Master's thesis

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

Christina Marie Krajci Berger

A decision support framework for holistic stormwater management planning

Master's thesis in Civil and Environmental Engineering
Supervisor: Tone Merete Muthanna
June 2022

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Kunnskap for en bedre verden

Preface

This project is the final work of the master's degree programme Civil and Environmental Engineering and the course Water Supply and Wastewater Systems, Master's Thesis at the Norwegian University of Science and Technology (NTNU). The subject of this thesis is developed in cooperation with Bærum Municipality and their ongoing innovation project *”Fremtidsrettet overvannshåndtering”*, which translates to ”Stormwater management for the future”. The cooperation began in the autumn of 2021, in the course Water and Wastewater Engineering, Specialization project. In the specialization project, documentation of stormwater measures in 11 building matters was compared to the municipal plans and strategies in Bærum Municipality. Although the documentation of stormwater measures was limited, the documentation that was found indicated that although Bærum Municipality based their strategy on the three-step strategic approach, the implemented solutions centered on detaining and delaying stormwater for a design event. This sparked an interest to investigate how water utilities can ensure a holistic stormwater management in decision-making processes. The purpose of this master's thesis is to develop a framework to facilitate long-term assessment of risk and performance. In addition, the advantages of using continuous simulation in a drainage network model to generate input to a hydrodynamic flood model will be explored.

I would like to express my deepest gratitude to my supervisor, Professor Tone Merete Muthanna, who has helped me navigate through this experience. Thank you for your positivity, enthusiasm and support, and for all your helpful feedback. Furthermore, I would like to thank PhD Candidates Vincent Pons and Elhadi Mohsen Hassan Abdalla for helping me with model calibration and programming in R and Python, as well as spending hours of your time brainstorming and discussing.

I would also like to thank:

- Alexander Achton-Boel at EnviDan for your guidance in using the MIKE 21 FMHD model.
- Reidar Kveine at Bærum Municipality for answering all my questions and helping me access data and information about the study area.
- Therese Holm Thorvaldsen and Hans Holtbakk Thoresen at Bærum Municipality for your cooperation throughout this project.
- DHI for providing necessary licenses to the MIKE software.
- My family and friends for your support throughout this process.

Trondheim, June 28th 2022

ChristinaMKBerger

Christina Marie Krajci Berger

Thesis structure

A master's thesis is usually written as an extensive report on the topic researched. This master's thesis is written in English and as a manuscript, following the structure of a research article. The aim of which is to make the research more accessible for an international audience. This thesis has been admitted to be presented at the International Water Association World Water Congress & Exhibition in Copenhagen in September 2022.

Although the thesis follows the structure of a research article, it is purposely more elaborate than required by guidelines for research articles. This is to ensure that the thesis meets the requirements of a master's thesis and consequently can be graded as such. The structure of this thesis is based on guidelines from Water Research, a journal of the International Water Association (IWA).

Sammendrag

Et rammeverk for beslutningsstøtte i planlegging av helhetlig overvannshåndtering

Overvann er en økende utfordring i urbane områder som følge av klimaendringer og fortetting. Kombinasjonen av disse faktorene bidrar til at overvannsmengdene overskrider kapasiteten i tradisjonelle rørsystemer. Dette skaper en rekke problemer, som bekkeerosjon, skade på infrastruktur og bygninger som følge av flom og forverring av leveforhold i akvatiske økosystemer. Disse utfordringene har ført til at nye strategier for overvannshåndtering har vokst frem. Flere av dem anbefaler å håndtere overvann ved å imitere naturlige hydrologiske prosesser. Ved bruk av lokale åpne løsninger der overvann utnyttes som en ressurs eller håndteres ved hjelp av infiltrasjon kan overvann gjenfinne sin plass i det urbane bybildet og vannkretsløpet.

For å planlegge overvannshåndtering er det nødvendig å innhente informasjon om overvannssystemets samlede atferd, dets interaksjon med omgivelsene og interaksjoner mellom enhetene som utgjør systemet. Integrert Infrastructure Asset Management (IAM) er en metode for å forvalte infrastrukturer som tar hensyn til at enhetene som sammen håndterer overvann er gjensidig avhengige av og påvirker hverandre. Metoden fasiliterer beslutningstaking ved å undersøke den nåværende tilstanden til infrastrukturen, definere langsiktige mål og etablere nødvendige tiltak for å nå de langsiktige målene. En forutsetning for metoden er at målene for overvannshåndtering er til stede på samtlige nivåer, fra strategisk planlegging (langsiktig perspektiv) til bygging av tiltak (kortsiktig perspektiv). Dette kan være utfordrende å oppnå, på grunn av usikkerhet om hvordan overvannstiltakene samhandler med hverandre og usikkerhet knyttet til fremtidig utvikling. Modeller kan benyttes for å omgå disse hindrene.

Det finnes en rekke overvannsmodeller, noen egnet for å modellere overvannsnettet, mens andre er egnet for flommodellering. SWMM er et eksempel på et modellverktøy som er egnet for å modellere hydrologiske prosesser og overvannsnettet. SWMM kan brukes til å modellere overvannskvalitet og -kvantitet. En begrensning med verktøyet er at det ikke er i stand til å modellere flom på terrengoverflaten. GIS-baserte verktøy kan brukes til å modellere flom på terrengoverflaten basert på analyse av terrengdata. Selv om denne metoden er rask, er den ikke i stand til å simulere dynamiske flomprosesser. Hydrodynamiske modeller basert på gruntvannslikningene kan simulere dynamiske flomprosesser, men er mindre effektive enn GIS-baserte modeller. Overvannsnettet spiller en viktig rolle ved flomhendelser, noe som bør tas høyde for i flommodellering. I flommodellen kan overvannsnettets kapasitet representeres som en konstant verdi, eller man kan koble modellen med en modell som er egnet for å simulere overvannsnettet, enten ved at modellene utveksler informasjon eller ved at den ene modellen mater den andre modellen med informasjon.

I Norge er tretrinnsstrategien en svært omforent metode for håndtering av overvann. Strategien omfatter 1) infiltrasjon av daglig regn, 2) fordrøyning av middels store regnhendelser og 3) sikring av trygge flomveier ved større regnhendelser. I en studie der planlagte overvannstiltak i elleve byggesaker i Bærum kommune ble kartlagt, ble det funnet at tiltakene i hovedsak ble dimensjonert for å håndtere trinn 2 i tretrinnsstrategien. For å oppnå en helhetlig overvannshåndtering er det nødvendig å sikre at de implementerte overvannstiltakene samsvarer med de langsiktige målene definert i overvannsstrategien. Planlegging av overvannshåndtering krever dessuten evaluering av risiko og ytelse i et langtidsperspektiv. Målet med denne masteroppgaven er å utvikle et rammeverk for å fasilitere evaluering av risiko og ytelse i nåværende og fremtidige overvannsstrategier. I tillegg ble fordelene ved å bruke kontinuerlig simulering i en semidistribuert konseptuell hydrologisk modell for å lage datainput til flomsimulering i en hydrodynamisk modell utforsket.

Da rammeverket ble utviklet ble det vektlagt at det skulle være kompatibelt med eksisterende verktøy, anvendbart i ulike nedbørsfelt, mulig å tilpasse til lokale målsettinger og behov, og anvendbart for å planlegge for mulige fremtidsscenarioer. Det endelige resultatet var en metode for å velge modellverktøy i overvannsplanlegging bestående av seks steg. Stegene var som følger: 1) Kontinuerlig simulering i semidistribuerte konseptuelle hydrologiske modeller, 2) identifisering av flomhendelser, 3) flommodellering i en GIS-basert modell, 4) evaluering av usikkerhetspunkter knyttet til GIS-modellens begrensninger, 5) flommodellering i en hydrodynamisk modell og 6) implementering av endringer i modellene for å undersøke fremtidsscenarioer. De ulike stegene kan utføres avhengig av hva brukeren ønsker å undersøke.

Potensielle fordeler ved å benytte kontinuerlig simulering i en semidistribuert konseptuell hydrologisk modell for å lage input til flomsimulering i en hydrodynamisk modell ble undersøkt ved å benytte to modeller for Nadderudfeltet i Bærum kommune. Dette området ble rammet av flom den 6. august 2016 som følge av ekstremregn. I denne studien ble en SWMM-modell brukt for å lage input til en modell laget i MIKE 21 FMHD. For å sikre at SWMM-modellen var egnet for å simulere høy vannføring ble Nashville-Sutcliffe Efficiency (NSE) brukt for å kalibrere seks av modellparametrene. Ti modeller oppnådde en NSE over 0.5, der den beste modellen oppnådde en NSE lik 0.64. Simulert flom fra kontinuerlig og hendelsesbasert simulering i den beste modellen ble brukt for å lage spatialfordelte tidsserier som ble matet inn i MIKE 21 FMHD-modellen som regn. Den kontinuerlige simuleringsperioden var fra april til oktober 2016, mens den hendelsesbaserte simuleringen startet 24 timer før ekstremnedbørshendelsen startet. I tillegg ble MIKE 21 FMHD-modellen brukt til å simulere flom basert på en antatt verdi for overvannsnettets kapasitet på 12,5 mm per time. Disse tre modelloppsettene ble brukt for å simulere flom i MIKE 21 FMHD i løpet av de første tre timene av ekstremregnet den 6. august 2016.

Simuleringen av flom i MIKE 21 FMHD viste at input fra den kontinuerlige og den hendelsesbaserte simuleringen i SWMM ga identiske resultater. Ettersom ingen av MIKE 21 FMHD-modellene ble kalibrert, var det vanskelig å vurdere hvorvidt det er fordelaktig å bruke SWMM for å representere overvannsnettets kapasitet ved flommodellering, eller om det er tilstrekkelig å anta en konstant verdi. At resultatene fra flommodellering i MIKE 21 FMHD basert på kontinuerlig og hendelsesbasert simulering i SWMM var identiske kan være forårsaket av at 1) det var tilstrekkelig å benytte en simuleringsperiode fra og med 24 timer før regnhendelsen startet for å etablere kapasiteten i nettverket i forkant av regnhendelsen, eller 2) SWMM-modellens manglende evne til å simulere fordrøyning medførte at den initielle kapasiteten i overvannsnettet ble overestimert uavhengig av valgt simuleringsperiode.

Grunnsteinen i metoden for valg av modeller for å fasilitere evaluering av risiko og ytelse var kontinuerlig simulering i flere forskjellige semidistribuerte konseptuelle hydrologiske modeller. Resultatene fra de ti beste SWMM-modellene viste at utfallsrommet fra de ti modellene samsvarte bedre med observert data enn den beste modellen alene. Bruk av ensemble modeller kan være nyttig i beslutningsprosesser, ettersom de gir et tydeligere bilde av de mulige utfallene av en hendelse. Dermed skaper de et bedre grunnlag for å evaluere risikoen av en hendelse opp mot akseptert risiko. Mulige fordeler med bruk av kontinuerlig simulering i planlegging av overvannshåndtering er at man kan evaluere nedbørsfeltets atferd under varierende forhold. Kontinuerlig simulering kan også være nyttig for å identifisere uønskede hendelser. Dette er spesielt relevant for langsiktig overvannsplanlegging, ettersom byutvikling, klimaendringer og alternative overvannsstrategier kan medføre at premissene for de uønskede hendelsene endres. En fordel med rammeverket er muligheten til å evaluere virkningen av implementerte overvannstiltak ved varierende regnhendelser og på tvers av de tre trinnene i tretrinnsstrategien.

Basert på flommodelleringen som ble gjennomført i denne studien ble det ikke identifisert noen fordeler ved å bruke kontinuerlig simulering i SWMM for å lage input til en MIKE 21 FMHD-modell. SWMM-modellen som ble brukt i denne studien var ikke i stand til å simulere fordrøyning. For å kunne fastslå med sikkerhet hvorvidt kontinuerlig simulering er fordelaktig for å representere overvannsnettet i flommodellering sammenliknet med hendelsesbasert simulering, er det nødvendig å undersøke metoden nærmere. Det anbefales å teste metoden grundigere ved å modellere flere typer regnhendelser og å bruke modeller som er bedre egnet for å simulere fordrøyning. Resultatene i denne studien fremhever viktigheten av å forstå hvordan modeller er bygget dersom de skal benyttes i beslutningsprosesser.

Table of Contents

List of Figures

List of Tables

Acronyms

CSO Combined Sewer Overflow.

GI Green Infrastructure.

GIS Geographic Information System.

IAM Infrastructure Asset Management.

LID Low Impact Development.

MIKE 21 FMHD MIKE 21 Flow Model, Hydrodynamic Module.

NSE Nashville-Sutcliffe Efficiency.

SWMM Storm Water Management Model.

SWMMR R Interface for US EPA'S SWMM.

A decision support framework for holistic stormwater management planning

- A case study from Bærum Municipality, Norway

Christina Marie Krajci Berger

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

Abstract

Stormwater is the cause of a multitude of problems, such as streambank erosion, degrading living conditions in aquatic ecosystems, and damage to buildings and infrastructures. Due to urbanization and climate change, runoff volumes are expected to increase, exceeding the capacity of traditional subterranean stormwater systems. Several strategies have been developed to describe how stormwater should be managed to meet the manifold objectives of stormwater management. To achieve a holistic stormwater management in alignment with its objectives, there is a need to systematically assess the behaviour of urban catchments, accounting for inter-dependencies between assets and future development. In this study, a decision support framework was developed to aid in long-term assessment of risk and performance in current and future stormwater strategies. In addition, the possible advantages of using continuous simulation in a semi distributed conceptual hydrological model to generate input to a hydrodynamic model was explored. The development of the framework resulted in a structured method utilizing modelling tools to investigate future development, identify unwanted events, and to assess the efficacy of stormwater measures outside their intended use. The simulated flooding based on input from continuous simulation was identical to that of an event-based simulation. Due to the inability of the semi distributed conceptual hydrological model to simulate detention, it could not be concluded that using continuous simulation to generate input to a hydrodynamic model was advantageous. The findings in this study accentuate the importance of understanding limitations of modelling tools when they are incorporated in decision-making processes.

Key words: stormwater management, model coupling, Infrastructure Asset Management, continuous simulation, flood modelling, risk assessment

1 Introduction

Stormwater is the cause of a wide range of problems in urban environments, including pluvial flooding, streambank erosion and pollutant distribution (Steiger 2022). The problems are intensified by climate change, causing more frequent extreme precipitation events (Fisher and Knutti 2016). This is an issue particularly in cities where urbanization, which tends to be accompanied by increased shares of impervious surfaces, prevents runoff from infiltrating the ground. The objective of urban stormwater management has traditionally been to avoid flooding by conveying runoff away from urban areas through subterranean systems. Throughout the past century, piping urban streams was a common practice in order to create space for city development (DSS 2015). The combined effects of climate change and urbanization contribute to generating runoff volumes exceeding the capacity of the traditional stormwater infrastructure (DSS 2015). Upgrading the system to convey the runoff generated by extreme precipitation events is financially infeasible (Rosenzweig et al. 2019). As a consequence, the traditional stormwater infrastructure is unfit to manage the challenges associated with stormwater, including but not limited to: health hazards; Combined Sewer Overflow (CSO)s; uncontrolled pluvial flooding; uncontrolled transportation of pollutants; degrading living conditions in aquatic ecosystems; obstruction of critical services; and damage to infrastructure and buildings.

