to be insufficient. However, this guideline is seen as conservative when designing to achieve specific targets such as the previously mentioned three-stage strategy (Paus and Braskerud, 2013).

Due to unexpected low performance using the original model setup, new simulations were run with various adjusted LID and sub-catchment characteristics. This process was conducted in an attempt to investigate the minimum criteria to achieve sufficient performance. The selected adjustments were chosen based on confidence in parameter values and presumptions of what could influence the performance. The majority of event-based simulation, run for the two to three sub-catchments investigated, showed marginal differences in performance. The adjustments that resulted in improved performance was increasing the surface area until one percent of the sub-catchments were occupied by LID, while simultaneously increasing the percentage of impervious area treated to 80%. This scenario is unrealistic as it assumes the necessary space is available. However, a model setup with these adjustments (B) was simulated for the full time period to investigate the necessary area needed to achieve sufficient performance and compare with the original model setup (A).

A challenge faced, was finding the best suited strategy to model the drainage area of the bioretention cells. The existing sub-catchments varied in sized and went beyond the targeted road surface. Consequently, the prefabricated bioretention cells became very small compared to the sub-catchment area. One of the scenarios investigated was changing the contributing drainage area to only contain road surface, resulting in a 100% impervious area. The amount of impervious area treated was set to 90% as some runoff is expected to bypass the bioretention cells. Assuming no runoff contribution from surrounding areas along the road is unrealistic, especially considering the topography of the case study. It is reasonable to assume that the steep hillside will cause less infiltration and more runoff from pervious areas. In urban contexts the soil is often more compact as well as permeable surfaces are increasingly being used as adaption measures to manage runoff (Davidsen et al., 2018). As a result, runoff from permeable surfaces is important to consider in runoff models when designing climate adaptation measures (Davidsen et al., 2018). However, the method was seen as a reasonable strategy due to the target being road runoff, but did not result in any significantly improved performance. The percent of bioretention surface area within each sub-catchment, still remained below one percent.

The flow duration curves for the adjusted model setup (B) showed some performance improvement for CSO1 and CSO2. The frequency reduction was however ten times larger for CSO1 than CSO2. Even though they have similar sized drainage areas and had the same number of bioretention cells implemented, the threshold flow for CSO1 is under one third of the threshold for CSO2. The capacity of CSO1 is consequently lower and the bioretention cells can pose a greater difference. The low threshold substantiates CSO1 having the highest measured hours with outfall loadings in 2018. CSO3 has a lower threshold value than CSO2 and the highest number of bioretention cells implemented, but appear to only result in a marginal difference. The significantly larger drainage area contributing (1.5 times larger compared to CSO2), combined with the general high threshold would likely be the reason for such poor performance. Considering the frequency reductions over the 21-year simulation period, they become marginal. Comparing CSO1 with 100 hours reduction over 21 years, the reduction is below five hours per year. Comparing with the hours of outfall loadings for 2018, it would represent less than two percent reduction in active hours per year.

Comparing the flow duration curves presented for model setup (A) and (B), there is a decrease in active hours achieved with adjusted surface area of the bioretention cells. The significant difference in performance reveal that the sizing of NBS and the hydraulic load is critical to achieve sufficient performance. Even though an evident performance was found with the bioretention cells representing 1% of the sub-catchment areas, this study substantiates the suggested guidelines of 5-10% (Minnesota Pollution Control Agency, 2008) through highlighting the importance of these parameters. Kristvik et al. (2019) investigated the performance of NBS in three different Norwegian cities, among them Bergen. The study found that the bioretention cell-to-catchment-area ratio should be higher than the applied 5% to improve the general performance at the Bergen site, due to the large amount of precipitation.

Increasing the surface area of NBS poses a challenge in urban areas as available space is limited. Spatial constraints was one of the reasons for investigating the performance of small online bioretention cells. Retrofit projects can especially be challenging as there are typically no areas assigned for implementing NBS in an already densely developed urban area. The results show that it would be insufficient to only target existing drains with the prefabricated bioretention cells, for this study area. An alternative solution would be to investigate the bioretention cells in combination with implementing other NBS. Previous research have found that combining different stormwater adaptation measures can increase the performance (Chen et al., 2019; Kristvik et al., 2019; Li et al., 2019). Combining different NBS can significantly reduce the required detention volumes (Kristvik et al., 2019), which can be challenging to achieve with spatial constraints. During high intensity rain, the effectiveness of NBS are generally low due to exceeding the storage capacities (Zolch et al., 2017). The storage capacity for a local area can therefore be increased by combining different NBS (Zolch et al., 2017).

As mentioned, NBS can provide important environmental, social and economic benefits (Raymond et al., 2017). NBS can increase the resilience of a local community by creating co-benefits on a neighboring scale (Morello et al., 2018). The implementation of bioretention cells can therefore create additional co-benefits, despite the low performances found in reducing CSO volume and frequency. Communities have different needs for co-benefits, while the ability to achieve these co-benefits may not coincide. The spatial limitations is an example of constraints to achieving desired co-benefits. To ensure an optimal solution, alternative green solutions should be compared (Sarabi et al., 2019). Often it can become a trade-off situation where green-grey integrations or hybrid solutions would be optimal. A holistic approach during the planning process is key to capturing the potential benefits from NBS (Raymond et al., 2017). Creating multifunctional spaces can in addition be an investment strategy for implementing NBS (Toxopeus and Polzin, 2017).

This study assessed the performance of implementing NBS through reduction in volume and frequency of CSOs. There are several indicators that are used to measure the performance of NBS, such as the effective impervious area (EIA). The EIA represents the degree to which impervious areas are hydraulically connected to the drainage system (Ebrahimian et al., 2018). It considers runoff losses along flow paths over impervious surfaces such as surface depressions and pavement cracks (Ebrahimian et al., 2018). Epps and Hathaway (2019) incorporated for example spatially-identified EIA information into a SWMM model to compare siting strategies for NBS retrofits. The performance of bioretention retrofits is dependent on construction and maintenance to uphold their function sufficiently. Low volume surface runoff can sometimes bypass the bioretention cell (Jarden et al., 2016), if not well constructed. In addition, rocks and debris can accumulated by the bioretention cell entrance and act as a barrier for runoff entering the cell during smaller storm events (Jarden et al., 2016).

6 Conclusion

This study investigated retrofitting combined sewer systems with NBS through catchment modelling. Placement criteria for finding suitable locations for online prefabricated bioretention cells was investigated with the city of Bergen, Norway, as case study. The performance was measured through the response of targeted CSOs using long-term climate scenarios.

Finding suitable locations for retrofitting NBS poses a challenge due to spatial limitations in dense urban areas. Placement criteria are highly individual for each catchment with some general recommendations, such as maximum slope and keeping sufficient distance to buildings. The study concludes that retrofitting existing drains alone with online prefabricated bioretention cells for the specific case study, will not achieve sufficient performance. The study revealed that the bioretention cell-to-catchment-area ratio together with the hydraulic load were important parameters for achieving sufficient performance. Increasing the bioretention surface area until it represented one percent of the drainage area combined with increasing the amount of impervious area treated to 80%, resulted in a small performance increase. This substantiates the general guideline for bioretention cells to represent a minimum of 5% of the catchment area (Minnesota Pollution Control Agency, 2008). Investigation of NBS performance prior to implementation is key to finding optimal solutions. A combination of NBS or a trade-off situation with green-grey integration may be the optimal solution, depending on the individual catchment.

Further research for the case study area should include evaluating potential combinations and performance of different NBS, for example combining the bioretention cells with green roofs. The investigated prefabricated bioretention cells could give a higher performance at a different location with less challenging topography and with different rain intensity. If sufficient performance is achieved, a cost-benefit analysis should be conducted including potential co-benefits. Future research should in general be directed towards finding optimal sustainable solutions for dense urban areas which results in increased resilience against climate change.

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Appendices

Appendix 1: Drain coefficient calculations

Appendix 2: Percent volume reduction

Appendix 3: Flow duration curves for finding the CSO thresholds

Appendix 4: Flow duration curves for climate scenarios

Appendix 5: Criteria investigation results

Appendix 6: R-scripts

Appendix 1: Drain coefficient calculations

q – outflow [mm/hr]

C_d – drain coefficient [$mm^{0.5}$/hr]

h – height of saturated media above the drain [mm]

n – drain exponent = 0.5   (typical value, making drain act like an orifice)

Q – flow [l/s]

C_o – orifice coefficient (drain) = 0.62

A_o – orifice area (drain) [m^2]

g – gravitational acceleration = 9.81 m/s2

A_{LID} – surface area of LID [m^2]

K_{sat} – Saturated hydraulic conductivity [cm/hr]

V – velocity [m/s]

Flow rate equation: $q = C_d * h^n$

Standard orifice equation: $Q = C_o A_o \sqrt{2gh}$

$$Q = q * A_{LID} \rightarrow q = \frac{Q}{A_{LID}}$$

$$q = \frac{C_o A_o \sqrt{2gh}}{A_{LID}}$$

$$C_d * h^n = \frac{C_o A_o \sqrt{2gh}}{A_{LID}}$$

With n = 0.5

$$C_d = \frac{C_o A_o \sqrt{2g}}{A_{LID}}$$

C_d assuming drain completely full:

$$C_d = \frac{0.62 * \pi * (0.05m)^2 \sqrt{2 * 9810 \frac{mm}{s^2}}}{2.1904m^2} * 3600 \frac{s}{hr} = 1121.01 \frac{mm^{0,5}}{hr}$$

Finding filling degree:

$$K_{sat} = 10 \frac{cm}{hr} = 0.1 \frac{m}{hr}$$

$$Q = q * A_{LID} = K_{sat} * A_{LID} = 0.1 \frac{m}{hr} * 2.19\, m^2 = 0.219 \frac{m^3}{hr} = 0.06083 \frac{l}{s}$$

Using PipeLife's tool for calculating the flow using Colebrook-White equation (PipeLife)

Input: Inside diameter = 100 mm

Roughness = 0.01 mm (according to the suggested value for plastic pipes)

Slope = 5 ‰

Output: v = 0.704 m/s

Q = 5.53 l/s

Filling fraction:

$$\frac{Q}{Q_{filled}} = 0.011$$

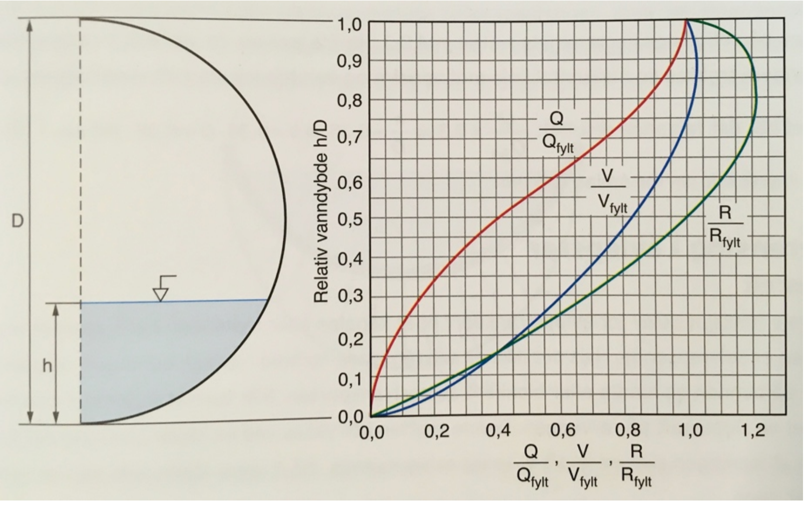


Figure: Partial filling degree diagram (Ødegaard and Norheim, 2014)

Using the figure above, the filling degree was found to be:

$$\frac{h}{D} = 0.08 \ \approx 0{,}1$$

where h is the height of water and D is the inside diameter.

Approximately 10 mm height of water is assumed to be flowing in the drain.

New drain coefficient found:

$$C_d = 1121.01 \frac{mm^{0,5}}{hr} * 0.1 = \ 112 \frac{mm^{0,5}}{hr}$$

Appendix 2: Percent volume reduction

The percent volume reduction achieved for each of the three targeted CSOs, with the different climate and model scenarios are shown in the table below.