As a response to the manifold challenges associated with stormwater, several terms have developed over the recent decades, describing the processes, practices, and objectives of stormwater management (Fletcher et al. 2015). Low Impact Development (LID) refers to systems and practices in stormwater management imitating natural watershed hydrology (EPA 2022). The aims of LID, as defined by the United States Environmental Protection Agency (EPA) (2022), are to protect water bodies from contamination and to protect aquatic ecosystems, by retaining stormwater through infiltration, evapotranspiration or stormwater harvesting. Green Infrastructure (GI) are measures that locally manage stormwater by: retention in soil systems, plant systems or permeable surfaces; stormwater harvesting; and storage, with the purpose of reducing stormwater flow to recipient water bodies and sewer networks (*Water Infrastructure Improvement Act* 2019). Although GI and LID have different definitions, they are often used interchangeably (Fletcher et al. 2015). Implementation of GI and LID is applicable at both local and regional scales, focusing on managing rain locally, and serving multiple objectives: cleaner air and surface waters, flood protection, and providing natural habitats for local ecosystems (EPA 2022). These are just two of many terms describing recommended practices and objectives of urban stormwater management. Other examples are Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SUDS) and Integrated Urban Water Management (IUWM). These concepts, much like LID and GI, state that the objectives of stormwater management are manifold, stressing the importance of managing stormwater as part of the hydrologic cycle and as an element interacting with and being part of the environment (Fletcher et al. 2015).

Managing urban water systems requires knowledge about the condition and performance of the system as a whole, its interaction with its environment, and the interactions in-between the various stormwater units that constitute the system (assets). Alegre and Coelho (2012) argue that urban water systems should be managed according to the Integrated Infrastructure Asset Management (IAM) approach, entailing the long-term assessment of the system performance, risk and cost. IAM differs from Asset Management (AM) by acknowledging interdependencies between assets and the various coexisting life times of individual assets. The integrated approach to IAM aims to assist decision-making by assessing the current status of the infrastructure, in terms of service and ownership, define the long-term objectives of the infrastructure, and assess necessary actions to reach the long-term goals (Alegre and Coelho 2012). The management approach specifies the need for full alignment between objectives and targets defined on the strategic level (long-term), decision-making on the tactical level (medium-term), and implementation on the operational level (short-term) (Alegre and Coelho 2012). In addition, Alegre and Coelho (2012) stress that integrated IAM should be based on the principle of PDCA (plan, do, check, act) to ensure that the applied methodology is constantly developed according to newfound information and knowledge about the infrastructure, or changed external factors, such as mutual interactions between assets and their environment.

Achieving full alignment between the main objectives of stormwater management and the implemented actions is complicated by uncertainty about the characteristics of urban catchments and uncertainty related to future development. Collecting observed data across the infrastructure can provide increased knowledge about the current state of the system. However, this is time consuming, and is of limited use for addressing future scenarios. Modelling tools can be utilized to overcome the uncertainty of both missing data and future development, being applicable for investigating inter-dependencies between assets, the effects of climate change and changed land use, and to evaluate stormwater management strategies (Alegre and Coelho 2012). Conducted research on stormwater infrastructure utilizing modelling tools ranges from assessment of pipe deterioration (Tscheikner-Gratl et al. 2014) to pollutant distribution (Liu et al. 2014). Pluvial flooding is a common subject to stormwater modelling, due to the expected increase in frequency and intensification of heavy precipitation events and limited historical data. Addressing the challenges associated with uncontrolled flooding, Skrede et al. (2022) developed a framework for identifying floodways suitable to be managed as stormwater infrastructure assets, incorporating flood modelling in risk analysis. Flood models are also utilized in planning matters, for instance for developing Cloudburst Management Plans (CMPs).

There exists several urban flood models, some of which are concerned with the subterranean network, while others simulate surface runoff (Figure 1). An example of an urban drainage network model is Storm Water Management Model (SWMM) from United States Environmental Protection Agency (US EPA), applicable for simulating stormwater quantity and quality. The tool is also applicable for simulating hydrological processes, and can be used to assess performance of LID measures. Surface flooding, defined as the water volume per time unit in a junction exceeding its maximum available depth, can also be simulated (Rossman 2015). However, the behaviour of flooded water after exiting the stormwater network is not within the system boundaries. Drainage network models are therefore not suitable for assessing risks associated with flooding, determined by the distribution, depth, and velocity of flood water (Guo et al. 2021). Nevertheless, simulated surcharge, such as node flooding in SWMM, can give valuable information about the stormwater network when modelling surface flooding (Guo et al. 2021).

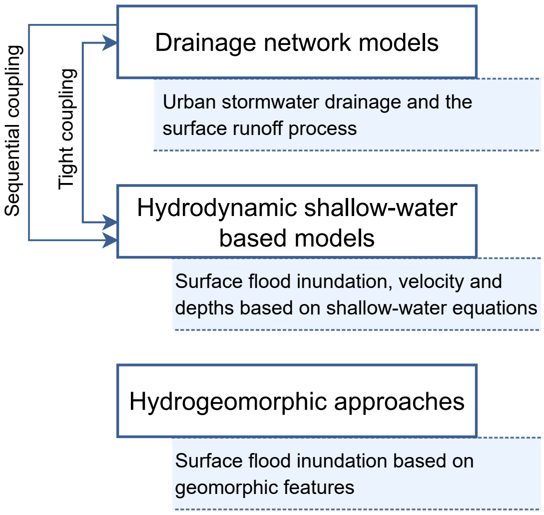


Figure 1: *Types of urban flood models and their areas of use. Modified from Guo et al. (2021).*

Unlike drainage network models, models based on hydrogeomorphic approaches, such as Geographic Information System (GIS)-based models, are capable of simulating the inundation of flooding based on terrain data analyses (Guo et al. 2021). However, they are incapable of simulating the dynamic flood process (Guo et al. 2021). SCALGO Live, an internet-based modelling tool developed by SCALGO, is an example of a GIS-based tool, in which flood paths, flooded areas and depth of flooded water can be simulated for a given rainfall depth, utilizing the *Flash Flood Map* function. The flash flood model is a stationary model in which rain is distributed uniformly and occurs instantaneously (ApS 2022). Routing flood paths based on terrain data alone, GIS-based models do not simulate the flow or velocity of flooded water, nor their effect on flowpaths. Tørudstad (2020) proposed a method for identifying points along flood paths which may be inaccurate due to the influence of velocity. The method involves identifying uncertainty points along flood paths, defined as points with uncertainty regarding the accuracy of the simulation owing to the limitations of GIS. Points with steep slopes and sharp turns were among the identified points, contributing to increase the velocity of flooding water, and being unlikely to be completed by water with high velocity, respectively. Tørudstad (2020) argued that hydrodynamic models can be applied for further analysis of these points. Hydrodynamic models based on shallow-water equations (SWE) are numerical models capable of simulating velocity, flow, depth and inundation of flooded water (Guo et al. 2021), and their influence on flood paths, overcoming the limitations of GIS-based models. In order to accurately simulate flooding in urban landscapes, both hydrodynamic models and models based on hydrogeomorphic approaches require accurate high-resolution topographical data in which urban structures such as buildings and roads are represented (Guo et al. 2021).

Stormwater networks are an important asset during flood events in urban catchments, removing stormwater volumes according to their capacity, and redistributing flooded stormwater through surcharge flow (Guo et al. 2021). One approach to account for stormwater networks in matters of flooding is stating the capacity of the stormwater network as a rain intensity and subtracting it from the rain input. In Utrecht Municipality in The Netherlands, the subterranean infrastructure is expected to manage events smaller than 20 mm/hour (Dai et al. 2017). In Malmö in Sweden, the dimensioning criteria of the network is 12 mm/h (Braskerud et al. 2017). Another approach to the issue is to couple network models with hydrodynamic models, as illustrated by arrows in Figure 1. Several methods have been developed for model coupling (Sañudo et al. 2020), some of which assume flow exchange occurs only from the stormwater network to the surface (sequential coupling), while others simulate the flow exchange between the pipe network and the surface (tight coupling) (Moges et al. 2020).

Uncertainty is an unavoidable issue in planning, and must be accounted for. Walker et al. (2013) argue that a sustainable plan is not only a plan that meets environmental, social and economic objectives for the present and future, it is also robust and adaptable to future development. The uncertainty associated with future development is commonly addressed by utilizing modelling tools to simulate possible scenarios (Kirchner et al. 2021). However, as modelling tools are incorporated in the planning process, so is the uncertainty related to the modelling process (Kirchner et al. 2021). In coupled models, uncertainty propagates as data is exchanged between models (Moges et al. 2020). Model uncertainty can be addressed by conducting an uncertainty analysis (Loucks et al. 2005).

In Norway, the three-step strategic approach for stormwater management has been adopted by water utilities, entailing retaining daily rain, detaining medium rainfall events, and safely transporting flooded water during extreme events. The strategy, developed by Lindholm et al. (2008), suggests a risk-based approach for dimensioning stormwater detention measures. By dimensioning measures for detaining a precipitation event with a large return period in areas where flooding can cause fatal damage, the probability of flooding is reduced, keeping the risk at an acceptable level. This criteria is implemented in Bærum Municipality, requiring that property owners dimension stormwater measures for detaining a precipitation event with a 25-year return period multiplied by a climate factor of 1.4 (Bærum Municipality 2017). Investigating planned stormwater measures in eleven building matters in Bærum, Berger (2022) found that the measures were dimensioned mainly for detention, and in seven of the cases the permitted outflow to the municipal stormwater network or a recipient water body was used as a premise for dimensioning detention volumes. Although several of the planned stormwater measures aligned with the aim of the three-step strategic approach and the principles of LID (i.e. swales and rain gardens), managing stormwater in open and green solutions, none of them were dimensioned for retention or water treatment (Berger 2022).

By focusing mainly on implementing stormwater measures dimensioned for detaining a precipitation event of a certain magnitude (step 2 of the three-step strategic approach), the other objectives of stormwater management in Bærum Municipality are neglected. In order to achieve a holistic stormwater management, as is the objective of the municipality in their ongoing innovation project, the implemented actions have to align with the manifold objectives formulated in their strategies.

Planning for holistic stormwater management requires assessment of risk and performance in a long-term perspective across the multifaceted objectives of stormwater management, taking into consideration the uncertainty of future development. This raises the need to systematically assess the behavior of urban catchments in a manner that accounts for 1) inter-dependencies between assets; 2) the multiple objectives of stormwater management; 3) city development; and 4) climate change. The aim of this study is to address this need by developing a framework to facilitate assessment of performance and risk of current and planned stormwater management strategies, considering the multiple objectives of stormwater management. The purpose of the framework is not to suggest assessment criteria from which decisions should be made. In addition, the possible advantages of using continuous simulation in a drainage network model to represent the network capacity in flood modelling will be explored. The objectives of the research conducted in this study are:

1. Develop a framework to facilitate long-term assessment of risk and performance in current and future stormwater management strategies.
2. Exploring the advantages of using continuous simulation in a semi distributed conceptual hydrological model to generate input to a hydrodynamic model.

2 Method and materials

The following chapter describes the methods used to 1) develop a framework to facilitate long-term assessment of risk and performance in stormwater management planning (chapter 2.1) and 2) generate input to a hydrodynamic model from continuous simulation in a semi distributed conceptual hydrological model (chapters 2.2-2.6). The semi distributed conceptual hydrological model used in this study was created with SWMM, and the hydrodynamic model was created with MIKE 21 FMHD. Both models cover Nadderud catchment in Bærum Municipality, and were created for the municipality by consulting firms. Figure 2 illustrates the structure of the modelling processes. To explore the possible advantages of utilizing continuous simulation in a SWMM model to generate input to a hydrodynamic model, the extreme precipitation event on August 6th 2016 was simulated with three approaches to represent the pipe network: using simulated flooding from 1) continuous simulation in SWMM and 2) a four day simulation period in SWMM, and 3) subtracting a constant value from the observed precipitation. The models used in this study did not account for snow, groundwater or sewage.

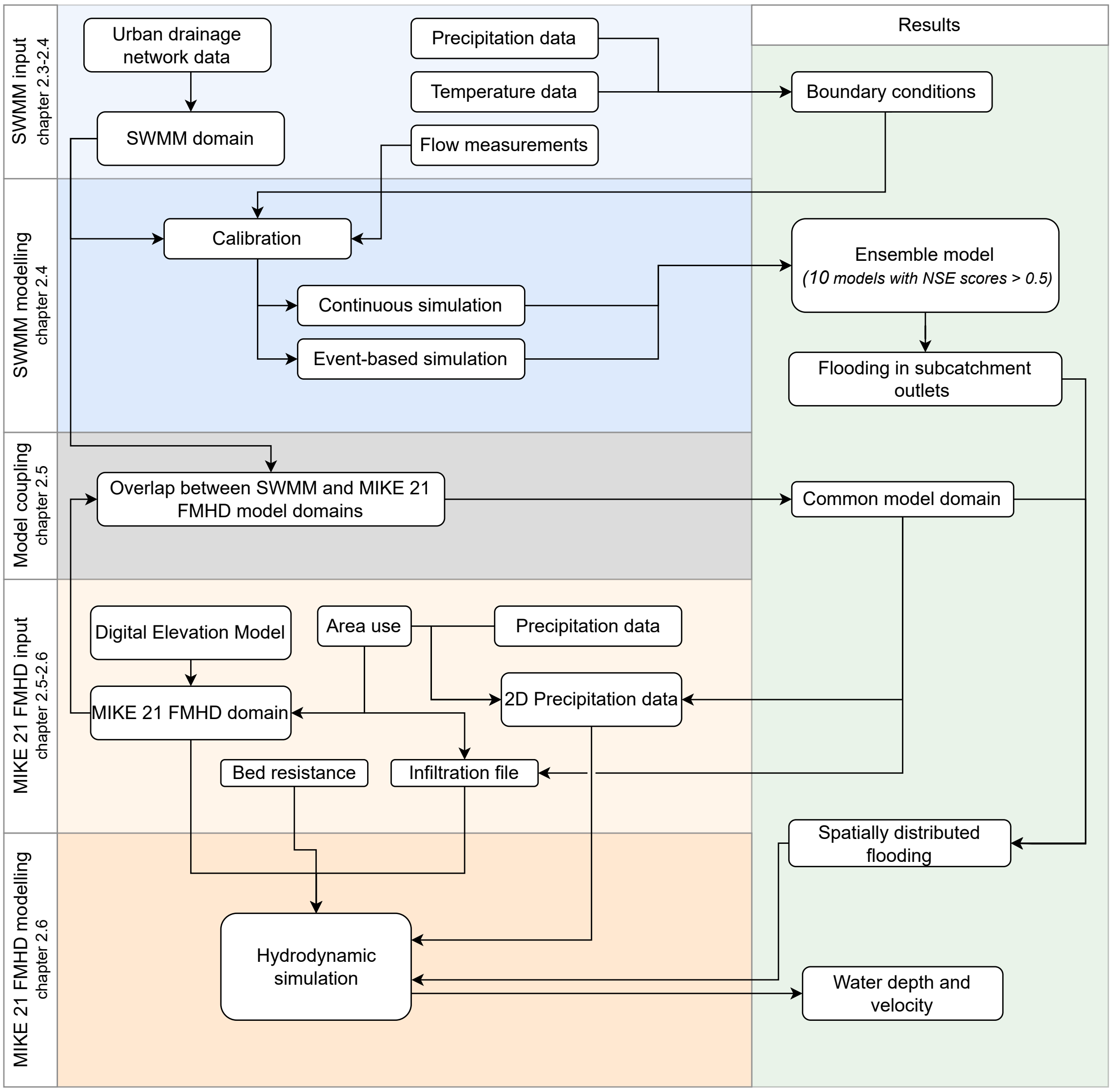


Figure 2: *Flowchart illustrating the methodology for simulating urban stormwater runoff and hydrological processes in SWMM and surface flooding in MIKE 21 FMHD, and the steps taken to couple the models.*

2.1 Developing the decision support framework

Developing a framework facilitating long-term assessment of risk and performance of current and future stormwater management strategies was an iterative process. Compatibility with existing methods and tools as well as applicability for various catchment characteristics were premises for developing the framework, ensuring flexibility to meet the needs and objectives of local utilities. For the same reason, criteria for risk and performance were not defined. The desired areas of use were to assess the state of existing stormwater networks and catchments and to plan for future stormwater management strategies, city development or climate change, focusing on assessment of risk and performance. The framework was developed to be compatible with a floodway management framework developed by Skrede et al. (2022).

To ensure applicability in stormwater management planning, it was seen necessary to include modelling. Aiming to facilitate holistic stormwater management, the framework suggests the use of models suitable for simulating surface flooding, the drainage network, and hydrological processes. In order to ensure reliable simulations of flood inundation, identification of uncertainty points related to the accuracy of GIS-based models (structural uncertainty points), as researched by Tørudstad (2020), was included in the framework. Continuous simulation was identified as a suitable approach to assess long-term performance and risk, ensuring inclusion of various rainfall characteristics. Another important feature was the possibility to investigate the performance of implemented stormwater measures outside their intended use, for instance to iteratively change the share of green roofs to assess their effect, if any, on pluvial flooding.

Accounting for the limitations and system boundaries of stormwater models, it was decided to include several model types in the framework. With respect to the stated criteria and the desired features, the framework resulted in a six step process: 1) continuous simulation in semi distributed conceptual hydrological models representing a catchment and its subterranean system, 2) identification of flooding events, 3) surface flood modelling in a GIS-based model, 4) assessment of reliability of GIS-based flood modelling, 5) surface flood modelling in a hydrodynamic model. Finally, if utilized to investigate alternative scenarios: 6) modification of catchment characteristics or precipitation data, after which step 1 is to be repeated. The presented order is not definite: Continuous simulation is the only premise for applying the method presented in the framework, and each step can be utilized to assess one or more objectives of stormwater management. Steps 2-4 can be performed according to the needed decision-making basis as defined by the utility.

2.2 Study area

The area investigated in this case study was Nadderud catchment in Bærum Municipality, situated by the inner Oslo Fjord. The inner Oslo Fjord has an annual precipitation of about 700 mm (NCCS 2022a), and has a warm-summer humid continental climate (dfb) (Kottek et al. 2006). The study area, illustrated in Figure 3, covers an area of 12.3 km^2. Bekkestua, indicated with a red dot in Figure 3, serves as a hub for public transportation. The area experienced severe flooding during an extreme precipitation event on August 6th 2016. The 86 mm rain event lasted for about 10 hours, and started after an 11 hour period with no measured precipitation. The precipitation data used in this study was collected from a weather station located in Nadderud (Figure 3).

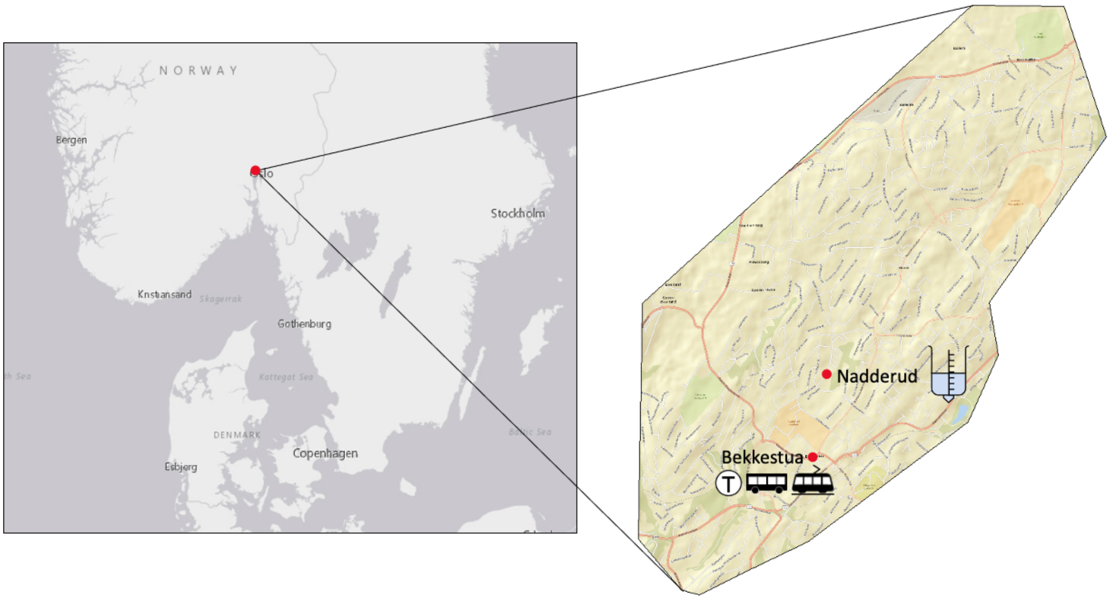


Figure 3: *Location of Nadderud catchment in Bærum Municipality. Bekkestua, indicated with a red dot, is a hub for public transportation, while Nadderud indicates the location of the local weather station.*

2.3 Data collection and data preprocessing

Precipitation data from Nadderud weather station, marked in Figure 3, was provided by Bærum Municipality. The station has a heated tipping bucket, and has been active since January 2016. Observed flow data from various locations in the municipality, covering varying time periods, were provided by Bærum Municipality, and used to calibrate the SWMM model. Temperature and wind measurements were accessed from Blindern station in Oslo Municipality, due to inconsistent temperature measurements from Nadderud and other nearby stations. Data from Blindern station was accessed from the Norwegian Centre for Climate Services (NCCS 2022b).

Precipitation data with 1 minute time steps was analyzed and preprocessed in the following manner: Negative measurements and measurements larger than 2 mm with the previous and following measurement being 0 mm were replaced with 0 mm. Excluding snow measurements was challenging because of lacking local temperature data. As a solution, data from November to March were not considered for use as model input. Precipitation events were identified in order to find suitable data for calibrating and testing the SWMM model. The events were defined by an initial and subsequent period of 6 hours or longer without precipitation. The duration and depth of each event were calculated, and events with durations shorter than 10 minutes and depths smaller than 1 mm were excluded. Finally, the events were paired with flow measurement data to ensure that there was measurement data overlapping with the precipitation data used for calibration. An extraction of the identified events is included in Appendix A. The time steps of the precipitation and measurement data were altered to 15 minutes for calibrating and 10 minutes for testing and running simulations in the SWMM model. For the precipitation, this was done by summation, whereas the time steps of the measured flow data used for calibration and testing were altered by calculating the mean flow.

2.4 SWMM modelling

This chapter presents the modelling steps in SWMM, illustrated in Figure 2. The SWMM model was created based on files from an existing urban drainage model covering Nadderud catchment, provided by Bærum Municipality. The simulation settings were identical for all simulations, and are presented in Appendix B.

In the existing drainage network data, the widths of all 725 subcatchments were set to 500 m. As illustrated in Figure 4a, the subcatchments in the model were irregularly shaped. Assuming a quadratic shape, the widths were recalculated as the square root of each area, width = $\sqrt{area}$ (Rossman and Huber 2016). Covering an extreme precipitation event in August 2016, precipitation timeseries from April 1st to October 31st 2016 were used to run continuous simulations. With this in mind, a 10-day period from August 9th to August 19th in 2017 with eight identified events was chosen for calibrating the SWMM model, having two datasets for observed flow. The measurement point used for calibration is situated nearby the weather station (Figure 3).

The model was created to represent a stormwater network, however, baseflows of various magnitudes and patterns similar to those of water consumption were observed in the measurement data during time periods with no precipitation. Base flow was not taken into consideration when calibrating the model, and therefore subtracted from the observed data before calibration was initiated. A base flow of 0.01 m^3/s was subtracted from the observed flow data used to calibrate the model. Throughout this thesis, 0.01 m^3/s has been subtracted from the presented observed flow data. The calibrated parameters and the upper and lower bounds for each parameter are summarised in Table 1. The parameters were calibrated assuming homogeneous values within all subcatchments/junctions/pipes in the system. Except for the widths and the calibrated parameters, the remaining parameters were kept unchanged from the original parameters in the model provided by Bærum Municipality. No LID or detention measures were implemented in the model. A summary of the SWMM model file is included in Appendix C.

Table 1: *Overview of calibrated SWMM parameters and their upper and lower bounds.*

Parameter	**Unit**	**Lower limit**	**Upper limit**
suction head	[mm]	1	60
soil saturated hydraulic conductivity (Ksat)	[mm/hr]	1	100
initial soil moisture deficit (IMD)	(volume of voids)/ (total volume) [1]	0	1
depression storage in impervious areas	[mm]	0	10
depression storage in pervious areas	[mm]	0	10
pipe roughness (Manning's roughness coefficient)	[1]	0.01	0.05

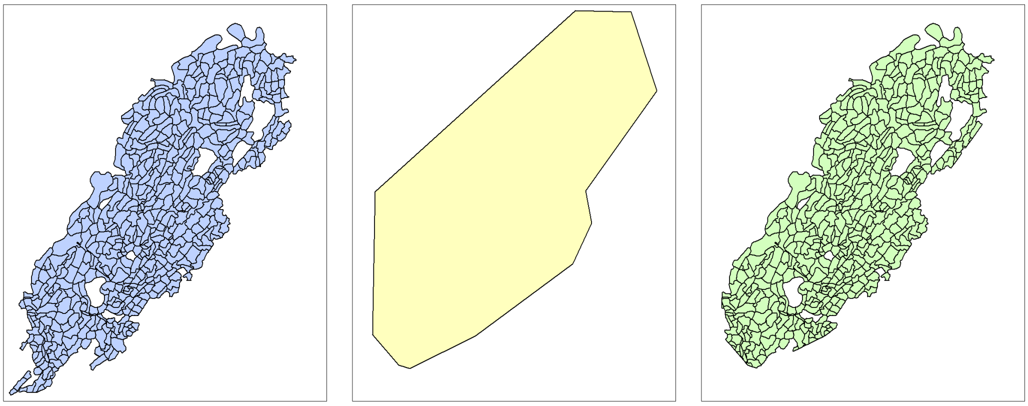
Aiming to obtain a model capable of simulating high flows and flooding, Nashville-Sutcliffe Efficiency (NSE) was used as the objective function for calibration. NSE calculates the squared difference between simulated and observed values, making it suitable to use as the objective function for predicting high and peak flows, however less suitable for predicting low flow (Krause et al. 2005). The calibration was executed utilizing Bayesian Optimization due to its efficiency. This optimization algorithm uses a surrogate model to approximate the real objective function and an acquisition function to decide which parameter to explore in the next iteration (Hennig et al. 2022). The surrogate model and acquisition functions used in this study were the Gaussian Process and Expected Improvement (EI), respectively. In the case of calibrating the six parameters, seven initial parameter sets were chosen at random within the specified ranges for each parameter (Table 1). The 10-day period in August 2017 was simulated in SWMM for all seven parameter sets, and their NSE score was calculated. Based on the initial parameter sets with known NSE scores, the uncertainty of the parameter sets with unknown scores were quantified by the Gaussian Process. Then, 100 iterations were ran in which the acquisition function was used to determine the next parameter set to be simulated in SWMM. Expected Improvement (EI) determines the next parameter set by weighing the options of exploiting solutions that are likely to give an improved model against exploring solutions with high uncertainties (Hennig et al. 2022). Based on the new parameter set with a known NSE score, the Gaussian Process recalculates the uncertainty distribution for the unknown NSE scores of the parameter sets that have not yet been simulated. The script used to calibrate the model in *R* using the R Interface for US EPA'S SWMM (SWMMR) library is included in Appendix D. A total of 107 parameter sets were simulated, 10 of which had NSE scores above 0.5, which is considered to be a satisfactory score (Moriasi et al. 2007). The best model achieved an NSE score of 0.64.

To assess the performance of the SWMM models with NSE scores > 0.5, the simulated and measured total inflow in the same junction as used for calibration were compared for three time periods within the continuous simulation period, illustrated in Figure 7. An overview of the parameter sets that achieved NSE scores above 0.5 is presented in Appendix E. Continuous simulations were run from April 1st to October 31st 2016 for all 10 parameter sets with NSE scores > 0.5. Additionally, all 10 parameter sets were used to simulate a 4-day period starting August 5th, 24 hours before the start of the extreme precipitation event. To visualize the distribution of simulation results in SWMM, the minimum and maximum value simulated by the 10 models were calculated for each time step of the simulation periods. To create input data to the MIKE 21 FMHD model, flooding in all 725 subcatchment outlet nodes were reported from the continuous and event-based SWMM simulations with the highest NSE score.

2.5 Model coupling

The coupling of the SWMM and MIKE 21 FMHD models assumed a one-directional flow from the drainage system to the surface (sequential coupling). The coupling methodology encompassed reporting flooding (m^3/s) from the outlet nodes of all 725 subcatchments and dividing the flooding by the areas (m^2) of each subcatchment, resulting in 725 new timeseries (m/s). The timeseries from subcatchments within the common model domain (Figure 4c) were intended used to generate spatially distributed precipitation data for the MIKE 21 FMHD model. This process encompasses creating a table with N timeseries and a grid file in which each cell is assigned a value between 1 and N. Using the toolbox in MIKE 21 FMHD, the time series data in column number i is assigned to all cells with value i. However, the MIKE 21 FMHD model required a grid file with 1x1 m^2 resolution. Creating a grid file with values from 1 to 725 in ArcMap, an application in ArcGIS Desktop developed by Esri, it was found that the resolution was too coarse for all subcatchments to be represented. As a solution, each cell was assigned the value of the subcatchment with the largest area within the cell. The resulting 506 subcatchments and their corresponding time series were used to generate input to the MIKE 21 FMHD model. The process of generating timeseries from flooding in each subcatchment, coupling the subcatchment names with integers and excluding the time series not represented in the grid file was done using Python (1995). The script is presented in Appendix F.