Original model setup: A

Adjusted model setup (increased LID surface area and hydraulic load): B

Percent volume reduction achieved						
Climate scenario	CSO1		CSO2		CSO3	
	A	B	A	B	A	B
1	2	50	2	37	5	46
2	2	51	3	36	4	46
3	2	49	3	37	4	46
4	2	49	3	36	4	45
5	2	48	3	36	4	46
6	2	49	3	36	5	46
7	2	49	3	37	5	46
8	2	49	3	36	4	45
9	2	49	3	36	4	46
10	2	51	3	36	5	46

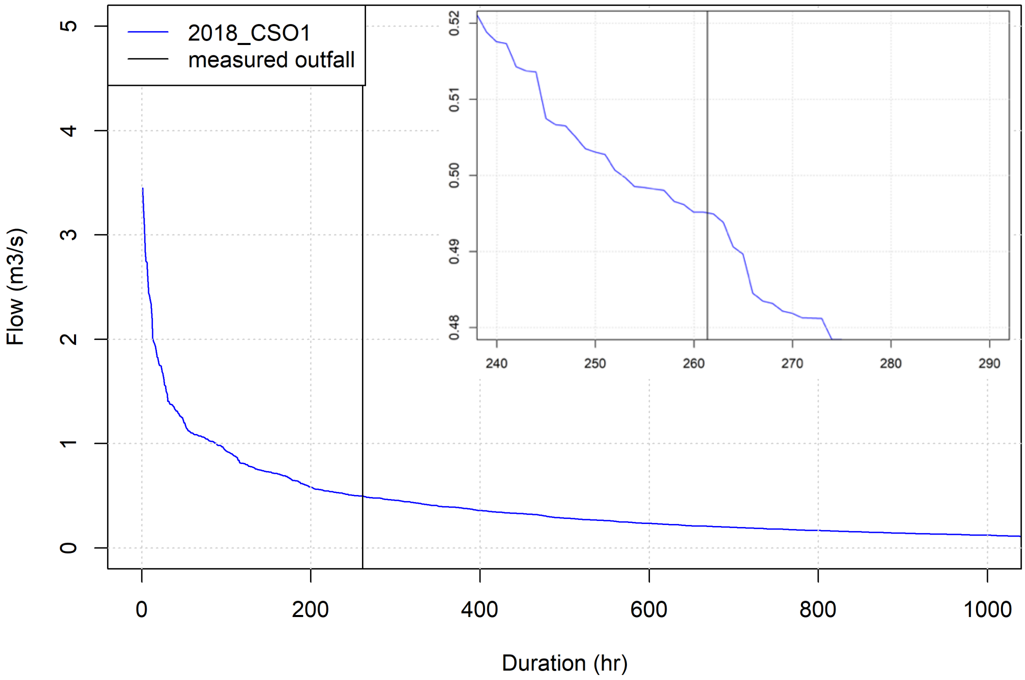
Appendix 3: Flow duration curves for finding CSO threshold

The table below shows the recorded number of hours with discharge for the three CSOs in 2018.

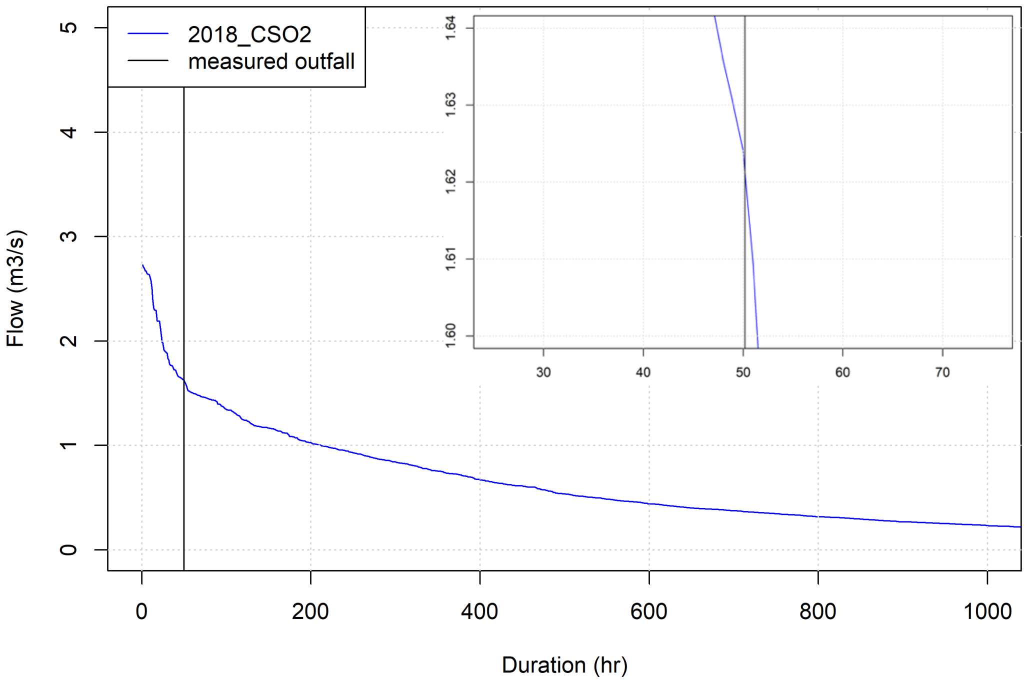
	Overflow for 2018 (hrs)	Threshold flow (m3/s)
CSO1	261.4	0.495
CSO2	50.2	1.622
CSO3	119.7	1.069

The following figures are flow duration curves for 2018 created to find the flow threshold where the CSOs are activated.

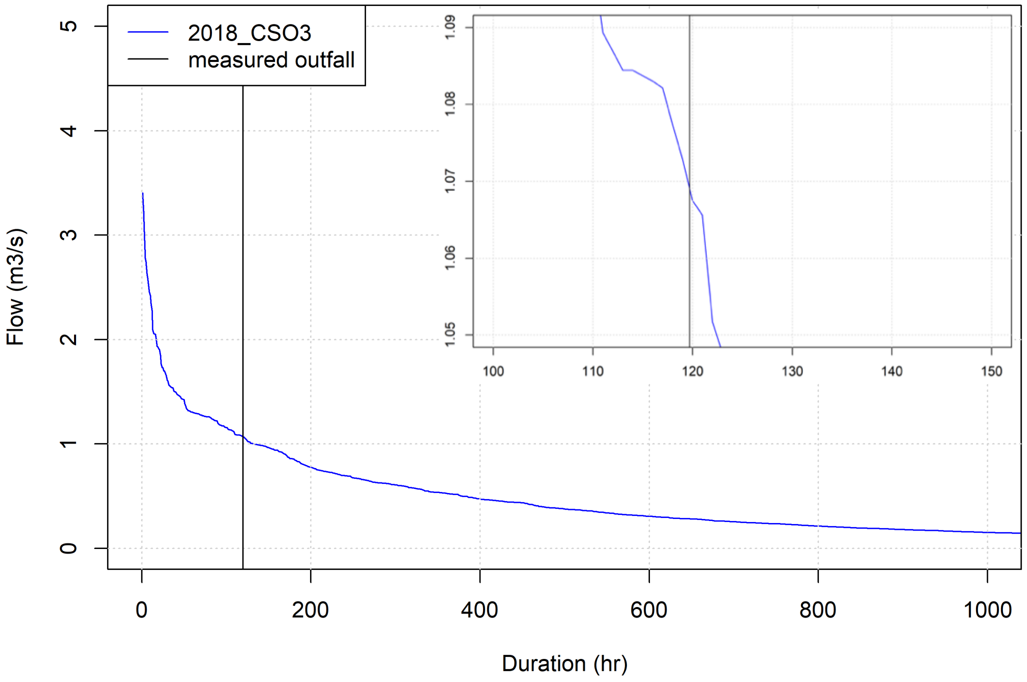
CSO1:



CSO2:


2018_CSO2
measured outfall
Flow (m3/s)
Duration (hr)
0
1
2
3
4
5
0
200
400
600
800
1000
1.60
1.61
1.62
1.63
1.64
30
40
50
60
70

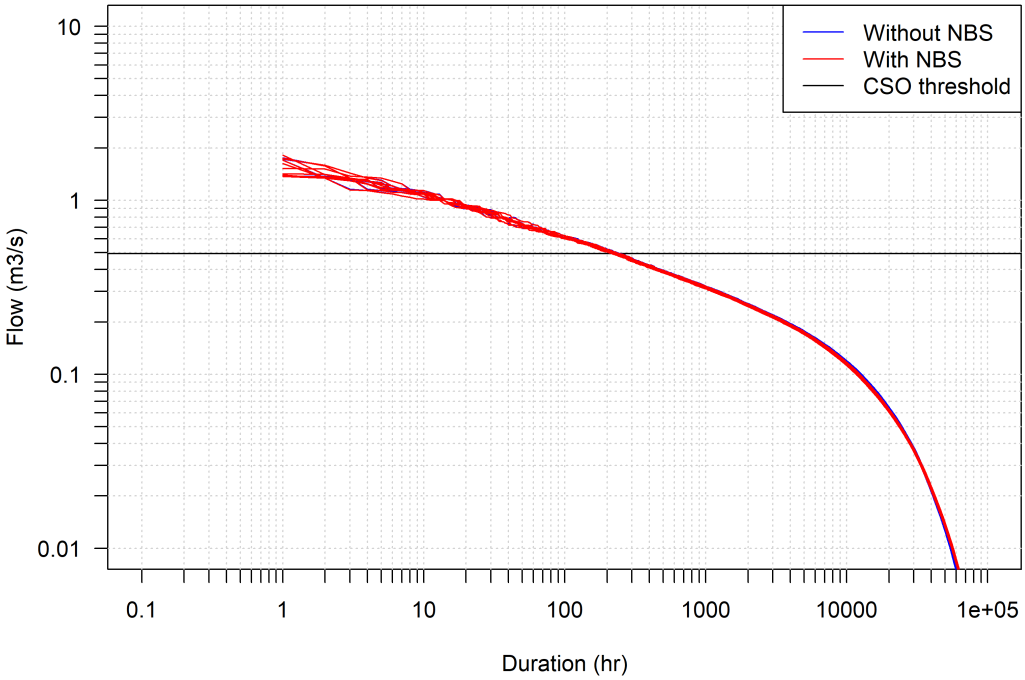
CSO3:


2018_CSO3
measured outfall
Flow (m3/s)
Duration (hr)
0
1
2
3
4
5
0
200
400
600
800
1000
1.05
1.06
1.07
1.08
1.09
100
110
120
130
140
150

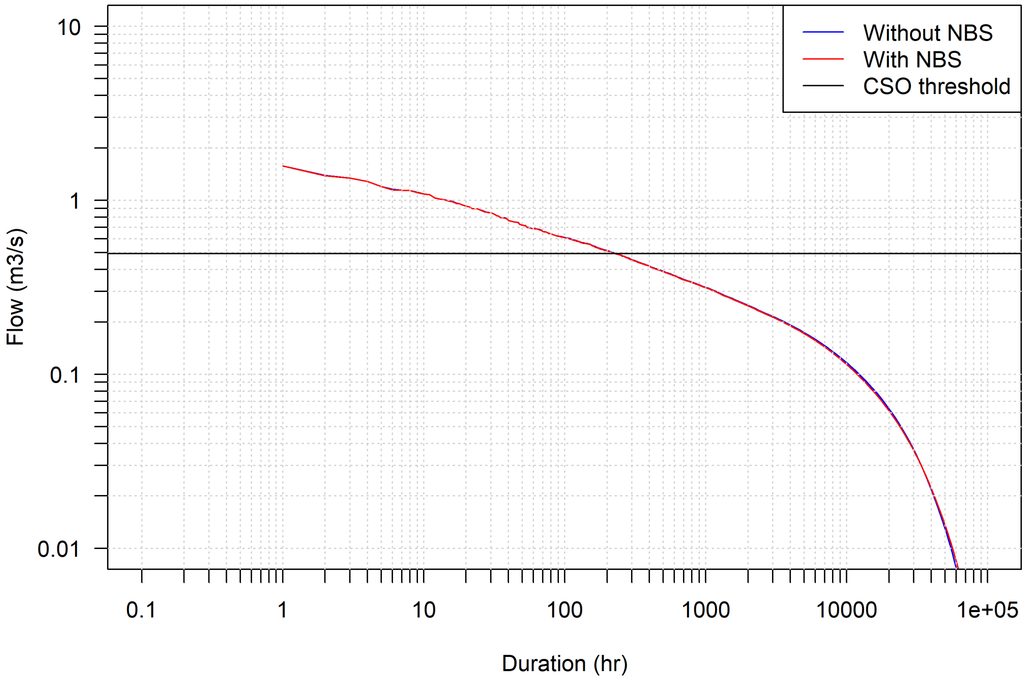
Appendix 4: Flow duration curves for climate scenarios

CSO1 – original model setup (A)

All climate scenarios with and without bioretention cells:

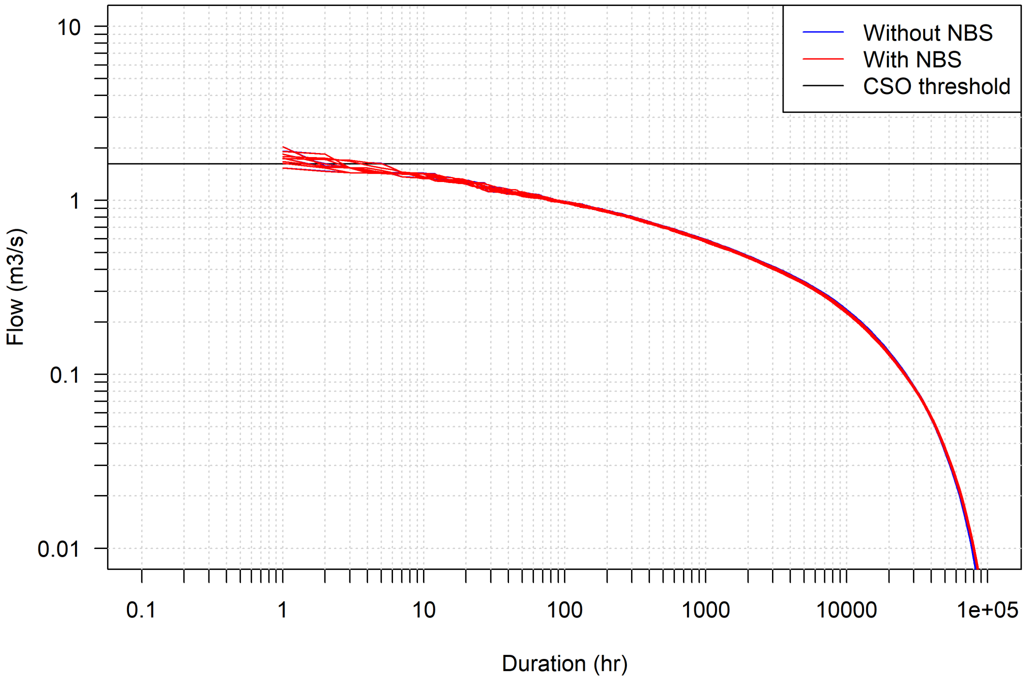


Median value of scenarios with and without bioretention cells:

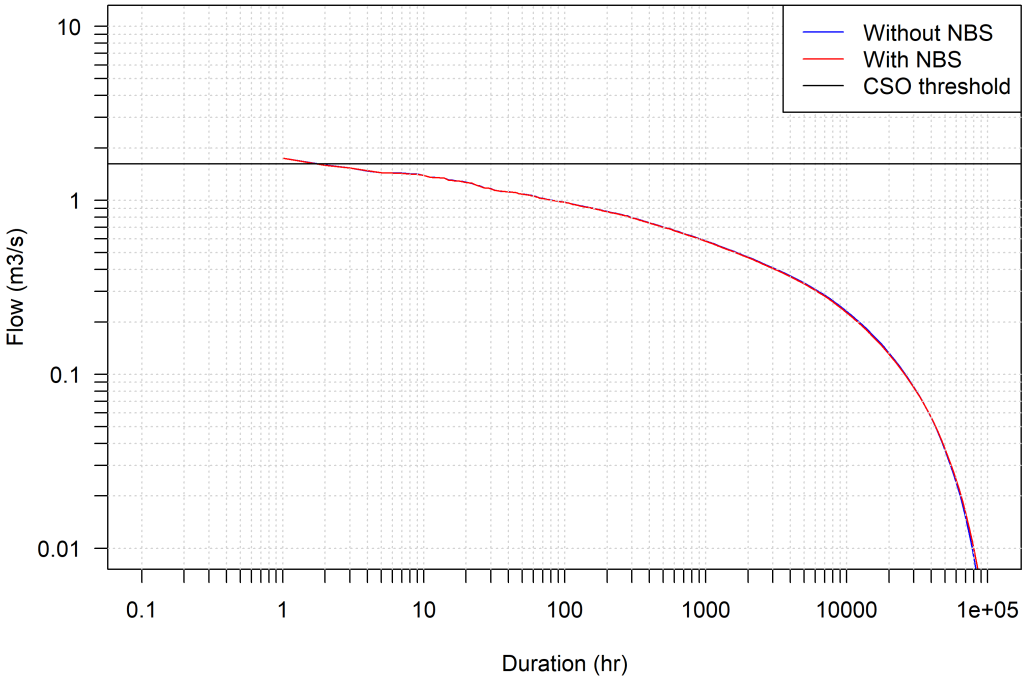


CSO 2 – original model setup (A)

All climate scenarios with and without bioretention cells:

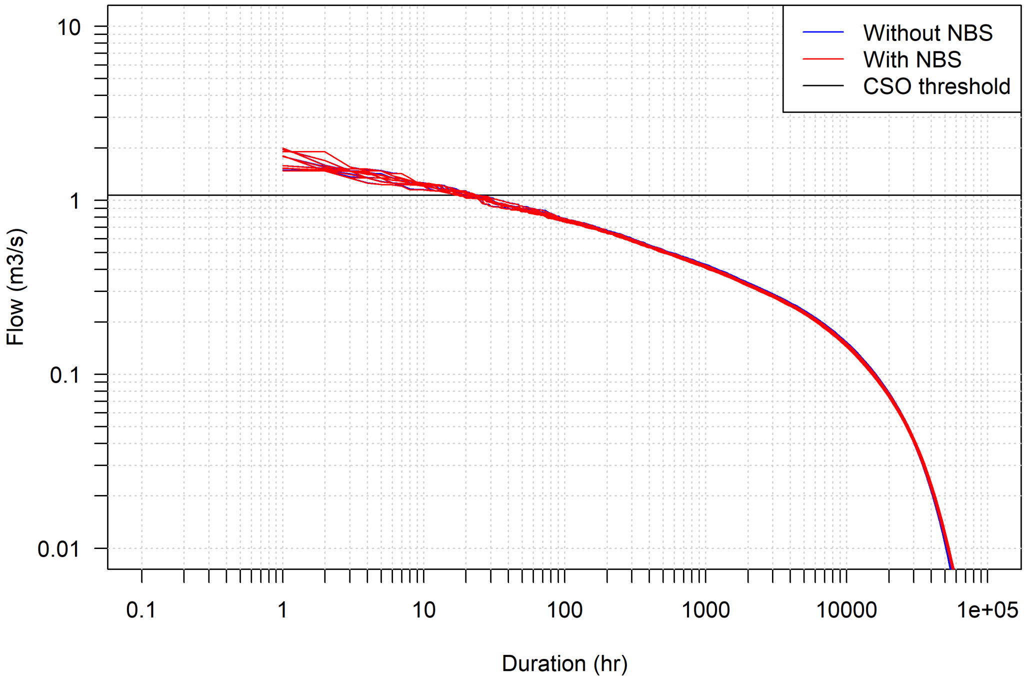


Median value of scenarios with and without bioretention cells:

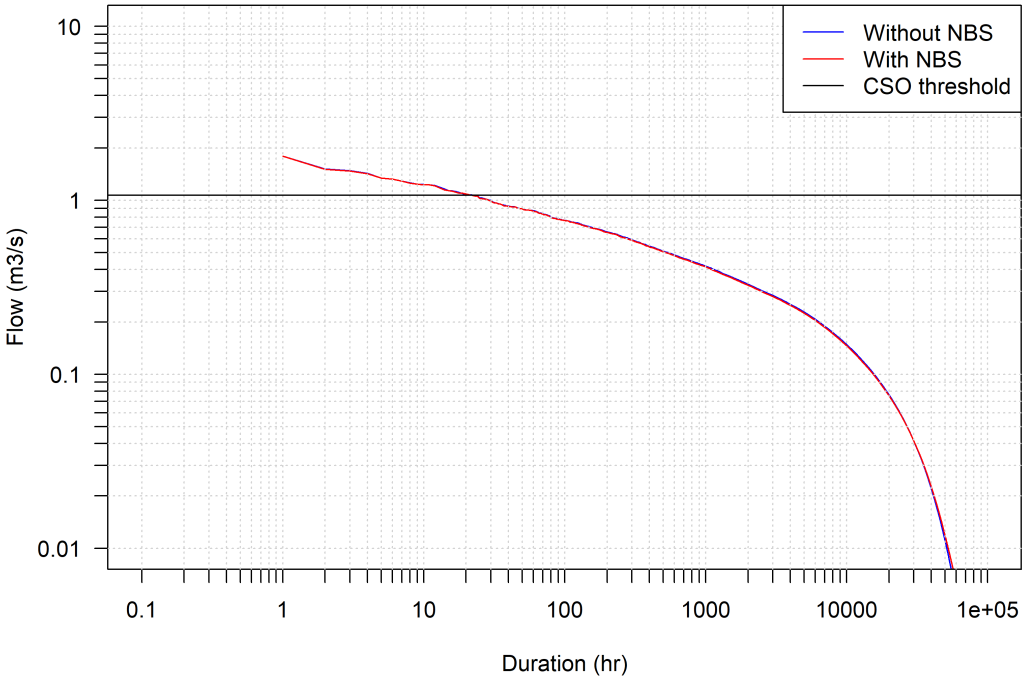


CSO 3 – original model setup (A)

All climate scenarios with and without bioretention cells:

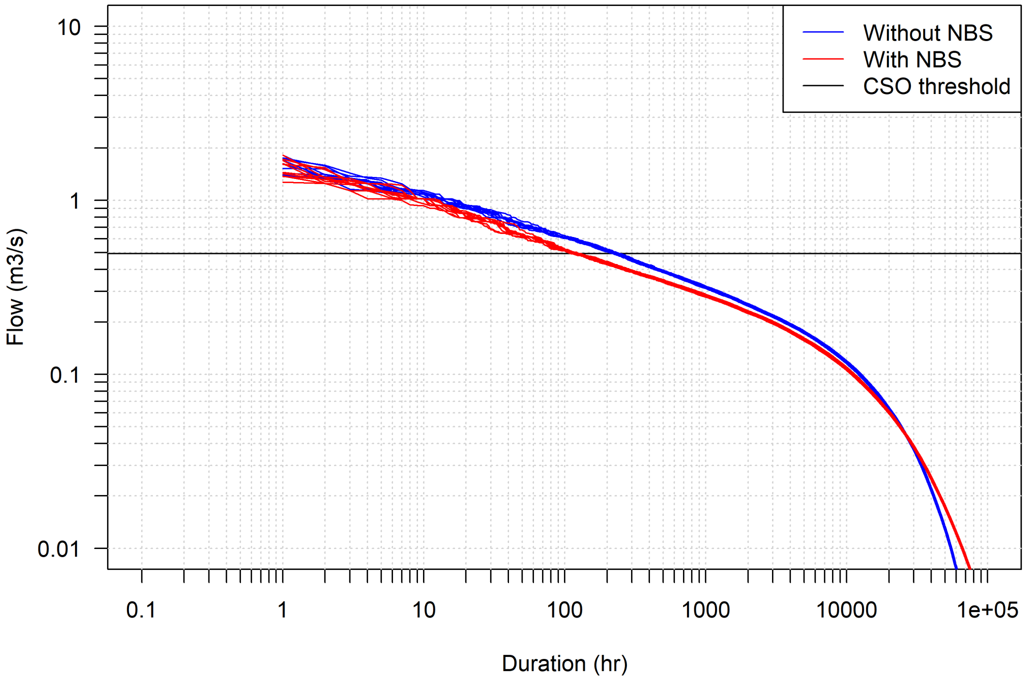


Median value of scenarios with and without bioretention cells:

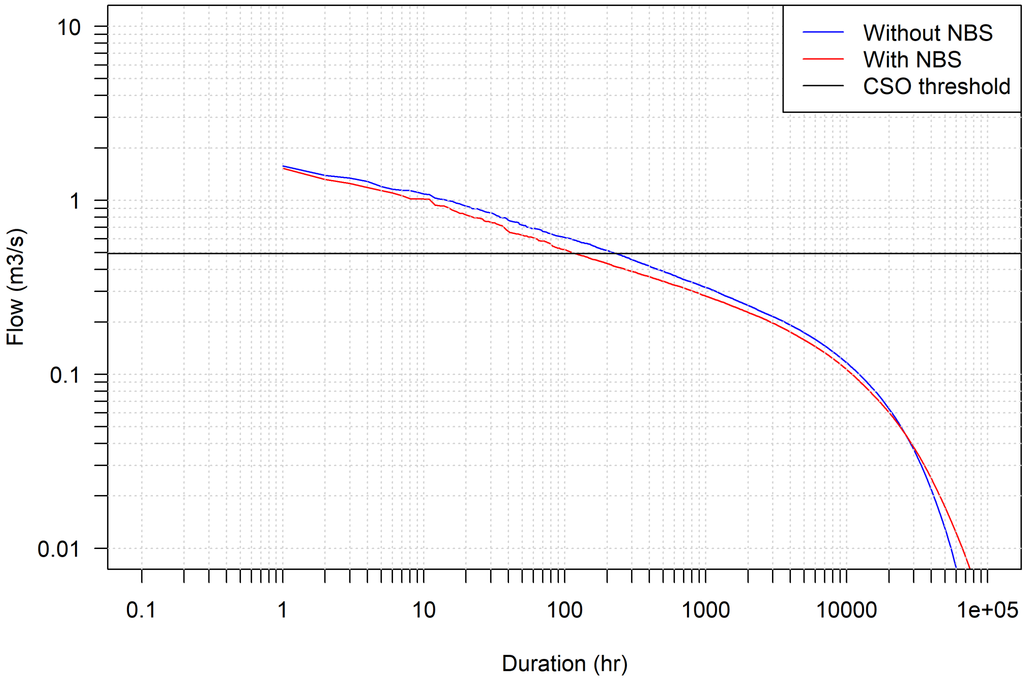


CSO 1 – *adjusted model setup (B)*

All climate scenarios with and without bioretention cells:

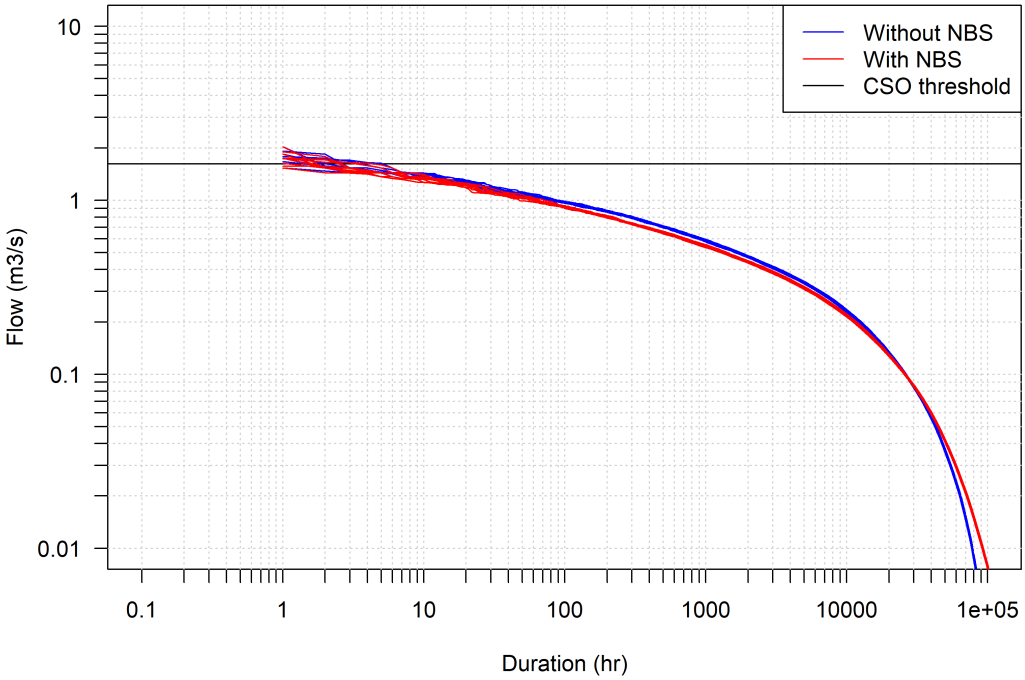


Median value of scenarios with and without bioretention cells:

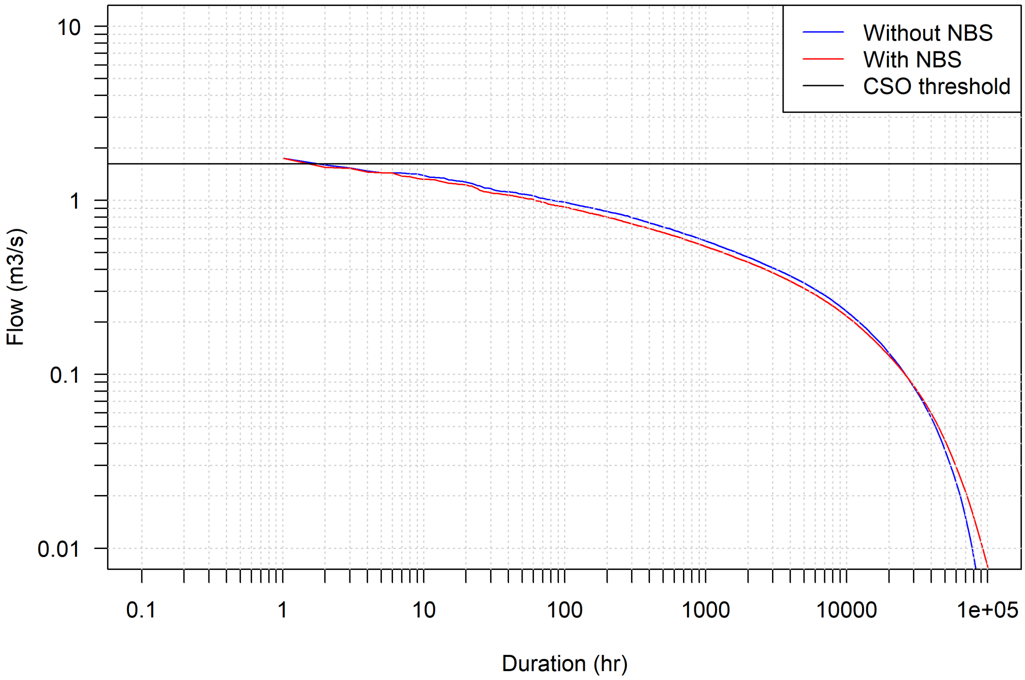


CSO 2 – *adjusted model setup (B)*

All climate scenarios with and without bioretention cells:

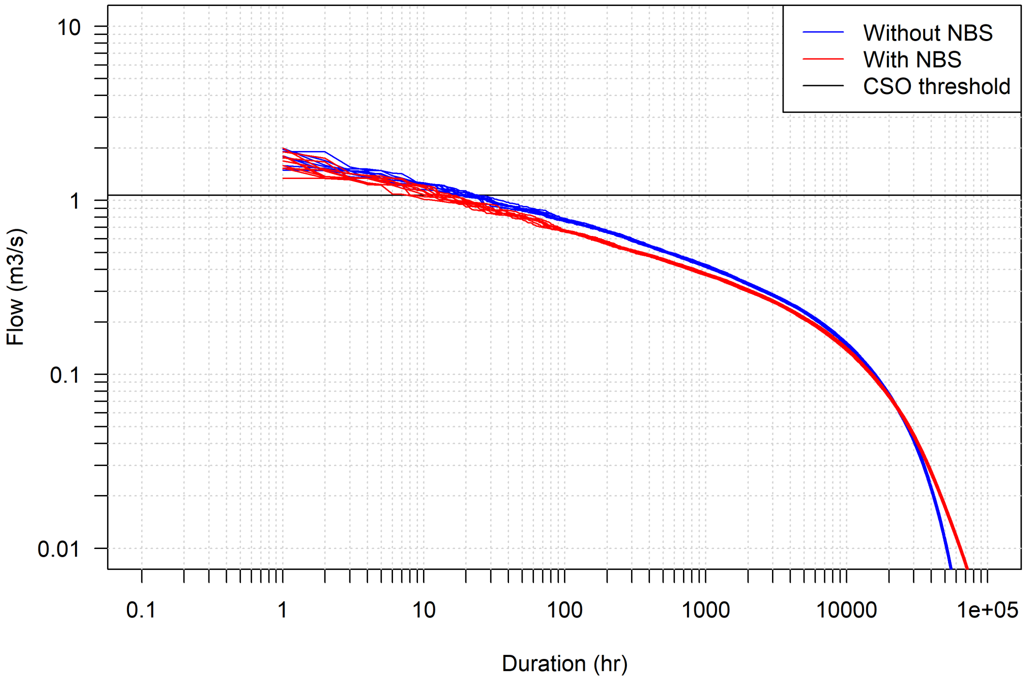


Median value of scenarios with and without bioretention cells:

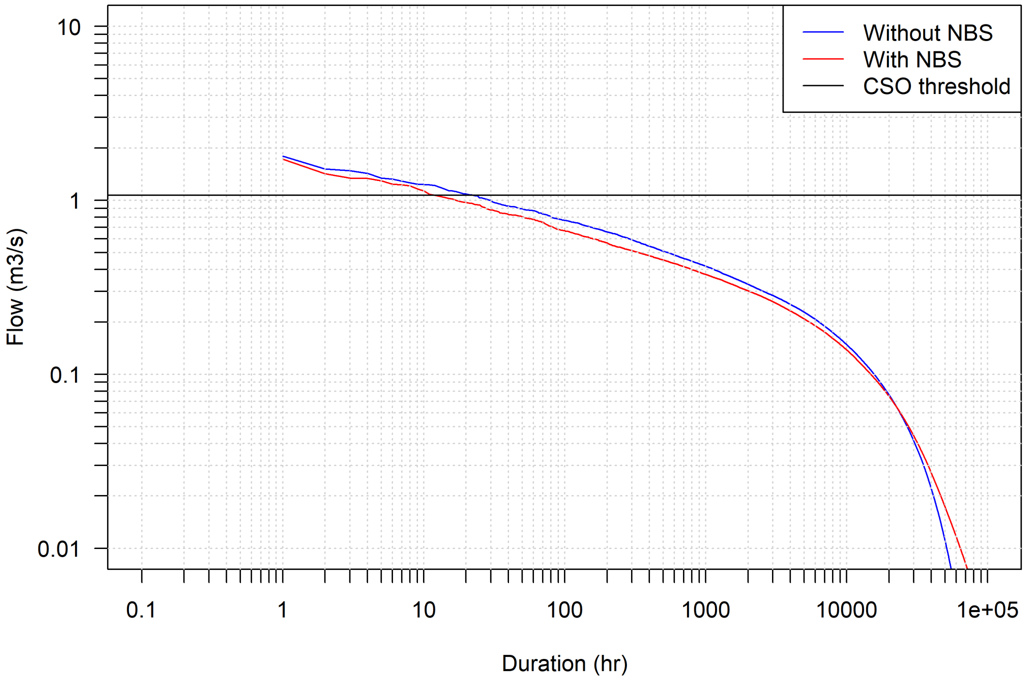


CSO 3 – *adjusted model setup (B)*

All climate scenarios with and without bioretention cells:



Median value of scenarios with and without bioretention cells:



Appendix 5: Criteria investigation results

The following results were developed through investigating minimum criteria for achieving sufficient performance by adjusting different bioretention and sub-catchment parameters. These are event-based results where two to three sub-catchments with implemented bioretention cells were investigated. The simulations with adjusted parameters are compared to the original model setup with and without LID.

The investigated precipitation events are from October 19th 2004, starting at 10:15 AM. Runoff for each of the adjusted scenarios are presented over a smaller section for easier comparison. For the final adjustment, applying precipitation from a different city, the event starts at 9:20 PM October 21st 2015.