A problem encountered when coupling the models was that the model domains were not overlapping. The model domains in the SWMM and MIKE 21 FMHD models are illustrated in Figure 4a and 4b, respectively. As a solution, the shape file defining the subcatchments in SWMM was cropped in ArcMap, using the MIKE 21 FMHD model domain. For all three surface flood simulations in MIKE 21 FMHD, precipitation data was only assigned to the area illustrated in Figure 4c. The study site illustrated in Figure 3 shows the domain in the MIKE 21 FMHD model (Figure 4b).



(a) *SWMM* **(b)** *MIKE 21 FMHD* **(c)** *Overlapping model domains*

Figure 4: *System boundaries in the (a) SWMM and (b) MIKE 21 FMHD models. Precipitation data in the MIKE 21 FMHD model was spatially distributed within the overlapping domain areas (c).*

2.6 MIKE 21 FMHD modelling

Although the spatially distributed flooding from simulations in SWMM was cropped according to the overlapping model domains, the domain of the MIKE 21 FMHD file remained unchanged to avoid altering the flood paths. The blank areas within the SWMM model (Figure 4c) were mainly forested areas. The precipitation and infiltration in areas outside the overlapping model domains (Figure 4c) and within the MIKE 21 FMHD model domain (Figure 4b) were set to 0 for all MIKE 21 FMHD simulations. In practice meaning that all rain falling in these areas was retained. The input Manning raster provided with the MIKE 21 FMHD model was unaltered, as was the elevation raster file, in which all buildings were assigned a height of 199 m.

Three different model configurations to represent the drainage network and infiltration processes were used to simulate the precipitation event on August 6th 2016:

1. Urban drainage network represented by subtracting up to 12 mm/h from the measured precipitation in areas with roads and roofs. Other areas within the overlapping model domains (Figure 4c) were assigned the observed precipitation data. This input refers to the ”2D Precipitation data” in Figure 2. Infiltration was accounted for by an infiltration file specifying infiltration rates, porosity, depth, leakage, and initial water volume.
2. Spatially distributed precipitation generated from subcatchment outlet flooding timeseries. Results from a continuous simulation (April 1st to October 31st) in the SWMM model with NSE score = 0.64. No infiltration.
3. Spatially distributed precipitation generated from subcatchment outlet flooding timeseries. Results from an event-based simulation (August 5th to August 9th) in the SWMM model with NSE score = 0.64. No infiltration.

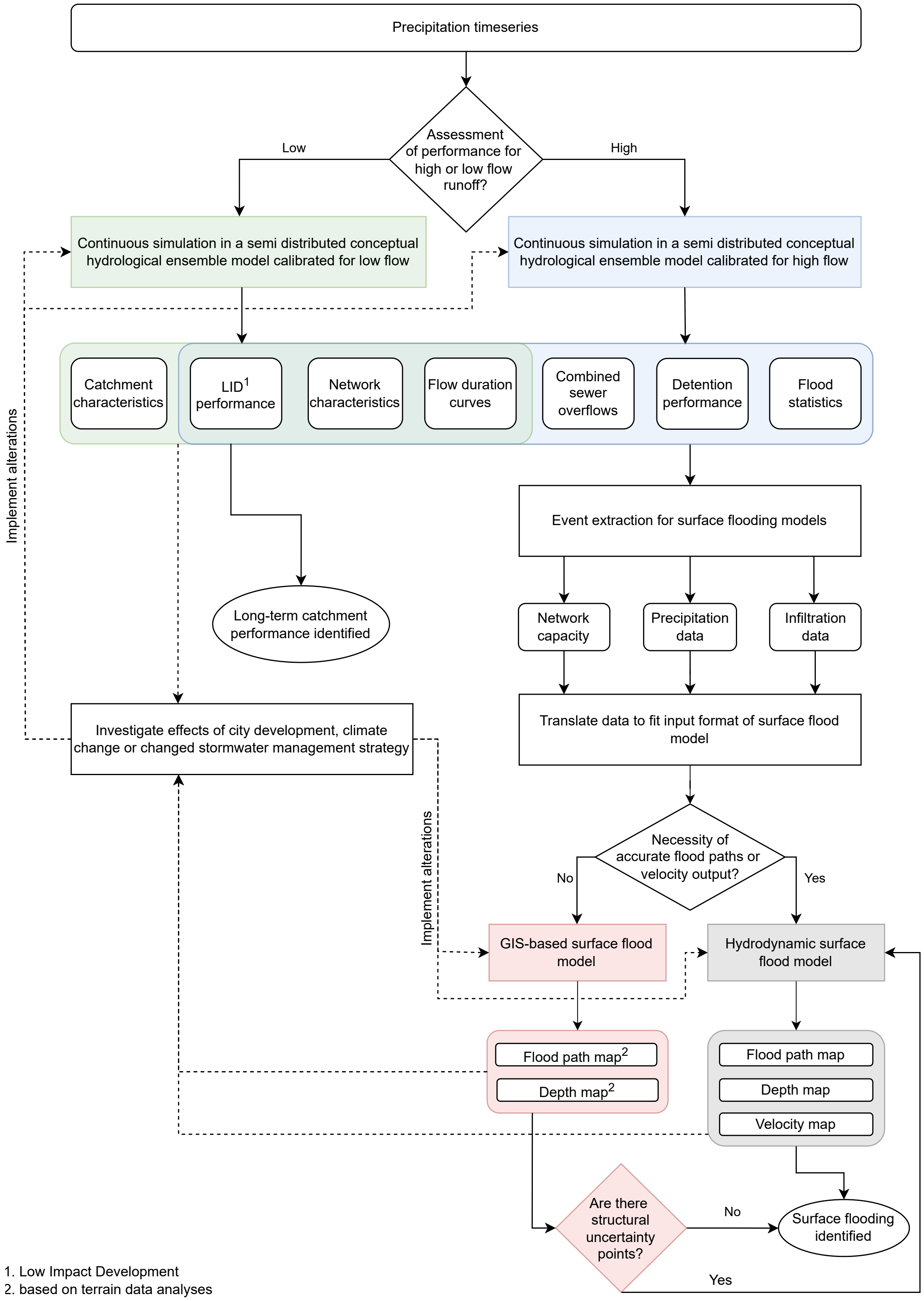
Infiltration was not simulated in the configurations using simulated flooding because it was already simulated in the SWMM model. The first configuration was not based on model coupling, making it necessary to simulate infiltration in the MIKE 21 FMHD model. Initially, the infiltration file provided with the MIKE 21 FMHD model was used to represent the infiltration, having a constant infiltration rate of 864 mm/day in cells with buildings or roads and 1440 mm/day in the remaining cells. Using this file when simulating the extreme event in August 2016 with precipitation data from Nadderud weather station, it was observed that the inundation extent was very limited. Knowing that the extreme precipitation event caused severe pluvial flooding, the infiltration file was modified: The infiltration file was cropped according to the area in Figure 4c, adjusting the infiltration rate to 0 in areas outside the overlapping domain areas. The infiltration rate was set to 0 mm/day for roofs and roads and remained unchanged from 1440 mm/day in other areas within the overlapping model domains (Figure 4c). In addition, the porosity was set to 0.5, infiltration depth = 0.3 m, leakage rate to the lower zone = 432 mm/day, and initial volume = 50%. These parameters were not spatially differentiated within the catchment. The parameters were set based on running the model for a few iterations until it was observed that the inundation extent increased. The capacity of the system was assumed to be 12 mm/h, which is the expected capacity of the drainage network in Malmö, Sweden.

The bed resistance was kept unchanged from the existing model setup for all three model configurations. Manning's M was set to 40 $m^{1/3}/s$ in cells with roads and roofs and 20 $m^{1/3}/s$ in the remaining cells. Due to the high computational cost of hydrodynamic models (Guo et al. 2021), the full event was not simulated. Instead, the first three hours (from 03:50 to 06:50) of the 10 hour precipitation event were simulated with each model configuration to assess whether continuous simulation in SWMM is advantageous to establish the initial conditions in the system. To facilitate result analysis, the area distribution of velocity and water depth were reported one, two and three hours after the start of the event in two areas within the catchment.

3 Results

In this chapter, the results attained from the methodology are presented in chronological order according to the structure of chapter 2. First, the framework developed to facilitate long-term risk and performance assessment in stormwater management planning is presented in Figure 5. Then, the results from modelling in SWMM are presented in Figures 6-8. Finally, the results from flood modelling in MIKE 21 FMHD are presented in Figures 10-13.

The framework in Figure 5 presents a guide for using modelling tools to investigate various aspects of stormwater management. The framework is structured such that the performance of the stormwater infrastructure on catchment scale can be assessed when subjected to long timeseries of precipitation data. By performing continuous simulation in semi distributed conceptual hydrological ensemble models calibrated to simulate low or high flows, the network capacity, retention in LID measures and frequency of CSOs can be investigated, amongst others. Furthermore, the continuous simulation can be used to identify areas that are more prone to flooding, and the initial state of the system prior to flooding events. Based on the flooding identified by continuous simulation, the flooding event can be simulated in a hydrogeomorphic (such as GIS-based) or hydrodynamic model, depending on the importance of simulating flood dynamics, taking into consideration the initial state of the system prior to the precipitation event. If the GIS-based model is chosen, the flood paths can be analysed for structural uncertainty points. If structural uncertainty points are identified, the framework suggests utilizing a hydrodynamic model to investigate these points further. The stapled lines indicate the process of altering the models to investigate the catchment under different conditions, such as climate change, city development, or alternative stormwater strategies.



1. Low Impact Development
2. based on terrain data analyses

Figure 5: *Framework to facilitate long-term assessment of risk and performance in stormwater management planning.*

The precipitation data used to calibrate the SWMM model is presented in the upper diagram in Figure 6. The middle and lower diagrams illustrate the calibrated inflow for the parameter set with NSE score = 0.64 (dark line), and the range of simulated inflow based on calibrated parameter sets with scores > 0.5 (shaded area). The black dots represent the observed flow. The middle diagram presents the whole calibrated period, whereas the lower diagram displays a zoomed-in 12-hour period from the middle diagram. These plots show that the best model was capable of identifying high peaks, however overestimating the lower peaks. Before the last peak in the middle diagram, there was initial flow in the node according to the observed measurements, but no initial flow in the simulated models. It can also be seen from Figure 6 that the simulated flow from the best SWMM model (dark line) was within the upper part of the simulated flow range.

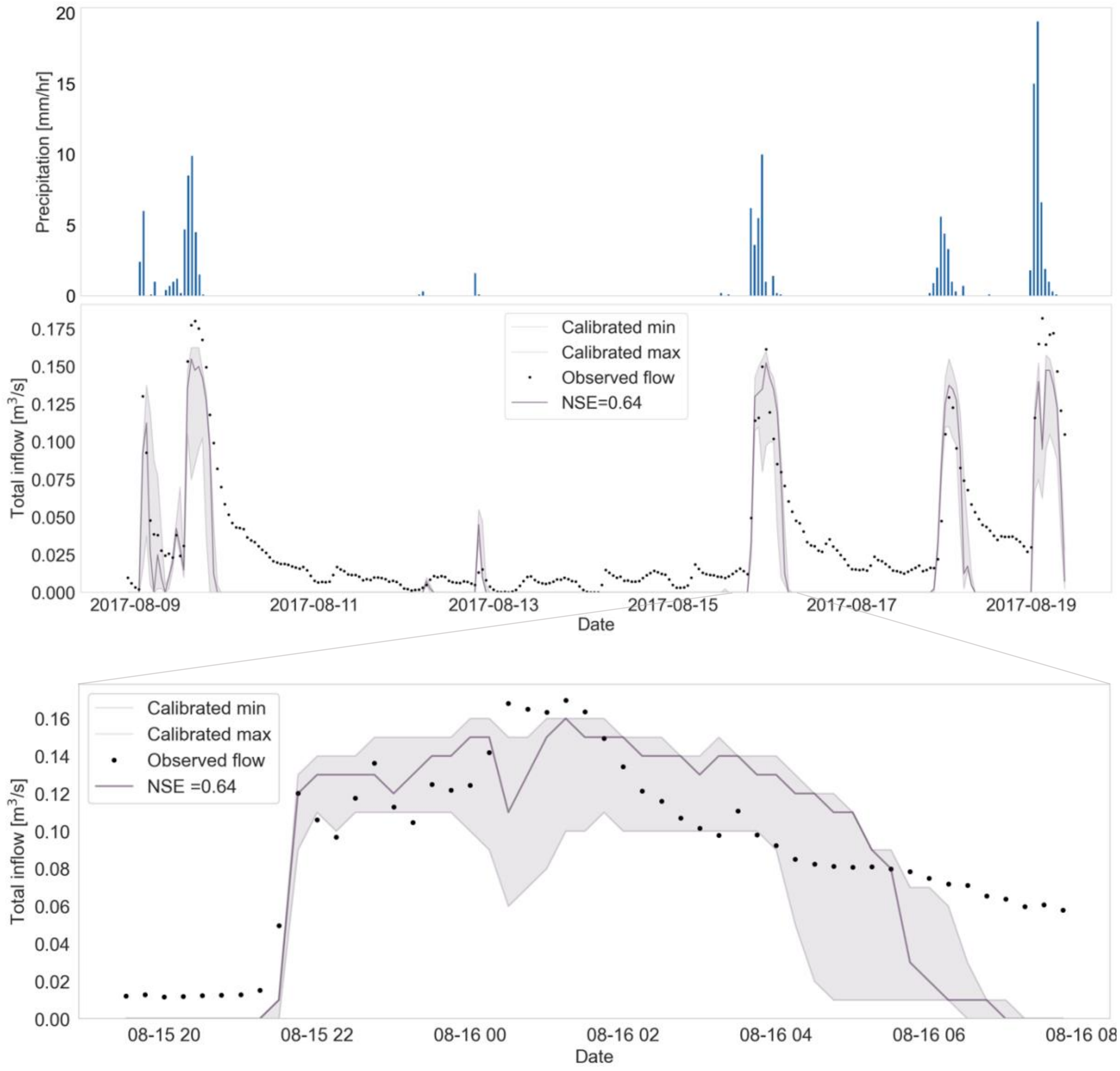
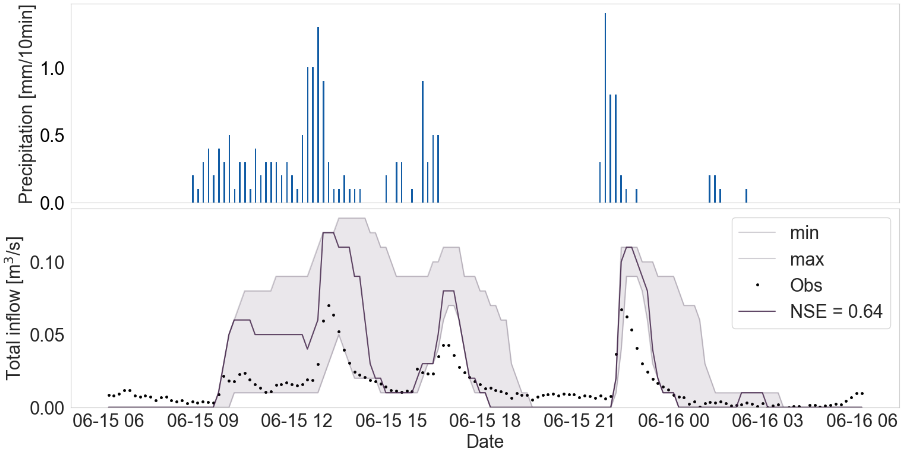
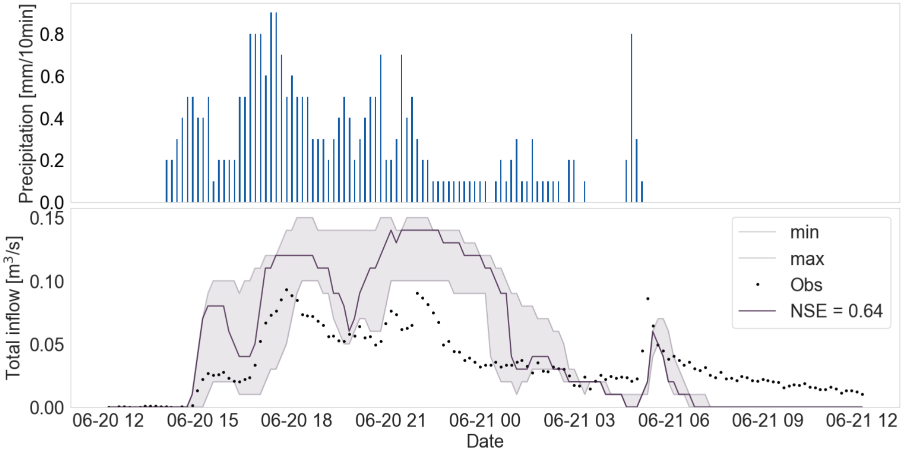