Abbreviations used in the following results:

BC1 – Bioretention cell 1 (sub-catchment 1)

BC2 – Bioretention cell 2 (sub-catchment 2)

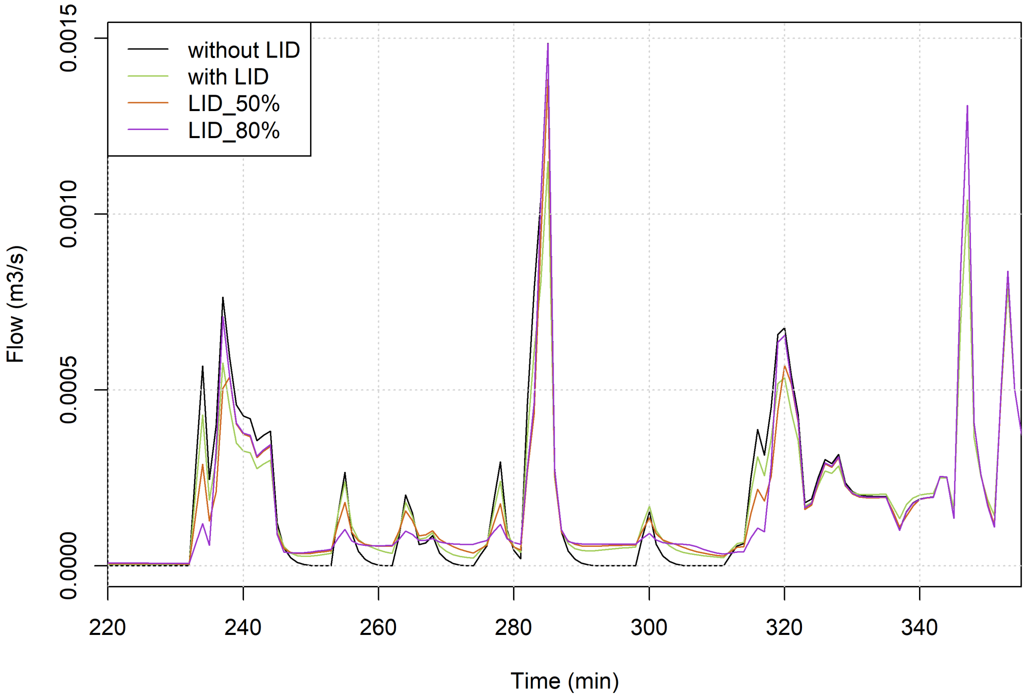
BC3 – Bioretention cell 3 (sub-catchment 3)

Without LID – results from original model setup (A)

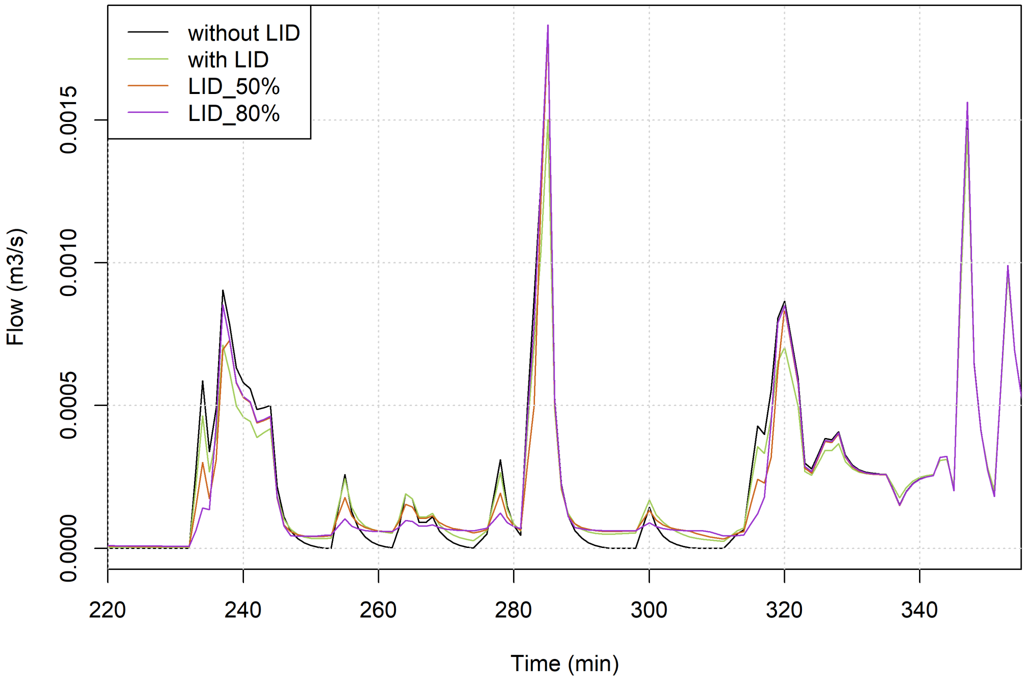
With LID – results from original model setup (A)

Increase the percent impervious area treated by the LID within a sub-catchment.

BC1: originally 25% impervious area treated

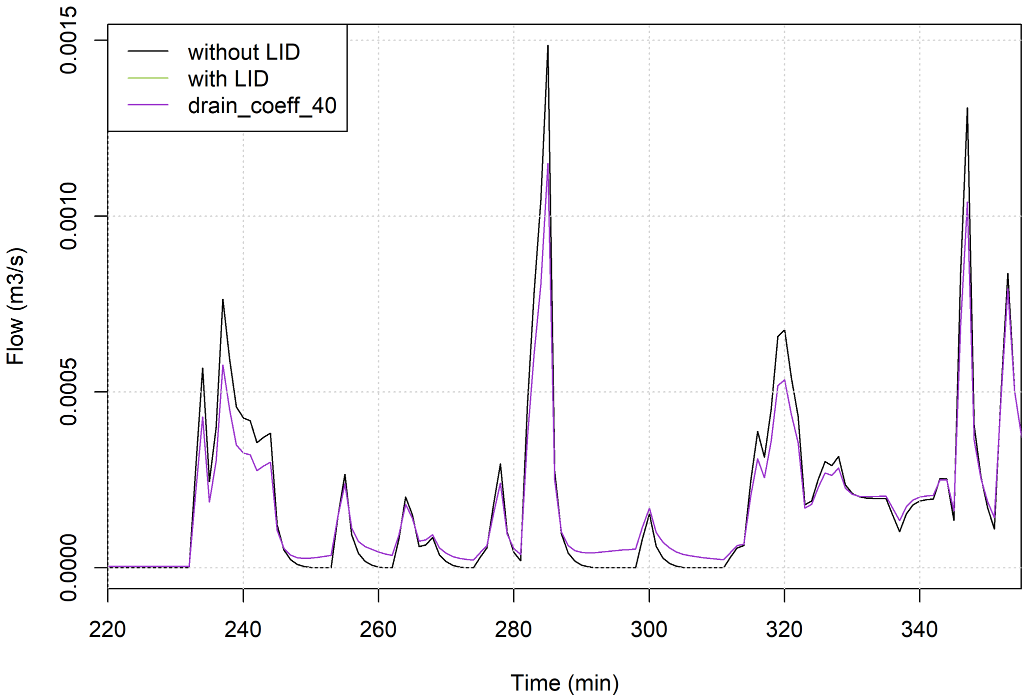


BC2: originally 22% impervious area treated

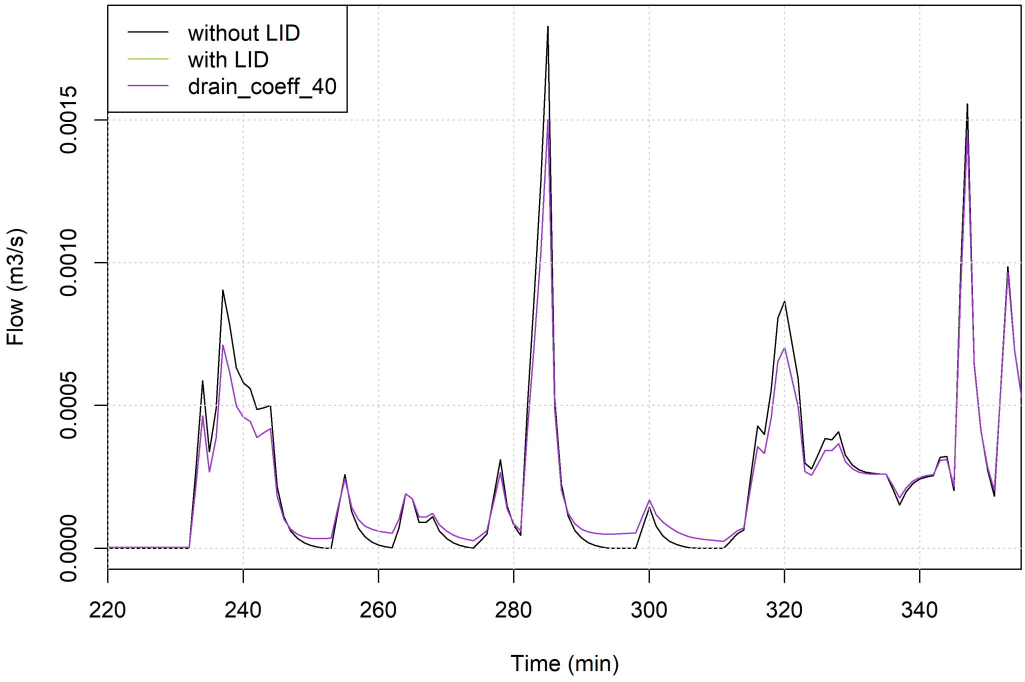


Changing the drain coefficient for the LID underdrain from 112 to 40.

BC1:

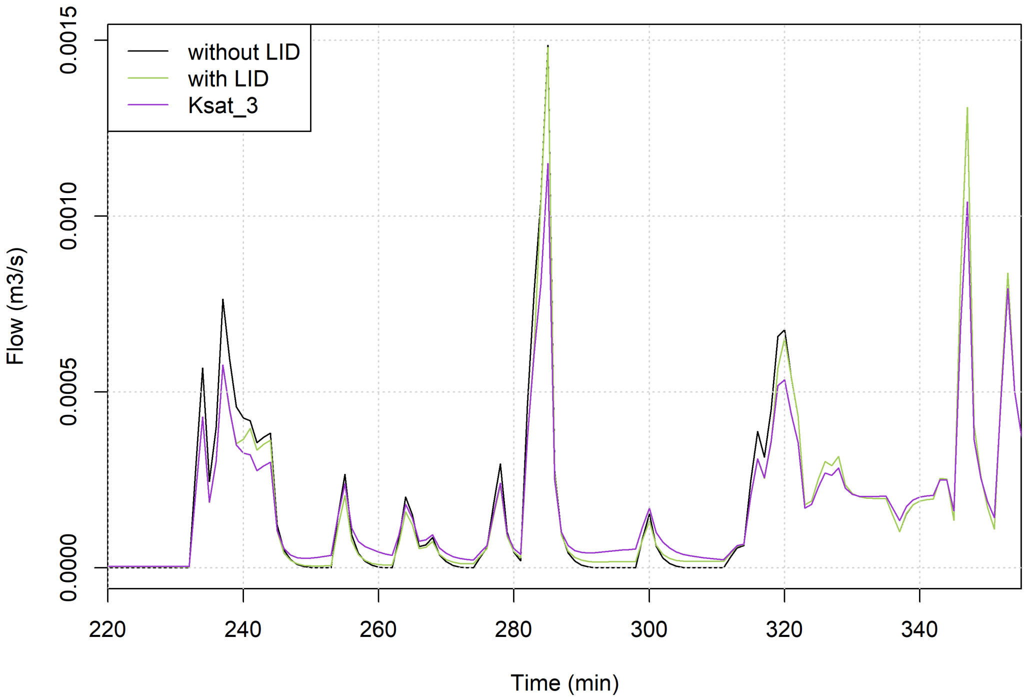


BC2:

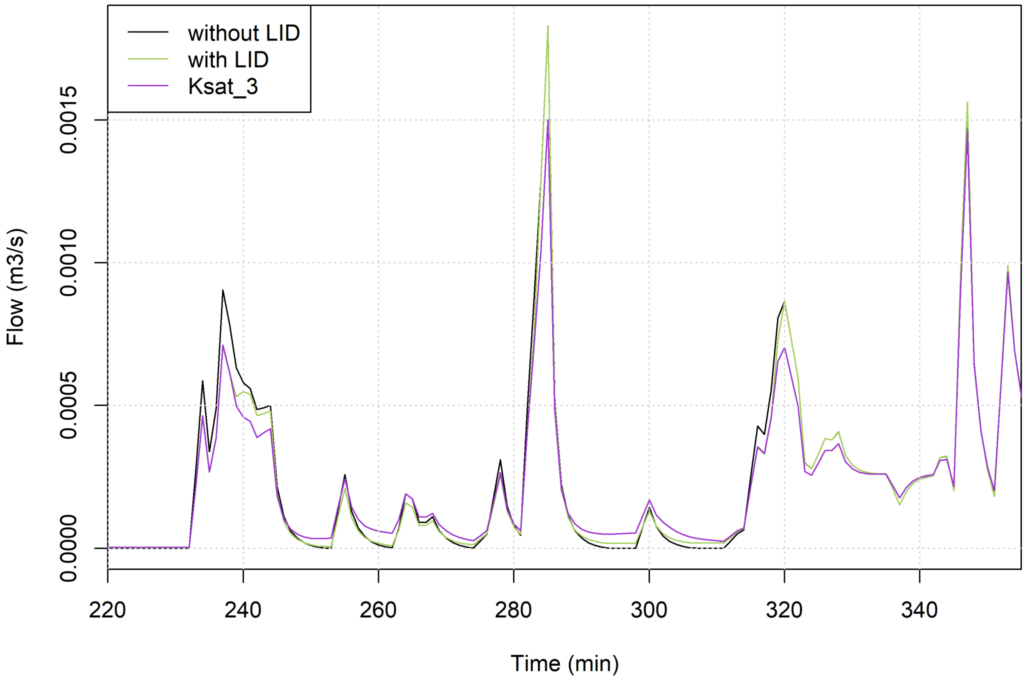


Changing K_{sat} to 3 cm/hr, from originally 10 cm/hr.

BC1:

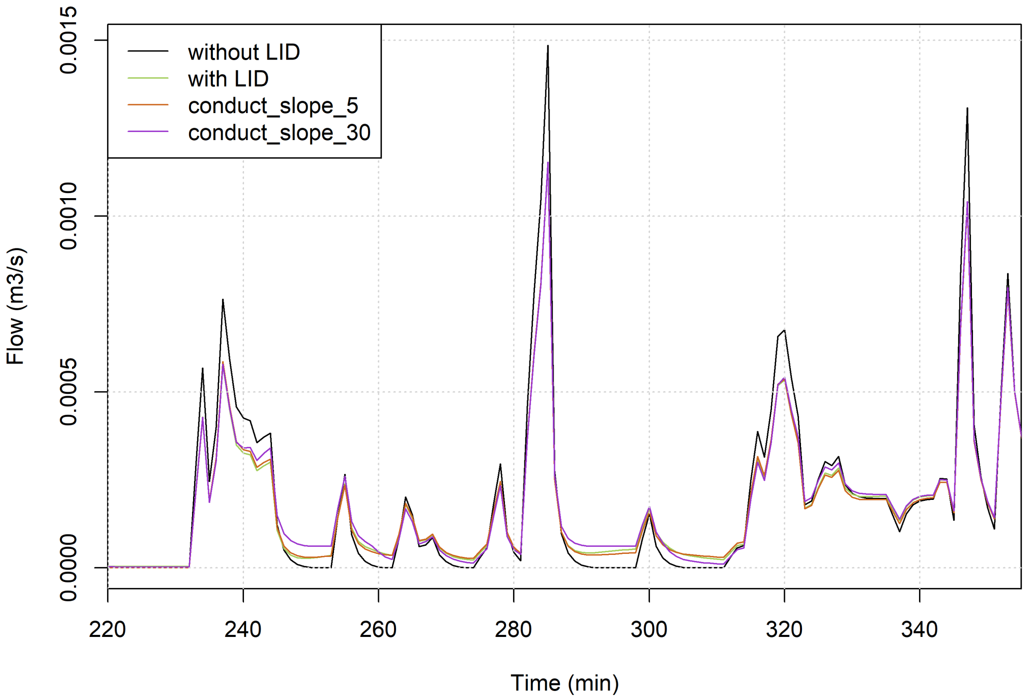


BC2:

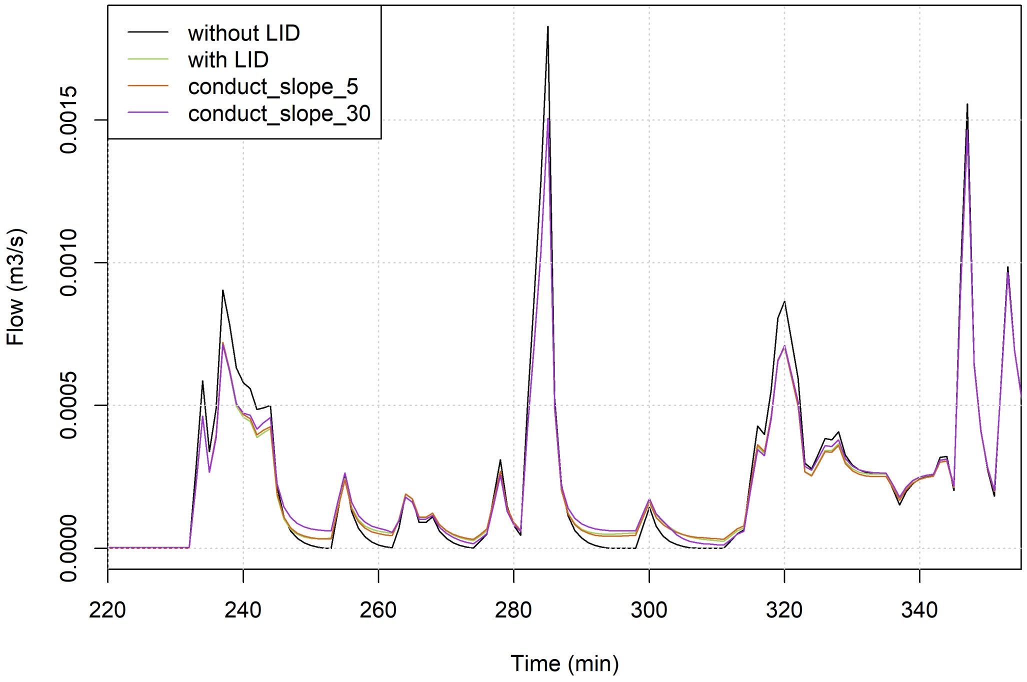


Changing the conductivity slope to 5 and 30, from originally 10.

BC1:

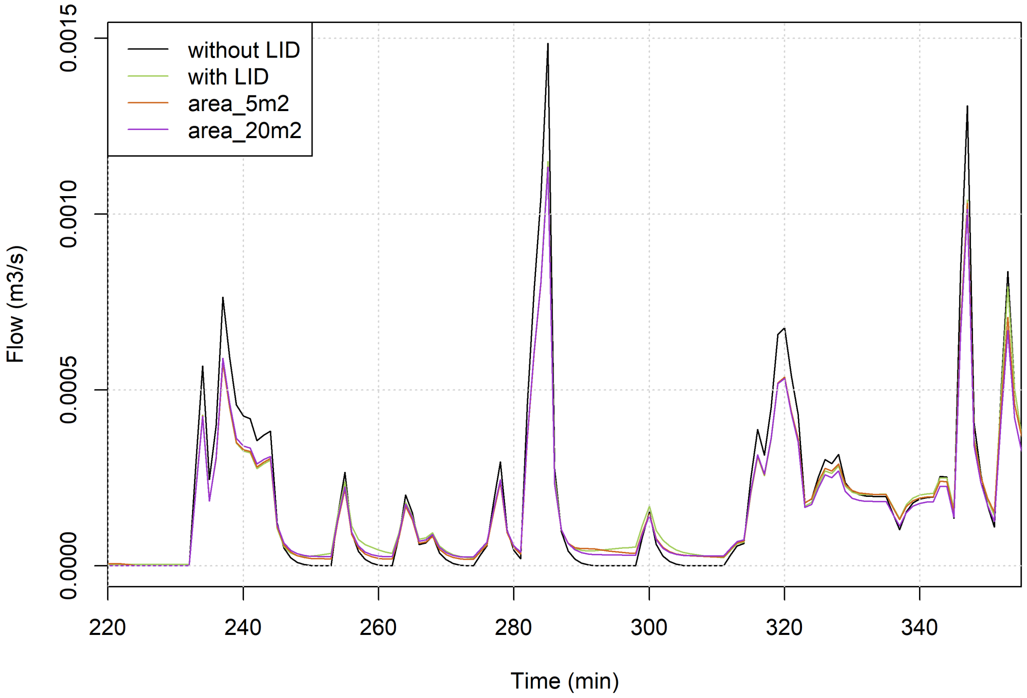


BC2:

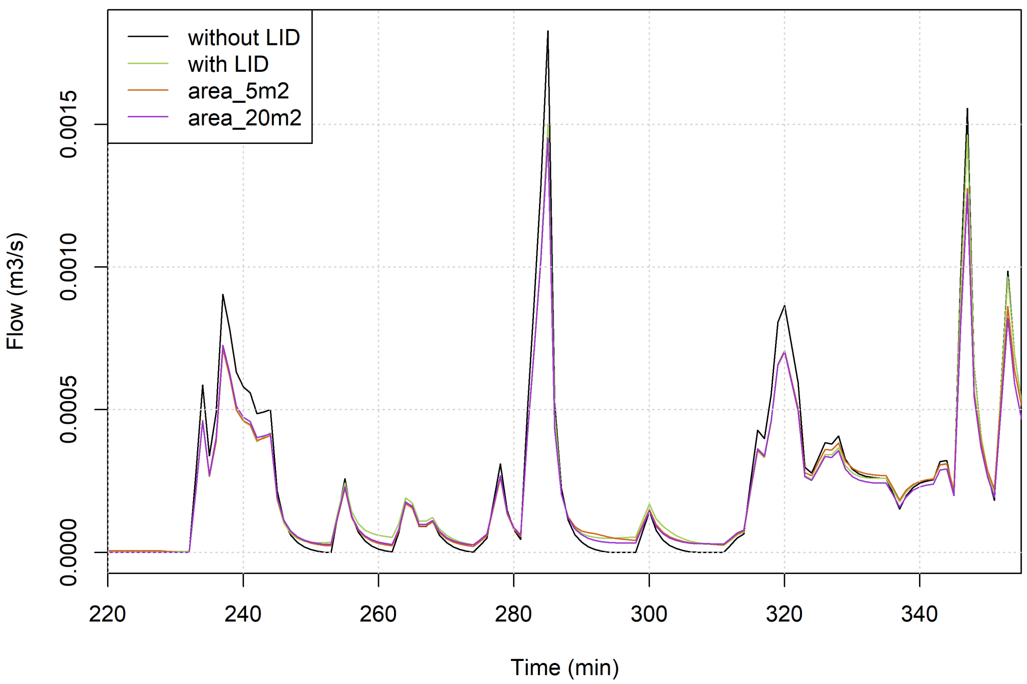


Increasing the surface area to 5m² and 20m², from originally 2.19m².

BC1:

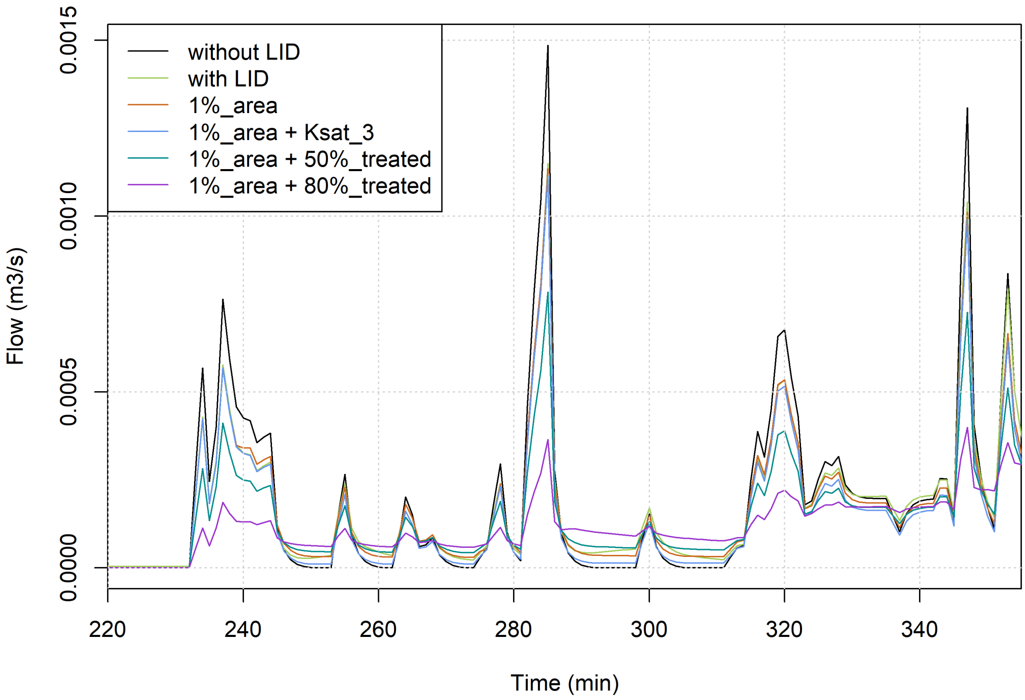


BC2:

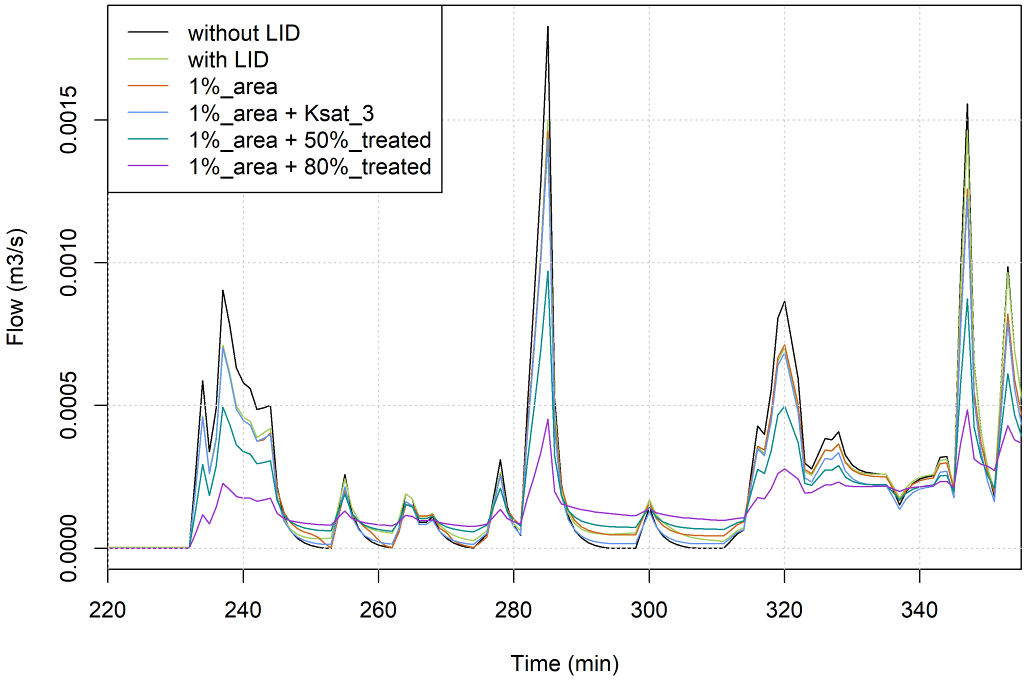


Increasing the LID surface area until it represents 1% of the sub-catchment.