Figure 6: *Results from calibrating the SWMM model. The top diagram displays precipitation data, the middle diagram displays observed (dots) and simulated total inflow by the best model (dark line) and the range of simulated inflows from the 10 best models in one junction from August 9th to August 19th 2017. The lower diagram shows a zoomed in 12-hour period from the middle diagram.*

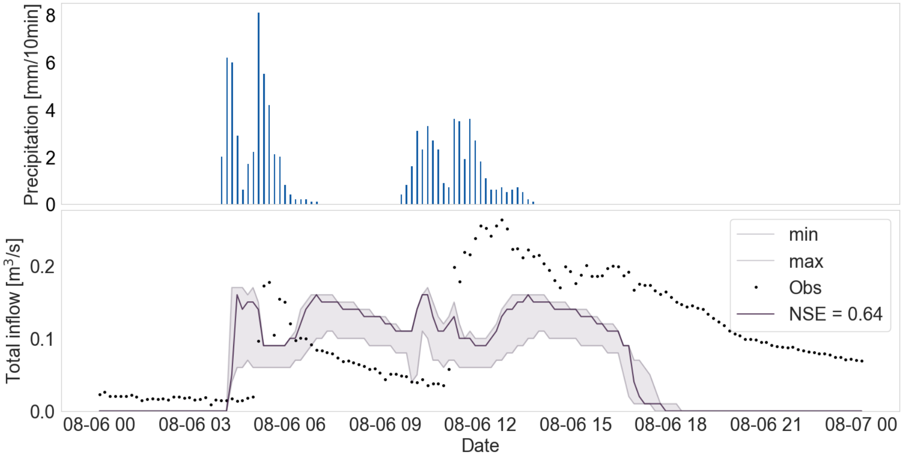
The simulated inflows from continuous simulation with the 10 best SWMM models are presented in Figure 7. The total inflow refers to the total inflow in the same node that was used to calibrate the models (Figure 6). The three precipitation events presented occurred in June (Figures 7a and 7b) and on August 6th 2016 (Figure 7c). In Figure 7a, the observed flows are within the range of the simulated flow in the beginning of the event. During the last two peaks, the models overestimate the flow compared to the observed data. The best model (dark line) overestimates flow peaks throughout the event. This can also be seen in Figure 7b. In Figure 7c, the observed flow is rarely within the range of the simulated flows. The magnitude of the first simulated flow peak, although shifted compared to the observed data, matches well with the observed flow. For the rest of the period, neither of the models managed to recreate the observed flow in terms of magnitude or shape.



(a) *June 15th to June 16th 2016*



(b) *June 20th to June 21st 2016*



(c) *August 6th 2016*

Figure 7: *Precipitation data and observed and simulated inflow in the junction used for calibrating the SWMM model from (a) June 15th to June 16th 2016, (b) June 20th to June 21st 2016, and (c) August 6th 2016. Measured inflow is represented by black dots. The shaded area represents the minimum and maximum simulated flow from continuous simulation with 10 models achieving NSE scores above 0.5 during calibration. The dark line shows total inflow from continuous simulation in the SWMM model with an NSE score of 0.64.*

Figure 8 shows the simulated system flooding from continuous simulation in the 10 best SWMM models. The upper diagram shows the total simulated period, from April to October 2016, whereas the middle and lower diagram presents the extreme precipitation event on August 6th 2016 and the simulated flooding caused by it. The range of system flooding and the system flooding of the best model in the event-based simulation (August 5th to August 9th) were identical to the graphs in the lower diagram. With the exception of two models simulating 20.3% and 5.0% larger volumes for the continuous simulation compared to the event-based simulation, the differences in the other eight models were less than 0.1%. The difference in total flooded water volume was 0.04% for the best model.

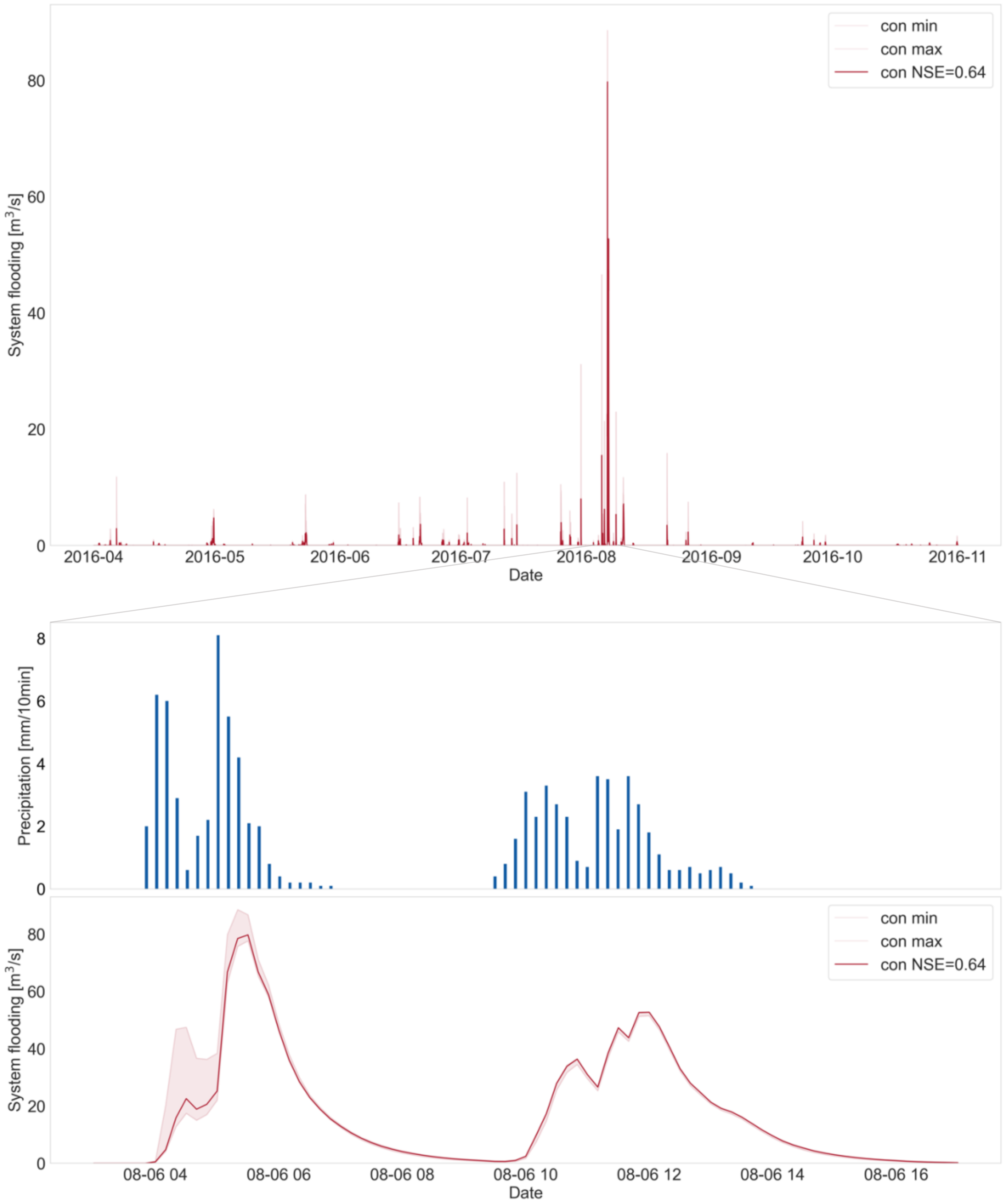


Figure 8: *The top diagram shows simulated system flooding from continuous simulation from April 1st to October 31st 2016. The middle and lower diagrams show the precipitation and system flooding on August 6th 2016. The dark red lines indicate the system flooding simulated by the SWMM model with an NSE score = 0.64, whereas the shaded area represents the range of flooding simulated by the 10 best models.*

The results from simulations in MIKE 21 FMHD were reported from one area downstream (area A) and one area upstream (area B) in the catchment, illustrated in Figure 9. The water depths and velocities during the first three hours of the extreme precipitation event in the two areas illustrated in Figure 9 are presented in Figures 10 and 12 (water depth) and Figures 11 and 13 (velocity). In both areas, the velocity and depth simulated with input from the SWMM models were identical. In the downstream area (Figure 10) it can be seen that the initial depth (04:50) is larger in the uncoupled model. Two hours after the precipitation event started (05:50), there are more areas with depths above 0.66 m (green) in the SWMM based results compared to the uncoupled model. Three hours into the event, water depths above 1 m (red) can be seen in the coupled models, whereas the largest depth in the uncoupled model was between 0.66 and 0.94 m (green). In the upstream area (Figure 12), the water is more shallow than in the downstream area for all model configurations. As for the downstream area (Figure 10), the simulated depths are higher in the coupled models compared to the uncoupled model.

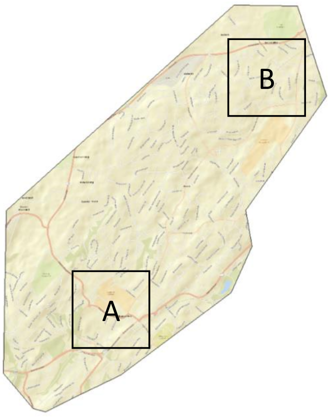


Figure 9: *The results from MIKE 21 FMHD simulations are presented for the two areas indicated by "A" and "B" within the model domain. Results from the downstream area (A) are reported in Figures 10 and 11, and the results from the upstream area (B) are reported in Figures 12 and 13.*

The velocities simulated with input from SWMM (Figures 11 and 13) are also identical. For both areas, it can be seen that the uncoupled model overestimates the velocity in the beginning of the event compared to the coupled models. It is evident that the simulated velocity in the uncoupled model is less than 0.5 m/s in both areas for all three reported time steps, and the extent of areas with velocities > 0 m/s is reduced over time. On the contrary, the velocity reaches up to 1 m/s in parts of the areas simulated with input from SWMM. In the downstream area (Figure 11) it is visible that the flooded water moves downstream in the catchment, and the extent of flooding water with velocities above 0 m/s is reduced. In the upstream part of the catchment (Figure 13), the overall speed is reduced from 05:50 to 06:50, as is the extent of flooded water with velocities above 0 m/s.

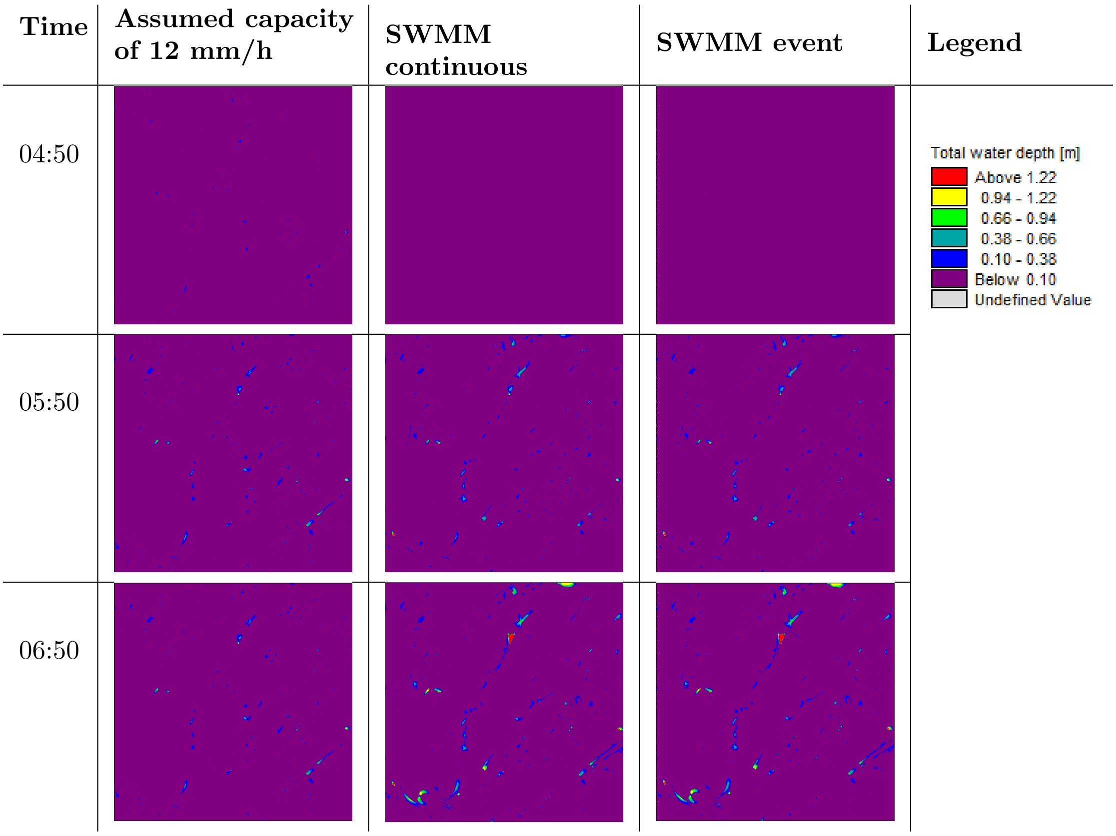


Figure 10: *Total water depth in the downstream area simulated in MIKE 21 FMHD for each of the three model configurations: Assumed capacity of the network corresponding to 12 mm/h for roofs and roads (column 2) and spatially and temporally distributed network capacity simulated with continuous simulation (column 3) and event based simulation (column 4) in SWMM. The total water depth is reported one, two and three hours after the start of the precipitation event.*