BC1:

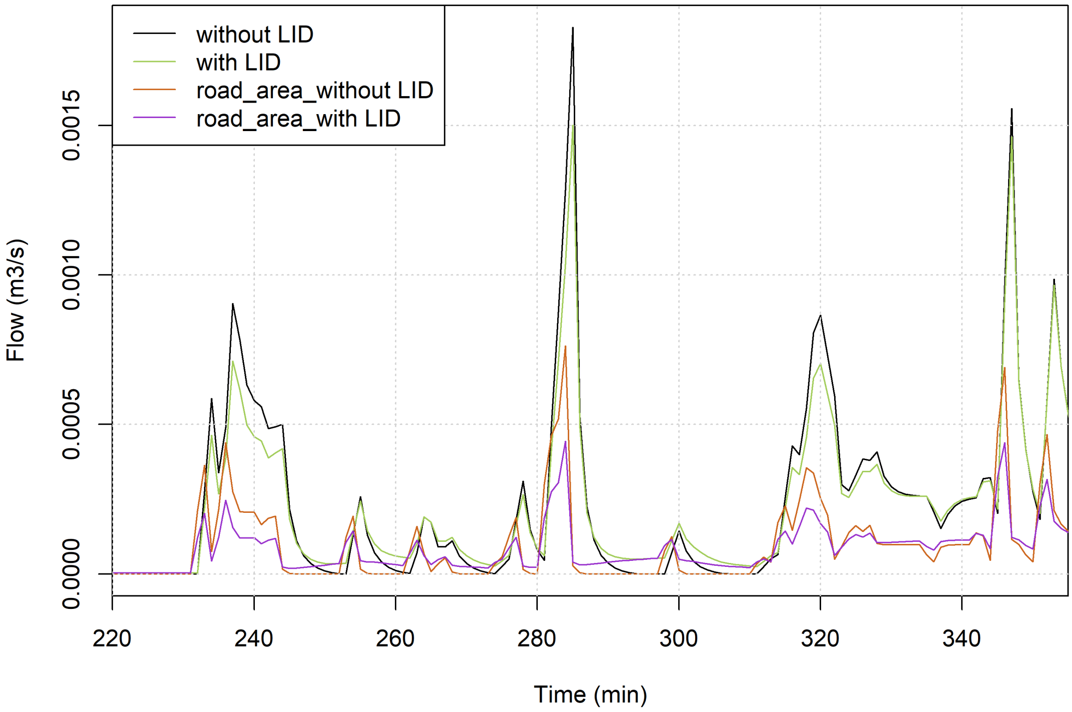


BC2:

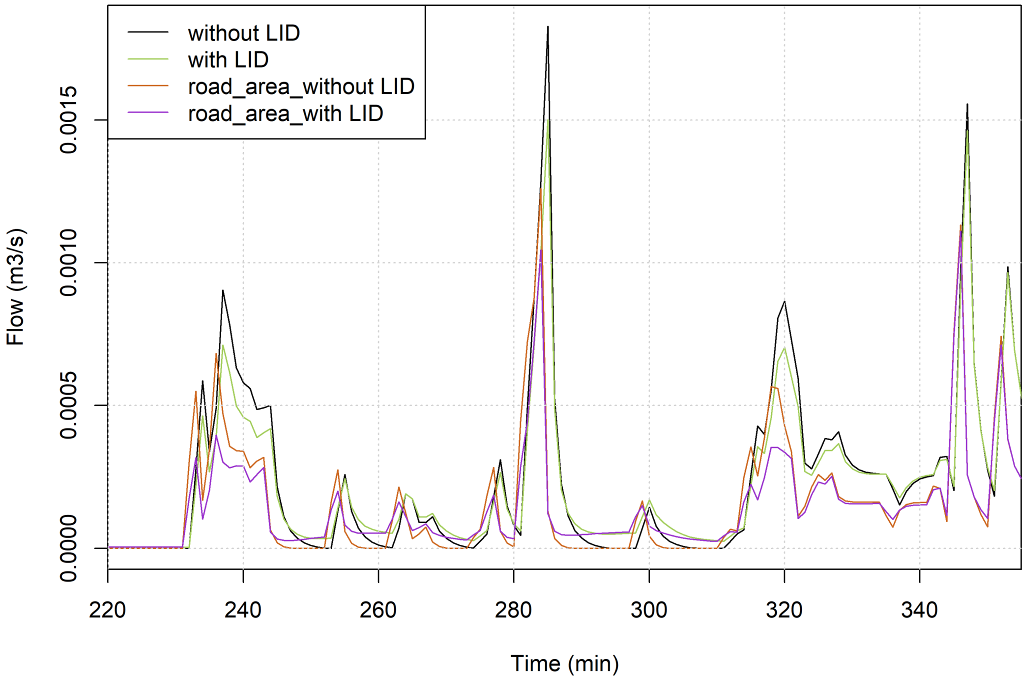


Changing the drainage area to only include area with road surface.

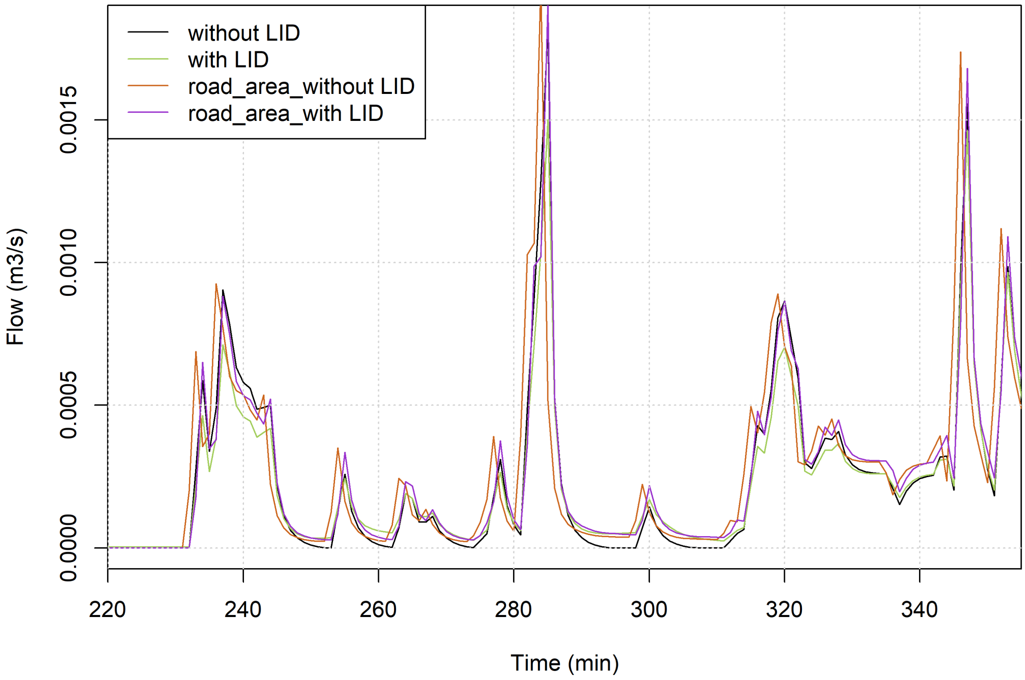
BC1:



BC2:

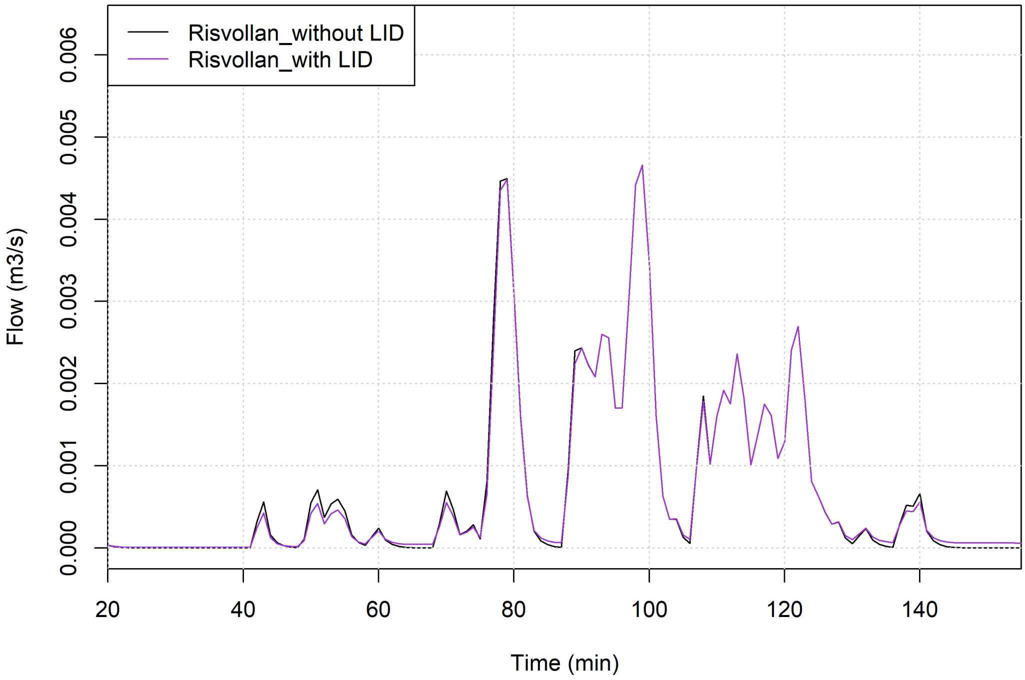


BC3:

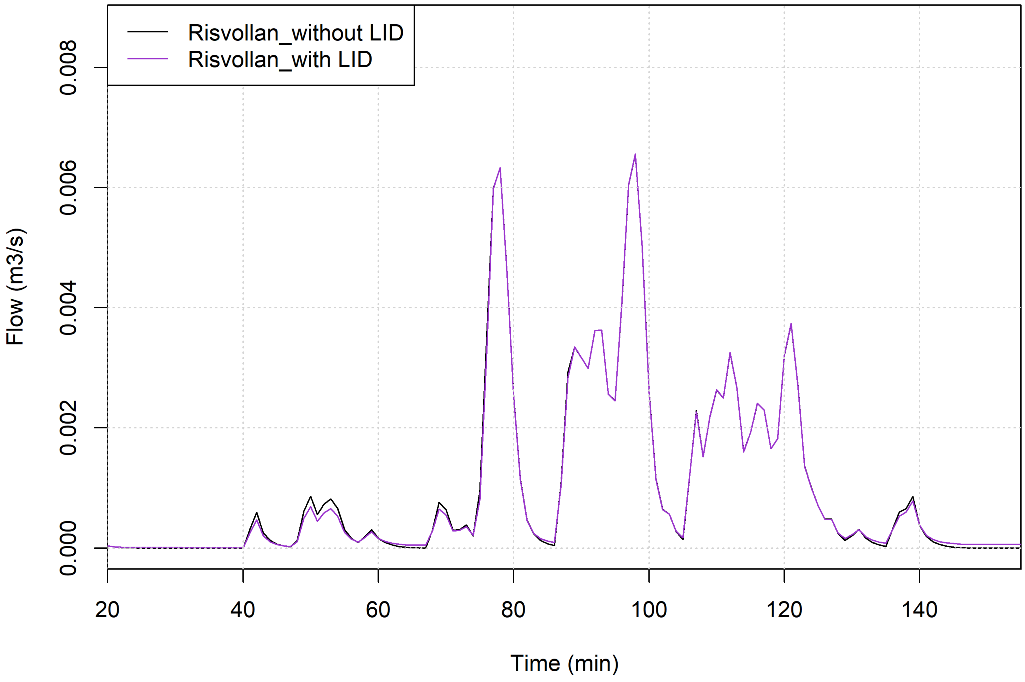

without LID
with LID
road_area_without LID
road_area_with LID
Flow (m3/s)
0.0000
0.0005
0.0010
0.0015
220
240
260
280
300
320
340
Time (min)

Testing with precipitation from Risvollan weather station (Trondheim).

BC1:



BC2:



Appendix 6: R-scripts

```
#Flow duration curves

dir <- "C://Users//martholl//Documents//PCSWMM//Output_//N_452043//"
dir2 <- "C://Users//martholl//Documents//PCSWMM//Output_//N_452043//
temp.txt"
new_q <- matrix(data = NA,ncol = 20,nrow = 184104)
cso1 <- matrix(data = NA,ncol = 20,nrow = 184104)

for (j in 1:20){
  #locate input files
  file_data <- paste0(dir,"result",j,".txt")
  #import our data
  dat1 <- readLines(file_data)
  n <- length(dat1)
  data1 <- dat1[9:n]
  write.table(data1,dir2,sep = "\t",col.names = FALSE,row.names =
FALSE,quote = FALSE)
  new_data <- read.table(dir2,header = FALSE,sep = " ")
  q1 <- new_data$V21 # this is the q
  n <- length(q1)

  #from 5min to hourly
  k <- 1
  for(i in seq(12,n,12)){
    new_q[k,j] <- sum(q1[(i-11):i])
    k <- k + 1
  }

  rank1 <- rank(-new_q[,j],ties.method = "first")
  pro1 <- 100*(rank1/(max(rank1)+1))
  cso1[,j] <- (pro1*max(rank1))/100

  print(j)
}
j <- 1

#########################################################
# plot all scenarios
tiff.file <- paste0(dir,"allscenarios.tiff")
tiff(tiff.file,width = 8,height = 6,units = "in",res = 400)
data_plot <- cbind(cso1[,1],new_q[,1])
data_plot <- data_plot[order(data_plot[,1]),]

plot(data_plot[,1],data_plot[,2],type="l", xlim=c(0.1, 10^5),
ylim=c(0.01, 10^1),
     xlab = "Duration (hr)",ylab = "Flow (m3/s)",col="blue",
log="xy", xaxt="n",yaxt="n")
at.x <- outer(1:9, 10^(-1:5))
at.y <- outer(1:9, 10^(-2:1))
lab.x <- ifelse(log10(at.x) %% 1 == 0, at.x, NA)
lab.y <- ifelse(log10(at.y) %% 1 == 0, at.y, NA)
axis(1, at=at.x, labels=lab.x, las=1)
axis(2, at=at.y, labels=lab.y, las=1)
abline(h=at.y,lty="dotted",col="lightgray")
```

```
abline(v=at.x,lty="dotted",col="lightgray")
#abline(h=0.015,lty="dotted",col="black") #threshold

for(j in 2:10) {
  data_plot <- cbind(cso1[,j],new_q[,j])
  data_plot <- data_plot[order(data_plot[,1]),]
  lines(data_plot[,1],data_plot[,2],log="xy",type = "l",ylim =
c(0.01,0.5),
       xlab = "Duration (hr)",ylab = "Flow (m3/s)", col="blue")
}

data_plot <- cbind(cso1[,11],new_q[,11])
data_plot <- data_plot[order(data_plot[,1]),]
lines(data_plot[,1],data_plot[,2],log="xy",type = "l",ylim = c(0.01,
10^1),
     xlab = "Duration (hr)",ylab = "Flow (m3/s)",col="red")
for(j in 12:20) {
  data_plot <- cbind(cso1[,j],new_q[,j])
  data_plot <- data_plot[order(data_plot[,1]),]
  lines(data_plot[,1],data_plot[,2],log="xy",type = "l",ylim =
c(0.01, 10^1),
        xlab = "Duration (hr)",ylab = "Flow (m3/s)",col="red")
}

legend("topright",legend = c("Without NBS", "With NBS"),
      lty = 1,col=c("blue","red"),cex = 1)
dev.off()

#########################################################
# plot medians

library(matrixStats)

tiff.file <- paste0(dir,"medians.tiff")
tiff(tiff.file,width = 8,height = 6,units = "in",res = 400)
new_q_without <- matrix(data = NA,ncol = 10,nrow = 184104)
new_q_with <- matrix(data = NA,ncol = 10,nrow = 184104)
cso1_without<- matrix(data = NA,ncol = 10,nrow = 184104)
cso1_with<- matrix(data = NA,ncol = 10,nrow = 184104)
# without
for (i in 1:10) {
  data_plot <- cbind(cso1[,i],new_q[,i])
  data_plot <- data_plot[order(data_plot[,1]),]
  new_q_without [,i]<-data_plot[,2]
  cso1_without [,i]<-data_plot[,1]
}
# with
k <- 1
for (i in 11:20) {
  data_plot <- cbind(cso1[,i],new_q[,i])
  data_plot <- data_plot[order(data_plot[,1]),]
  new_q_with [,k]<-data_plot[,2]
  cso1_with [,k]<-data_plot[,1]
  k <- k +1
```

```
}
# median
median_q_without <- rowMedians(new_q_without)
median_q_with <- rowMedians(new_q_with)
median_cso1_without <- rowMedians(cso1_without)
median_cso1_with <- rowMedians(cso1_with)

# max
max_q_without <- rowMaxs(new_q_without)
max_q_with <- rowMaxs(new_q_with)
max_cso1_without <- rowMaxs(cso1_without)
max_cso1_with <- rowMaxs(cso1_with)

# min
min_q_without <- rowMins(new_q_without)
min_q_with <- rowMins(new_q_with)
min_cso1_without <- rowMins(cso1_without)
min_cso1_with <- rowMins(cso1_with)


plot(median_cso1_without,median_q_without,type="l", xlim=c(0.1,
10^5), ylim=c(0.01, 10^1),
     xlab = "Duration (hr)",ylab = "Flow (m3/s)",col="blue",
log="xy", xaxt="n", yaxt="n",lwd=1)

#lines(max_cso1_without,max_q_without,log="xy",type =
"l",ylim=c(0.01, 10^1),
#      xlab = "Duration (hr)",ylab = "Flow (m3/
s)",col="blue",xaxt="n",yaxt="n",lty=2)

#lines(min_cso1_without,min_q_without,log="xy",type =
"l",ylim=c(0.01, 10^1),
#      xlab = "Duration (hr)",ylab = "Flow (m3/
s)",col="blue",xaxt="n",yaxt="n",lty=2)

lines(median_cso1_with,median_q_with,type="l", xlim=c(0.1, 10^5),
ylim=c(0.01, 10^1),
      xlab = "Duration (hr)",ylab = "Flow (m3/s)",col="red",
log="xy", xaxt="n", yaxt="n",lwd=1)

#lines(max_cso1_with,max_q_with,log="xy",type = "l",ylim=c(0.01,
10^1),
#      xlab = "Duration (hr)",ylab = "Flow (m3/
s)",col="red",xaxt="n",yaxt="n",lty=2)

#lines(min_cso1_with,min_q_with,log="xy",type = "l",ylim=c(0.01,
10^1),
#      xlab = "Duration (hr)",ylab = "Flow (m3/
s)",col="red",xaxt="n",yaxt="n",lty=2)


at.x <- outer(1:9, 10^(-1:5))
at.y <- outer(1:9, 10^(-2:1))
lab.x <- ifelse(log10(at.x) %% 1 == 0, at.x, NA)
```

```
lab.y <- ifelse(log10(at.y) %% 1 == 0, at.y, NA)
axis(1, at=at.x, labels=lab.x, las=1)
axis(2, at=at.y, labels=lab.y, las=1)
abline(h=at.y,lty="dotted",col="lightgray")
abline(v=at.x,lty="dotted",col="lightgray")
#abline(h=0.015,lty="dotted",col="black") #threshold
legend("topright",legend = c("Without NBS","With NBS"),lty = 1,
       col=c("blue","red"),cex = 1)
dev.off()
#########################################################
```

```
#Flow duration curves for 2018 rainfall

dir <- "C://Users//martholl//Documents//PCSWMM//Output_//2018//"
dir2 <- "C://Users//martholl//Documents//PCSWMM//Output_//2018//
temp.txt"
new_q <- matrix(data = NA,ncol = 1,nrow = 8760)
cso1 <- matrix(data = NA,ncol = 1,nrow = 8760)

#locate input files
file_data <- paste0(dir,"N_502700",".dat")
#import our data
dat1 <- readLines(file_data)
n <- length(dat1)
data1 <- dat1[3:n]
write.table(data1,dir2,sep = "\t",col.names = FALSE,row.names =
FALSE,quote = FALSE)
new_data <- read.table(dir2,header = FALSE,sep = " ")
q1 <- new_data$V6 # this is the q
n <- length(q1)

#from 5min to hourly
k <- 1
for(i in seq(12,n,12)){
  new_q[k,1] <- sum(q1[(i-11):i])
  k <- k + 1
}

rank1 <- rank(-new_q[,1],ties.method = "first")
pro1 <- 100*(rank1/(max(rank1)+1))
cso1[,1] <- (pro1*max(rank1))/100

#########################################################
#plot all results
tiff.file <- paste0(dir,"N_502700_3.tiff")
tiff(tiff.file,width = 8,height = 6,units = "in",res = 400)
data_plot <- cbind(cso1[,1],new_q[,1])
data_plot <- data_plot[order(data_plot[,1]),]

plot(data_plot[,1],data_plot[,2],type="l", xlim=c(100,150),
ylim=c(1.05,1.09),
     xlab = "Duration (hr)",ylab = "Flow (m3/s)",col="blue")
grid(col="lightgrey")
abline(v=119.7,lty=1,col="black") #threshold
legend("topright",legend = c("2018_CSO3","measured outfall"),
       lty = 1,col=c("blue","black"),cex = 1)
dev.off()
#########################################################
```

```r
#Testing adjusted model setups
#

dir <- "C://Users//martholl//Documents//PCSWMM//Output_//testing//
new_catchment//BC3//"
dir2 <- "C://Users//martholl//Documents//PCSWMM//Output_//testing//
new_catchment//BC3//temp.txt"
new_q <- matrix(data = NA,ncol = 4,nrow = 713)
cso1 <- matrix(data = NA,ncol = 1,nrow = 713)
for (j in 1:4){
  #locate input files
  file_data <- paste0(dir,"result",j,".dat")
  #import our data
  dat1 <- readLines(file_data)
  n <- length(dat1)
  data1 <- dat1[3:n]
  write.table(data1,dir2,sep = "\t",col.names = FALSE,row.names =
FALSE,quote = FALSE)
  new_data <- read.table(dir2,header = FALSE,sep = " ")
  q1 <- new_data$V6 # this is the q
  n <- length(q1)
  new_q[,j] <- q1

  print(j)
}
for (i in 1:713){
  cso1[i,1] <- i*5
}
#########################################################
#plot all results
tiff.file <- paste0(dir,"new_catchment_BC3.tiff")
tiff(tiff.file,width = 8,height = 6,units = "in",res = 400)

data_plot <- cbind(cso1[,1],new_q[,1])
#xlim=c(225,350),
plot(new_q[,1],type="l",
     xlab = "Time (min)",ylab = "Flow (m3/s)",col="black")

lines(new_q[,2],type = "l", col="darkolivegreen3")
lines(new_q[,3],type = "l", col="chocolate3")
lines(new_q[,4],type = "l", col="darkorchid3")


grid(col="lightgrey")

legend("topleft",legend = c("without LID (A)","with LID
(A)","road_area_without LID (B)","road_area_with LID (B)"),
       lty =
1,col=c("black","darkolivegreen3","chocolate3","darkorchid3"),cex =
1)
dev.off()
#########################################################
```