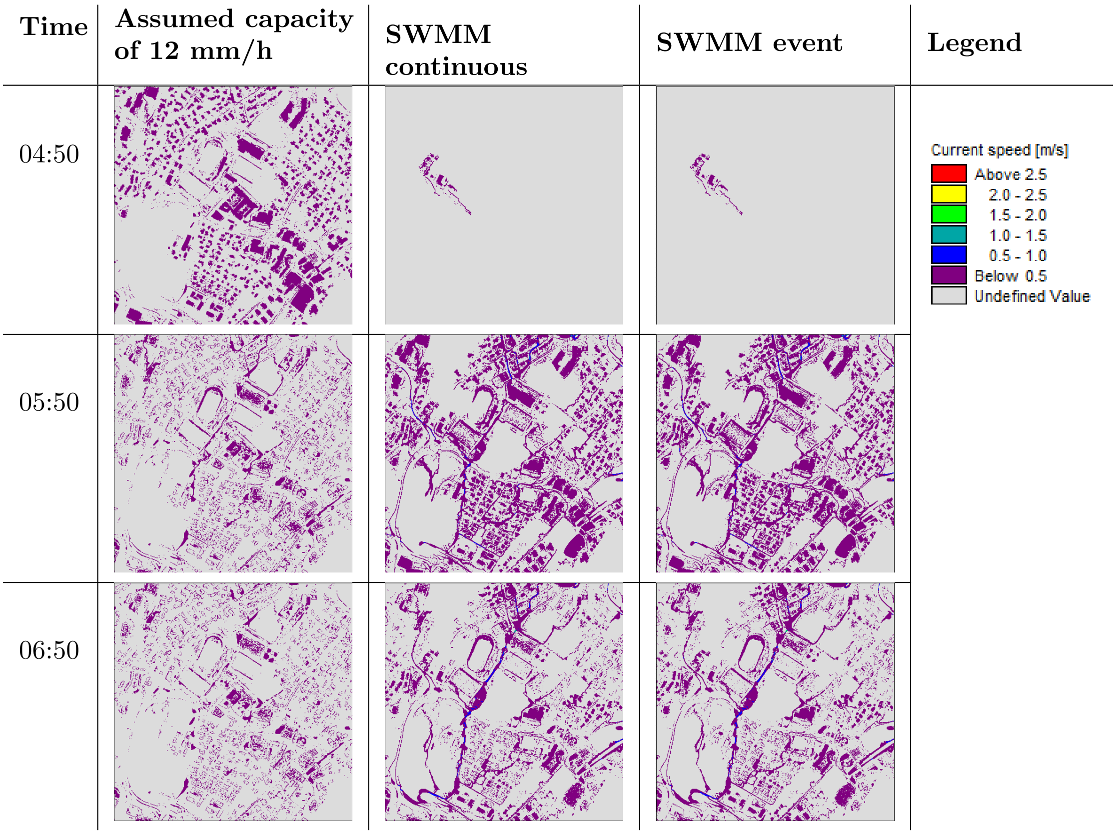


Figure 11: *Current speed in the downstream area simulated in MIKE 21 FMHD for each of the three model configurations: Assumed capacity of the network corresponding to 12 mm/h for roofs and roads (column 2) and spatially and temporally distributed network capacity simulated with continuous simulation (column 3) and event based simulation (column 4) in SWMM. The velocity is reported one, two and three hours after the start of the precipitation event.*

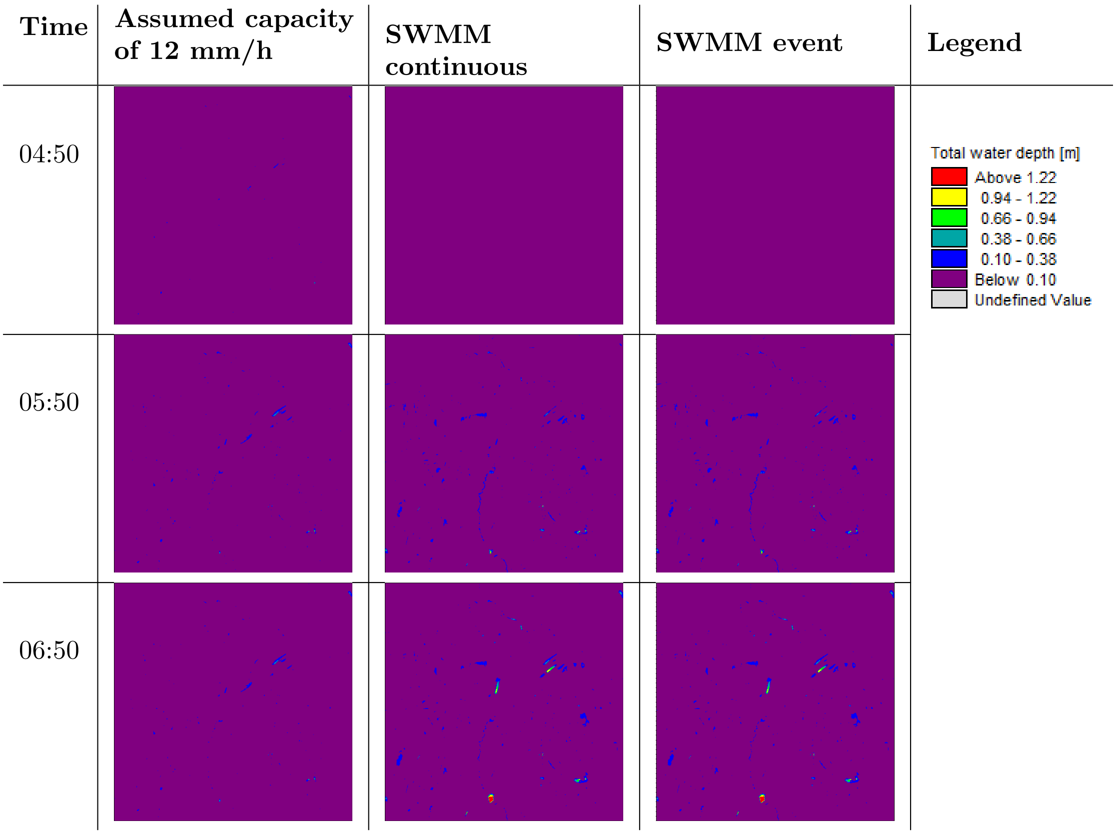


Figure 12: *Total water depth in the upstream area simulated in MIKE 21 FMHD for each of the three model configurations: Assumed capacity of the network corresponding to 12 mm/h for roofs and roads (column 2) and spatially and temporally distributed network capacity simulated with continuous simulation (column 3) and event based simulation (column 4) in SWMM. The total water depth is reported one, two and three hours after the start of the precipitation event.*

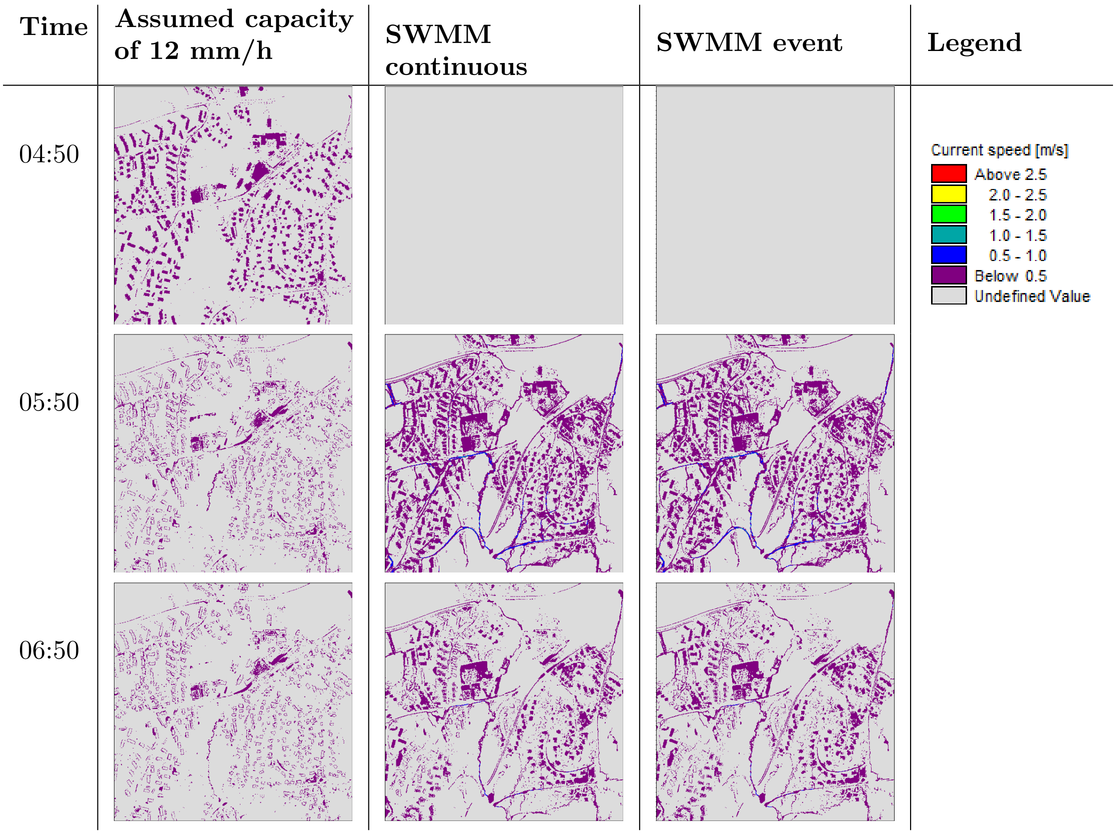


Figure 13: *Current speed in the upstream area simulated in MIKE 21 FMHD for each of the three model configurations: Assumed capacity of the network corresponding to 12 mm/h for roofs and roads (column 2) and spatially and temporally distributed network capacity simulated with continuous simulation (column 3) and event based simulation (column 4) in SWMM. The velocity is reported one, two and three hours after the start of the precipitation event.*

4 Discussion

This chapter discusses the results from the model simulations presented in chapter 3, and the possible areas of use of the framework presented in Figure 5. Then, the use of continuous simulation in stormwater management planning will be discussed, followed by a discussion of considering model uncertainty in risk assessment. Finally, topics that should be investigated further are presented.

4.1 SWMM and MIKE 21 FMHD results

The SWMM model was calibrated with the purpose of generating input representing the spatially distributed system capacity for a hydrodynamic surface flood model based on continuous simulation. Hence, the ability of simulating high flow and peaks was valued, resulting in the use of NSE as the objective function for calibrating the model. The results in Figures 7a and 7b indicate that the model with NSE = 0.64 generally overestimated the peaks, from which it can be deduced that flooding would be overestimated as well. The fact that the model with the highest NSE score was in the upper part of the flow range was not unexpected, as the calculation of NSE scores is based on the squared difference, weighing the model's ability to recreate high flows above its ability to recreate low flows (Krause et al. 2005). In Figure 7c, showing the simulated and observed flow during the extreme precipitation event in August 2016, the ability of the SWMM models to replicate the observed flow is poor. In the beginning of the event, the simulated peak occurs before the observed peak. One possible explanation is that the model underestimates the time of concentration. However, the results in Figure 7a-7b indicate that there is no temporal shift in the initial simulated flow increase compared to the observed data.

In Figure 7c, the highest peak in observed inflow at about 12:00 can be explained by the second peak in precipitation causing ponded water on the surface in upstream areas from the junction to re-enter the system alongside the latest rainfall. The models underestimate the inflow from 12:00 and througout the rest of the event. This can be caused by not allowing ponding on top of the nodes in SWMM, meaning that flooded water cannot re-enter the system. This can lead to an underestimation of flow in the drainage network. Owing to the limitations of SWMM, the model cannot simulate the characteristics of surface flooding, meaning that if ponding is allowed, the flooded water can re-enter the system only through the same junction from which it exited. The implications of this is that flooded water can be stored in upstream areas in the catchment, when in reality, the flooded water would potentially flow on the surface towards downstream areas and re-enter the system through other junctions. When using the reported flooding in SWMM to represent the system in MIKE 21 FMHD simulations of surface flooding, the option of not allowing ponding can cause an underestimation of the drainage network capacity.

A higher NSE score could have been achieved by calibrating additional parameters to those presented in Table 1, or choosing another set of parameters for calibration. Another approach that could improve the NSE score is to classify subcatchments according to their characteristics, such as the share of imperviousness, and calibrate the model with different parameter sets for each class. From the middle diagram in Figure 6, it can be seen that the pattern in the base flow was not replicated by the models. This was expected, as they were not calibrated to simulate wastewater and groundwater. To improve the model's ability to simulate high flow, the base flow could have been calibrated. If there are large variations in base flows within the catchment, this could have an impact on flooding.

The identical results from the MIKE 21 FMHD models with input from continuous and event-based simulations in SWMM (Figures 10-13) indicate that a 24-hour warm-up period prior to the start of the precipitation event was sufficient to capture the initial state of the system, in terms of infiltration capacity, evapotranspiration and system capacity. Both MIKE 21 FMHD model configurations coupled with SWMM had identical model properties, the only difference being the time period simulated. The rapid decline after simulated peak flows (Figure 6) imply that the SWMM model was not capable of simulating detention. This limitation of the SWMM model can have the implication that the necessary time period to establish initial conditions in terms of system capacity would be low regardless of the simulated precipitation event, given that the time to empty the system is shorter than the period without rain. Whether the event-based SWMM model used in this study is capable of simulating flooding caused by long periods of heavy rain cannot be assessed from the results presented in this study. However, this is a possible weakness of the model: If the time period for emptying the network after a rainfall event is underestimated, the model could overestimate the initial system capacity when conveying runoff from the next precipitation event and thereby underestimate flooding.

Comparing the results from the coupled and uncoupled approaches in MIKE 21 FMHD (Figures 10-13), it becomes apparent that the simulations ran with input from the SWMM models estimate higher depths for all time steps compared to the uncoupled approach. Representing the system capacity by the constant value of 12 mm/h, the uncoupled model fails to account for the decrease in available capacity in the network over time. On the other hand, the SWMM model used to generate input to the MIKE 21 FMHD model (NSE = 0.64) generally overestimates the inflow (Figure 7a and 7b), and it is likely that the flooding is also overestimated. The decrease in the extent of velocities higher than 0 m/s in the uncoupled model (Figures 11 and 13) may be caused by the infiltration and leakage to lower zones being higher than the precipitation rate. The accumulated precipitation during the 10-hour event was 86 mm, corresponding to 206 mm/day. The infiltration rate assigned to areas without roads and buildings was 1440 mm/day, and the leakage rate was 432 mm/day in the whole catchment. Among the three time steps reported, the highest velocity observed at 04:50 can be caused by the peak in precipitation at 8 mm/10 min, corresponding to 1153 mm/day (Figure 8). The velocities simulated by the coupled models show that the extent of velocities above 0 m/s in the downstream area decreases from 05:50 to 06:50, however the maximum reported velocity increases (Figure 11). This can be explained by the accumulation of flooded water. The velocities in the upstream area, reported in Figure 13, show that both the velocities and the extent of flooded water with velocities above 0 m/s decrease from 05:50 to 06:50. The difference between simulated velocity in the two areas can be explained by the upstream area being drained, whereas the downstream area continues to receive flooded water. In addition, it is possible that the drainage network in the upstream area restored its capacity. None of the MIKE 21 FMHD models were calibrated, and it cannot be concluded from this limited case study which approach is preferable to account for the drainage network in hydrodynamic models. An advantage to the SWMM based approach is that the system's role in redistributing stormwater is accounted for, as well as the spatially and temporally distributed capacity of the network.

4.2 Applicability of the developed framework in stormwater management planning

The framework developed to facilitate long-term assessment of performance and risk suggests utilizing continuous simulation in a semi distributed conceptual hydrological ensemble model calibrated for low or high flow as the initial step (Figure 5). SWMM is an example of a semi distributed conceptual hydrological model, and thus the discussion of the SWMM results in chapter 4.1 concerning the model's ability to identify peaks at the expense of simulating low flow demonstrate why there is a need to calibrate the models according to the assessment of low or high flow scenarios. For instance, to simulate retention of daily rain, step 1 of the three-step strategic approach, calibrating the model to replicate low flows, favoring a high accuracy of simulated water volumes, would be preferable.

The range in inflow simulated with the 10 best SWMM models (Figure 6-7) is more successful at capturing the observed flow compared to the best model. This is why the framework suggests using ensemble models instead of one model. Ensemble modelling is discussed more in-depth in chapter 4.4. Continuous simulation was incorporated into the framework to facilitate the assessment of performance and risk over time for various objectives of stormwater management. The possible advantages of continuous simulation are discussed further in chapter 4.3. The choice between surface flood models is determined based on the need to assess the dynamic processes of surface flooding or the need for accuracy in inundation maps. If there is no need, the use of a GIS-based model is recommended. Otherwise, a hydrodynamic model is recommended. GIS-models are included in the framework despite their limitations because they are far more computationally efficient than hydrodynamic models. However, the limitations of GIS-based modelling are taken into account by incorporating a methodology for identifying structural uncertainty points in the inundation map developed by Tørudstad (2020). This process for modelling surface flooding exploits the efficiency of GIS-based models and the accuracy of hydrodynamic models.

Including the drainage network, hydrological processes and flooding, the framework facilitates assessment of the combined effect of all assets in the stormwater system in managing stormwater of various precipitation characteristics. In addition, the performance of stormwater measures outside their intended use can be assessed, such as the effect of retention measures during flooding events. The possibility of monitoring the whole catchment in the context of multiple stormwater objectives can be beneficial to the PDCA principle, an important principle in integrated IAM (Alegre and Coelho 2012). Based on the knowledge gathered from monitoring the existing system, one can identify whether it is necessary to alter the integrated IAM process in order to achieve full alignment between the levels of planning (Alegre and Coelho 2012). The use of a semi distributed conceptual hydrological model and surface flood models in series enables the possibility of iteratively altering the placement and share of LID measures or alterations in network capacity while keeping track of their contribution to flood mitigation. Research by Haghighatafshar et al. (2018) suggest that LID measures can play an important role in flood mitigation. Although it cannot be concluded that either of the approaches for representing the network capacity and infiltration in MIKE 21 FMHD is more accurate based on the results in this case study, taking into account retention in LIDs in surface flood modelling can have an impact on the results. Another advantage of using a model such as SWMM to account for infiltration and system capacity is that the uncertainty of the model can be analysed. This is discussed further in chapter 4.4.

The combined results from semi distributed conceptual hydrological models and surface flood models can be used to assess risk and performance in a long-term perspective, which can assist decision-making processes in stormwater management planning. The example of iteratively changing implementation of LID measures to investigate their contribution in flood mitigation demonstrates the possibility of modelling future development. The dashed arrows in the framework (Figure 5) illustrate the process of altering the precipitation data to account for climate change and altering the models to investigate the effects of changed land use or alternative stormwater management strategies.

4.3 Use of continuous simulation in stormwater management planning

The simulated system flooding reported in Figure 8 demonstrates how continuous simulation can be used to identify flooding. Seen in context with the precipitation data and the initial state of the system, preconditions for flood events can be identified. This demonstrates how continuous simulation in a computationally efficient model such as SWMM can be used to identify unwanted events, as well as the circumstances causing the unwanted event to happen. However, the continuous simulation may not be adequate to assess the risk associated with the event. For instance, a SWMM model is unsuitable to assess the consequences of flooding, requiring information about inundation, depth and velocity. The flooding simulated by continuous simulation in SWMM is still useful, as the results can be used to determine which events to investigate further in surface flood models. This is highly relevant for assessing risk and performance when simulating alternative future scenarios to assist long-term stormwater management planning. The combined effects of changes in land use and changed precipitation patterns due to climate change can cause unexpected problems that can be identified with continuous simulations. In addition to identifying unwanted events, continuous simulations can be used to identify how often unwanted events almost occur. An almost occurrence of flooding could be that parts of the stormwater system frequently operate at maximum capacity.

The system flooding reported in Figure 8 can be used to plot a flood duration curve, giving information about the duration of flooding above a certain threshold within the simulated period. A flood duration curve can be used to assess how often flooding occurs within a catchment, and based on the acceptable frequency of flooding, actions to reduce flooding or secure controlled flooding can implemented. The same principle applies to flow duration curves. The stormwater overflow to recipient water bodies can be monitored given that overflows are included in the model. If SWMM is used to model a combined sewer system, CSOs can also be simulated. Generating a flow duration curve for overflow can be valuable to assess erosion or pollution in urban streams over time. Although SWMM cannot model streambank erosion, a flow duration curve can provide valuable information if the influence of the inflow rate on the velocity in the stream has been established. It also requires knowledge about the stream's critical erosion velocity. A quick clay slide that occurred in Gjerdrum Municipality in December 2020 caused in part by the increase in runoff due to urbanization (Ryan et al. 2021) demonstrate the importance of monitoring overflows from the stormwater network. Utilizing modelling tools is not a prerequisite for creating flow duration curves, as they can be plotted from longer time series of observed data. Continuous simulation can be used to generate longer time series if needed, or it can be used to create flow duration curves from simulated scenarios of future development.

4.4 Considering model uncertainty in risk assessment

The mismatch between the inflow simulated by the best SWMM model and the observed inflow reported in Figure 7 demonstrates why using only the best calibrated model can be unfavorable when utilizing models in decision-making processes. The range between the minimum and maximum simulated flows can be interpreted as a range of possible outcomes. The range does not represent the total range of possible outcomes and does not give any information about their probabilities. It merely represents the simulated flows based on 10 different parameter sets achieved by using one optimization algorithm to optimize one objective function by changing the values of six parameters. If the main purpose of the model was to simulate low flows, another objective function would have been more suitable for calibrating the model. That would cause the flow simulated with the highest scored model to look different from the best model calibrated with NSE, highlighting the importance of understanding how models have been created when incorporating them in decision-making processes.

Although the range between the minimum and maximum simulated flow in Figure 7 does not represent a probability space, it visualizes the uncertainty in the simulated results. If the best SWMM model created in this study was used to assess flood risk in Nadderud, it is likely that the flooding would have been overestimated, as seen in Figure 7b. This would in turn lead to an overestimation of the risk. If risk treatment was conducted based on the overestimated risk, the costs could potentially have been disproportionately large compared to the real flood event. Although the range of outcomes from the 10 SWMM models collectively manage to replicate the observed data better than the single simulation result from the best model, they show a limited range of outcomes, being calibrated on the same dataset with the same calibration method. This ensemble of models could have been more equipped to replicate the behaviour of the real system if they were calibrated with different optimization algorithms on different timeseries of observed data, optimizing various objective functions. The range of outcomes from an improved ensemble of models, each model optimized to accurately replicate peaks, low flow, high flow or base flow, could be useful to assess risk, and in turn implement actions to reduce the risk if it exceeds the acceptable risk level.

Another approach to address the model uncertainty could be to conduct an uncertainty analysis in order to find the likelihood of the simulated outcomes (Loucks et al. 2005). This could be beneficial in risk assessment, as it would allow for decision-making to be based on the probability of the modelled outcome. This is central in risk assessment, as the level of risk is defined by the combination of probability and consequences of an event. Rather than just assessing the consequences of an event, uncertainty analyses can be used to assess whether that outcome is probable. The uncertainty in the SWMM were propagated when the model was used to create input to simulate flooding in MIKE 21 FMHD. Accumulating the uncertainties in the two models mean that the uncertainty of the simulation results from MIKE 21 FMHD reported in Figures 10-13 would be greater than the uncertainty of the SWMM model alone. This does not necessarily imply that model coupling is unfavorable compared to assuming a constant capacity of the system network. However, the propagation of uncertainty should be examined to ensure that the results from the MIKE 21 FMHD model based on input from simulations in SWMM can be understood before using the simulated flooding to assess risk.

4.5 Further work

The research conducted in this study was limited to the use of two model types to simulate flooding in one study area without altering the models to simulate future development. Hence, the framework developed to facilitate long-term assessment of risk and performance should be tested for various scenarios in order to evaluate its applicability in stormwater management planning. The framework could also benefit from guiding the user in calibrating models according to the specific stormwater process in question, and in creating ensemble models suitable to capture the behaviour of the catchment.

To ensure that the inaccuracies of simulated inundation in GIS-based models owing to their inability to simulate flood dynamics are identified, the methodology developed by Tørudstad (2020) should be verified in various catchments. This could potentially contribute to further development of the method.

Based on the flood simulations in MIKE 21 FMHD, no advantages of using continuous simulation compared to using event-based simulation in SWMM to represent the drainage network and infiltration were identified. Owing to the poor ability of the SWMM models used in this study to simulate detention processes, the methodology should be investigated further in models suitable for simulating detention. Furthermore, the method should be tested on rainfall events of various characteristics. The necessary simulation period to ensure accurate initial conditions of the stormwater system prior to flood events should also be examined.

5 Conclusion

In this study, a framework was developed to facilitate long-term assessment of risk and performance in stormwater management planning. The resulting framework describes an approach that utilizes modelling tools for investigating the current situation and future scenarios in urban catchments, taking into consideration the manifold stormwater processes. To address the limitations of stormwater models and the necessity to assess risk and performance in the context of the various objectives of stormwater management, the framework consisted of three model types: semi distributed conceptual hydrological models, GIS-based models, and hydrodynamic models. Furthermore, continuous simulation in ensemble models was identified as a suitable methodology to ensure that undesirable events in future scenarios can be identified and to account for the range of possible outcomes, respectively. The events that should be modelled in surface flood models are determined based on the results from the continuous simulation. The limitations of using GIS-based models to simulate inundation was accounted for in the framework. The approach to utilize modelling tools suggest that surface flood modelling should be based on the results from the semi distributed conceptual hydrological ensemble model, taking into consideration system boundaries of the model types. This enables the possibility to track the influence of changes within the system boundaries of the semi distributed conceptual hydrological model on the flooding simulated by surface flood models. Based on the discussion of the applicability of the framework in stormwater management planning, it can be concluded that utilizing modelling tools is necessary in order to achieve a holistic stormwater management, both in terms of planning for future development and to investigate the accumulated effects of implemented stormwater measures regardless of their intended purpose. Secondly, understanding how models are created when used as basis for decision-making processes was identified to be of great importance.

This study also explored the advantages of using continuous simulation in a semi distributed conceptual hydrological model to generate input to a hydrodynamic model. A SWMM model and a MIKE 21 FMHD covering Nadderud catchment were used for this purpose. To compare the simulated flooding in MIKE 21 FMHD based on input from continuous simulation, the MIKE 21 FMHD was also run with input generated in SWMM with an event-based simulation starting 24 hours prior to the beginning of the precipitation event. No differences were observed in simulated flooding between the two approaches to generate model input to MIKE 21 FMHD. It was concluded that this could be explained by one of two reasons: 1) Including a 24-hour period prior to the precipitation event was sufficient to ensure accurate initial conditions, or 2) the poor ability of the SWMM model to simulate detention, meaning that the modelled stormwater system is emptied faster than a real system with detention measures. These approaches were compared to representing the system capacity in the MIKE 21 FMHD model by a constant value. As none of the models were calibrated, it proved challenging to compare the simulated flooding from assuming a constant capacity and using input from SWMM. Regardless, it was concluded that using a semi distributed conceptual hydrological model to create input to a hydrodynamic model has the advantages of accounting for the spatial and temporal variation in system capacity, and the drainage system's role in redistributing flooded water. Based on the results in this study, it cannot be concluded that there are advantages of using continuous simulation compared to event-based simulation in a semi distributed conceptual hydrological model to generate input to a hydrodynamic model. The methodology should be tested further to investigate whether the inability of the SWMM model used in this study to simulate detention affected the results. In addition, the possible advantages of the method when simulating flooding caused by long periods of heavy rain should be explored.

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Appendix

A Precipitation events

Event	Depth [mm]	Start	Stop	Duration [min]	Intensity [mm/min]	Stations
...	...	...	...	...	...	...
22	86.3	2016-08-06 03:52:00	2016-08-06 13:41:00	589	0.1465	sid21934 sid129251
23	5.6	2016-08-07 14:54:00	2016-08-07 17:51:00	177	0.0316	
24	13	2016-08-08 06:16:00	2016-08-08 08:45:00	149	0.0872	
25	34.2	2016-08-09 13:55:00	2016-08-10 07:41:00	1066	0.0321	
26	4.5	2016-08-12 11:37:00	2016-08-12 17:12:00	335	0.0134	sid21934 sid129251 sid20346 sid20293
27	14.4	2016-08-20 19:13:00	2016-08-21 02:50:00	457	0.0315	
28	4.7	2016-08-25 11:25:00	2016-08-25 16:29:00	304	0.0155	
29	8.3	2016-08-26 02:21:00	2016-08-26 06:50:00	269	0.0309	
30	4.1	2016-09-11 00:11:00	2016-09-11 06:18:00	367	0.0112	
31	9.8	2016-09-23 06:01:00	2016-09-23 14:38:00	517	0.0190	
32	2.8	2016-09-26 07:49:00	2016-09-26 08:22:00	33	0.0848	
33	3.1	2016-09-27 18:40:00	2016-09-27 21:35:00	175	0.0177	
34	6.1	2016-09-29 02:20:00	2016-09-29 11:39:00	559	0.0109	
35	6.1	2016-10-16 16:40:00	2016-10-17 13:27:00	1247	0.0049	
36	2.9	2016-10-20 05:37:00	2016-10-20 16:40:00	663	0.0044	
37	5.7	2016-10-24 12:41:00	2016-10-25 04:33:00	952	0.0060	
38	9.1	2016-10-31 15:01:00	2016-11-01 07:58:00	1017	0.0089	
39	2.3	2017-04-12 02:28:00	2017-04-12 04:02:00	94	0.0245	sid21934 sid129251 sid1787 sid1982 sid1938 sid1952 sid20346 sid20293'
40	16.7	2017-04-12 19:03:00	2017-04-13 19:23:00	1460	0.0114	
41	22.2	2017-04-24 03:03:00	2017-04-25 01:50:00	1367	0.0162	
42	3.2	2017-04-28 14:40:00	2017-04-28 18:31:00	231	0.0139	
43	1.1	2017-05-07 05:13:00	2017-05-07 09:33:00	260	0.0042	
44	34	2017-05-09 20:28:00	2017-05-11 08:09:00	2141	0.0159	
45	1.9	2017-05-14 06:16:00	2017-05-14 12:12:00	356	0.0053	
46	23.2	2017-05-15 20:41:00	2017-05-17 06:12:00	2011	0.0115	
...	...	...	...	...	...	...

B Simulation options in SWMM

Overview of the chosen simulation options in the SWMM model.

Tab	**Simulation option**	**Model setting**
General	Process Models	Rainfall/Runoff Flow Routing
	Routing Model	Dynamic Wave
	Infiltration Model	Green-Ampt
	Routing Options	Allow Ponding: No Minimum Conduit Slope: 0%
Dates	Antecedent Dry Days	14
Time Steps	Routing Step (seconds)	1
	Steady Flow Periods	Skip Steady Flow Periods System Flow Tolerance: 5% Lateral Flow Tolerance: 5%
Dynamic Wave	Inertial Terms	Keep
	Normal Flow Criterion	Slope & Froude
	Force Main Equation	Hazen-Williams
	Surcharge Method	Extran
	Time Step for Conduit Lengthening (sec)	0
	Minimum Nodal Surface Area (sq. meters)	1.167
	Minimum Trials per Time Step	8
	Head Convergence Tolerance (meters)	0.0015
	Number of Threads	1

C Summary of SWMM model file

The table shows a summary of parameters in the SWMM model .inp-file for subcatchments, pipes and manholes. "Unique values" means that the value of the parameter for each subcatchment/manhole/pipe varies. One value indicates that the value of the parameter has been used for all subcatchments, manholes, or pipes. "NaN" means "undefined". "Calibrated" means that the parameter is one of the calibrated parameters, an overview of which can be found in the method chapter of the thesis.

Subcatchments	
Area	unique values
%Imperv	unique values
Width	$\sqrt{area}$
%Slope	0.5
CurbLen	0
SnowPack	NaN

Subareas	
N-imperv	0.01
N-perv	0.1
S-Imperv	calibrated
S-Perv	calibrated
PctZero	25
RouteTo	Outlet
PctRouted	NaN

Junctions	
Elevation	unique values
MaxDepth	unique values
InitDepth	0
SurDepth	0
Aponded	0

Conduits	
Roughness	calibrated
InOffset	0
OutOffset	0
Initial flow	0
Maximum flow	0

D R script for SWMM model calibration

```r
library(dplyr)
library(swmmr)
library(DEoptim)
library(zoo)
library(ggplot2)
library(magrittr)
library(tibble)
library(hydroGOF)
library(rBayesianOptimization)
library(ParBayesianOptimization)

setwd("C://Users//cmberger//Documents//Model")

inp_file = file.path("SWMM_model_area.inp") # name of SWMM model file

# altering calibrated parameters and setting up the SWMM model for each
iteration
obj_fun_BO <- function(Suction1,Ksat1,IMD1,SImp,Sp,Rough1) {
   inp <- read_inp(inp_file)

  inp$infiltration <- transform(
    inp$infiltration,
    Suction=rep(Suction1,725), # storage capacity impervious areas
    Ksat=rep(Ksat1,725), # storage capacity impervious areas
    IMD=rep(IMD1,725) # storage capacity impervious areas
  )

  inp$subareas <- transform(
    inp$subareas,
    "S-Imperv" = rep(SImp, 725), # depression storage impervious areas
    "S-Perv" = rep(Sp, 725)) # depression storage pervious areas

  inp$conduits <- transform(
    inp$conduits,
    Roughness=rep(Rough1, 3519) # pipe roughness
  )

  val_m <- inp$options$Value
  val_m[12] <- start_date
  val_m[13] <- start_time
  val_m[14] <- start_date
  val_m[15] <- start_time
  val_m[16] <- end_date
  val_m[17] <- end_time
  inp$options <- transform(
    inp$options,
    Value = val_m
  )
  # write new inp file to disk
  tmp_inp <- tempfile()
  tmp_rpt_file <- tempfile()
  tmp_out_file <- tempfile()
  write_inp(inp, tmp_inp)

  swmm_files <- suppressMessages(run_swmm(tmp_inp, stdout = NULL, rpt = tmp
_rpt_file, out = tmp_out_file ))
  on.exit(file.remove(unlist(swmm_files)), add = TRUE)

  # read simulation results
  sim <- read_out(
    file = swmm_files$out,
```

```
    iType =1,
    vIndex = 4,
    object_name = "J21934" # name of junction with observed data
  )[["J21934"]]$total_inflow
  # calculate goodness-of-fit

  sim <- as.array(coredata(sim))
  if(length(Qobs_comp)-length(sim) == 0){
    nse1 <- hydroGOF::NSE(sim = as.array(sim),obs=as.matrix(Qobs_comp[1:(le
ngth(Qobs_comp))]))
  }
  if(length(Qobs_comp)-length(sim) == 1){
    nse1 <- hydroGOF::NSE(sim = as.array(sim),obs=as.matrix(Qobs_comp[1:(le
ngth(Qobs_comp)-1)]))
  }
  if(length(Qobs_comp)-length(sim) == 2){
    print('ok')
    nse1 <- hydroGOF::NSE(sim = as.array(sim),obs=as.matrix(Qobs_comp[2:(le
ngth(Qobs_comp)-1)]))
  }
  nse1 <- ifelse(is.na(nse1)==TRUE,-999,nse1)
  print(nse1)
  plot(Qobs_comp, type="l", lwd=2, ylim=c(0, max(Qobs_comp,na.rm=T)*1.3),co
l="blue",
       xlab = "Date", ylab = "Runoff (mm)", main=nse1)
  lines(sim,col="orange",lwd=2)

  list(Score = nse1, Pred = 0)

}

path <- paste0("calibration_rain.csv" )
event <- read.table(path, sep=",", header=TRUE)
precip <- event[,3]
Qobs <- event[,4]

plot(Qobs,type="l",main="Observed flow")
Qobs_comp <- ifelse(Qobs-0.01>0,Qobs-0.01,0) # subtracting 0.01 m3/s from Q
obs to remove base flow
event[,1] <- as.POSIXct(event[,1], tz="", format="%Y-%m-%d %H:%M:%S")
date1 = event[,1]

time11 <- format(event[,1] , format="%H:%M")
date11 <- format(event[,1], format = "%m/%d/%Y")

n <- length(time11)
start_date <- date11[1]
start_time <- paste(time11[1],"00",sep = ":")
end_date <- date11[n]
end_time <- paste(time11[n],"00",sep = ":")
date1<- date

P <- precip
data_swmm_RAIN <- data.frame(cbind.data.frame(date11,time11,round(P,2)))
file2 <- "input_bayopt.dat" # file name of .dat file
write.table(data_swmm_RAIN,file2,sep = " ",col.names = F,row.names = F,quot
e = F) # saving .dat file





# defining limits for calibration of parameters
search_bound <- list(Suction1 = c(1,60),
                           Ksat1 = c(1,100),
                           IMD1 = c(0, 1),
                           SImp = c(0, 10),
                           Sp = c(0, 10),
                           Rough1 = c(0.01, 0.05))

# running Bayesian Optimization with objective function = NSE, acquisition
function = Expected Improvement (EI), 100 iterations, 7 initial parameter s
ets. The function bayesOpt uses Gaussian Process as the surrogate model
bayes_RES <- bayesOpt(FUN = obj_fun_BO, bounds = search_bound,
                        initPoints = 7,iters.n = 100, acq = "ei",
```

E Calibration results

NSE score	**suction head**	**Ksat**	**IMD**	**S$_{imp}$**	**S$_p$**	**Roughness**
0.639396	45.98779	1.0	0.000000	0.0	8.357471	0.020421
0.633606	60.00000	1.0	0.000000	0.0	10.000000	0.020939
0.606619	1.00000	1.0	0.000000	0.0	5.147015	0.024671
0.601472	60.00000	1.0	0.000000	10.0	9.450638	0.019456
0.601350	1.00000	1.0	0.000000	10.0	6.596257	0.019459
0.595469	60.00000	1.0	0.000000	10.0	2.975425	0.020227
0.568845	1.00000	1.0	0.999995	0.0	0.000000	0.025502
0.533960	1.00000	1.0	0.000000	10.0	0.000000	0.027116
0.516005	60.00000	1.0	1.000000	10.0	1.763152	0.019333
0.510385	16.30855	1.0	0.000000	0.0	0.000000	0.029709

F Python scripts

In [1]:

```
import pandas as pd
import numpy as np
import datetime as datetime
outlet_path = './bayopt_new/'
subc_path = './subcatchment_data/'
precip_path = './Precip_data/'
```

In [2]:

```
# read dataframe with attribute table, including subcatchment IDs, areas, outlet
nodes and their
# assigned integer (OBJECTID_1):
subc = pd.read_csv(subc_path+'Subcatchment_id.txt', sep = ';', index_col=None, d
ecimal=',',
                    usecols=['Area', 'OBJECTID', 'CatchID', 'Outlet'])
# new column: area [m2] from existing area column [ha]
subc['Aream2'] = subc['Area']*10000
# creating a new column for catchment outlet node IDs that is identical to the n
ode IDs from SWMM
subc['Jun']='J'+subc['Outlet']
# reading the simulated flooding (10 min time steps) in all outlet nodes from th
e continuous (con)
# and 4day (ev) simulations
con = pd.read_csv(outlet_path+'SWMM_bayopt_new_outlet_all.csv', sep = ' ')
ev = pd.read_csv(outlet_path+'SWMM_bayopt_new_outlet_all_aug.csv', sep = ' ')
# reading precipitation data from 2016 with 10 min time steps
precip = pd.read_csv(precip_path+'2016_10.csv', header=None)
# reading table with 506 old column numbers between 1 and 725, and 506 new colum
n numbers from 1 to 506.
subc_col = pd.read_csv(subc_path+'arcgis_attr_table.csv',sep=';')
subc_new_col = pd.read_csv(subc_path+'new_col_nmbr.csv',sep=';')
```

In [3]:

```
# creating date columns from the precipitation dataframe for the flooding result
s
dates_con = precip[0][1:30815]
dates_ev = precip[0][18147:18737]
```

In [4]:

```python
# creating dictionary with the outlet nodes and the subcatchment IDs (integer)
pair_name = dict(zip(subc.Jun, subc.OBJECTID))
# creating dictionary with the subcatchmeent IDs and areas
pair_area = dict(zip(subc.OBJECTID, subc.Aream2))
# creating dictionary with initial subcatchment IDs (1,725) and their newassigned value (1,706)
temp_cols = dict(zip(subc_col.OBJECTID, subc_col.Col_nmbr_1))
# creating dictionary from 706 IDs to 506 IDs
reas_cols = dict(zip(subc_new_col.Value, subc_new_col.new_col_nmbr))

new_con_cms = pd.DataFrame()
new_con_mmday = pd.DataFrame()

# Creating a new dataframe with integer columns instead of outlet junction names - 1,725
for col in con:
    for jun in pair_name:
        if jun == col:
            new_con_cms[pair_name[jun]]=con[col] # each column is named a value between
            # 1 and 725 according to pair_name dictionary

# Converting from m3/s to mm/day
new_con_mmday = pd.DataFrame()
for col2 in new_con_cms: # iterate over time series columns (unit m3/s)
    for n in pair_area: # iterate over 725 subcatchment numbers and subcatchment areas
        if n == col2: # if subcatchment number = time series column
            area = pair_area[n] # find the area of the subcatchment from dictionary
            new_con_mmday[n]=new_con_cms[col2]*1000*60*60*24/area # converting from m3/s to mm/day
new_con_mmday.index=dates_con # adding datetime index
new_con_mmday = new_con_mmday.reindex(columns=list(range(1,726))) # arrange columns in ascending order

# creating a new dataframe only containing timeseries from subcatchments included in the 1x1 m resolution in the
# grid file used to generate spatially distributed data in MIKE21HD
con_mm_day_temp = pd.DataFrame()
for col3 in new_con_mmday: # iterate over dataframe with 725 columns
    for temp in temp_cols: # iterate over 706 subcatchments
        if col3 == temp_cols[temp]: # check if subcatchment is included in the new raster
            con_mm_day_temp[temp_cols[temp]]=new_con_mmday[col3]

con_mm_day_redistr = pd.DataFrame()
for col4 in con_mm_day_temp:
    for old in reas_cols:
        if col4 == reas_cols[old]: # check if the subcatchment is included in the final grid file
            con_mm_day_redistr[reas_cols[old]]=con_mm_day_temp[col4]
```

In [5]:

```
new_ev_cms = pd.DataFrame()
new_ev_mmday = pd.DataFrame()

for col in ev:
    for jun in pair_name:
        if jun == col:
            new_ev_cms[pair_name[jun]]=ev[col]

new_ev_mmday = pd.DataFrame()
for col2 in new_ev_cms:
    for n in pair_area:
        if n == col2:
            area = pair_area[n]
            new_ev_mmday[n]=new_ev_cms[col2]*1000*60*60*24/area
new_ev_mmday.index=dates_ev
new_ev_mmday = new_ev_mmday.reindex(columns=list(range(1,726)))

ev_mm_day_temp = pd.DataFrame()
for col3 in new_ev_mmday:
    for temp in temp_cols:
        if col3 == temp_cols[temp]:
            ev_mm_day_temp[temp_cols[temp]]=new_ev_mmday[col3]

ev_mm_day_redistr = pd.DataFrame()
for col4 in ev_mm_day_temp:
    for old in reas_cols:
        if col4 == reas_cols[old]:
            ev_mm_day_redistr[reas_cols[old]]=ev_mm_day_temp[col4]
```

In [6]:

```
# Creating a new column with 0 precipitation/flooding, to be assigned to the mis
sing overlap between the domains of
# the MIKE21 and SWMM models.
con_mm_day_redistr['507']=[0.0]*len(con_mm_day_redistr[4])
ev_mm_day_redistr['507']=[0.0]*len(ev_mm_day_redistr[4])
start = '2016-08-06 03:50:00'
stop = '2016-08-06 23:40:00'
# Creating time series for the precipitation event + 4 hours after it stopped ra
ining (14:40).
con_mike = con_mm_day_redistr[start:stop]
ev_mike = ev_mm_day_redistr[start:stop]
```

In [7]:

```
con_mike.to_csv(outlet_path+'con_timeseries_new.txt')
ev_mike.to_csv(outlet_path+'ev_timeseries_new.txt')
```

NTNU

Norwegian University of
Science and Technology