Master's thesis

NTNU
Norwegian University of Science and Technology

Nadja Grozdanic

A risk-based assessment on the hydraulic performance of conventional, hybrid and blue-green stormwater solutions

Evaluating the effects of NBS for flood reduction and resilience

Master's thesis in Civil- and Environmental Engineering
Supervisor: Tone Merete Muthanna
June 2023

NTNU
Norwegian University of
Science and Technology

Nadja Grozdanic

A risk-based assessment on the hydraulic performance of conventional, hybrid and blue-green stormwater solutions

Evaluating the effects of NBS for flood reduction and resilience

Master's thesis in Civil- and Environmental Engineering
Supervisor: Tone Merete Muthanna
June 2023

Norwegian University of Science and Technology

NTNU
Norwegian University of Science and Technology

ABSTRACT

The combined effects of climate change, urbanization and exceeded stormwater systems impose the risk of pluvial flooding. Over the recent years, flood management has moved from a resistance-based to a risk-based approach, which focuses on risk reduction and climate resilience. Nature-based solutions (NBS) offer an alternative approach for managing stormwater, with potentials to mitigate flood risk and facilitate resilience. In Norway, NBS are normally established within the 3-step approach (3SA) and designed with perceived worst-case events, which is inconsistent with risk-based flood management and the objective of the 3SA to build robust systems.

This study has undertaken a scenario analysis to evaluate the potential effects of nature-based step 1 and 2 solutions on managing pluvial flooding and building resilience. It has also investigated the feasibility to transition completely from grey solutions to NBS exclusively. Two climate adaptation scenarios, the hybrid and the blue-green system, have been developed in compliance with the 3SA and evaluated against the conventional system scenario, also known as the "do-nothing" scenario. The hydraulic performance was assessed with coupled 1D/2D modeling and precipitation ensembles of extreme events in past and future climate. The performance was quantified with a risk-based approach and the resilience measured by a relative delta change-factor method. The flood risk assessment demonstrated the potentials of NBS to reduce the flood risk and to be more effective than grey solutions, implying a complete transition is feasible. It illustrated that an ensemble-approach is necessary for reliable results and assessing the robustness of solutions, which strongly encourages a risk-oriented decision-making in flood management. Based on the results, the hybrid system represented the most effective and robust solution, attaining the highest risk reduction and the smallest range of ensemble-uncertainty. The relative delta change-factor failed to indicate the climate resilience of the stormwater systems, but reflected pronounced impacts of climate change and urbanization on the flood risk.

SAMMENDRAG

De kombinerte virkningene av klimaforandringer, urbanisering og utdaterte overvannsystemer medfører en økt risiko for pluvial flom. Situasjonen belyser behovet for risiko-basert flomhåndtering og klimatilpasning. Naturbaserte løsninger har blitt foreslått som effektive tiltak for å dempe flomrisikoen og fasilitere klimaresiliens. I Norge er disse vanligvis etablert i forbindelse med tretrinnsstrategien for overvannshåndtering og dimensjonert utifra konstruerte enkelthendelser, noe som er uforenelig med en risiko-basert strategi og formålene til tretrinnsstrategien om robuste systemer.

Denne oppgaven har tatt for seg en scenario-analyse for å vurdere de potensielle effektene til naturbaserte trinn 1 og 2 løsninger på flomhåndtering og klimaresiliens. Mulighetene for å kobles av ledningsnettet og håndtere overvannet utelukkende på overflaten ble også undersøkt. To ulike klimatilpasningscenarioer, det hybride og det blå-grønne systemet, har blitt utviklet i henhold til tretrinnsstrategien og blitt evaluert mot det eksisterende, konvensjonelle system scenarioet. Den hydrologiske ytelsesevnen ble vurdert gjennom koblet 1D/2D modellering og ensembler av ekstremnedbør i fortidens og fremtidens klima. Ytelsesevnen ble kvantifisert ved en risiko-basert metode og en relativ delta change-factor (CF) ble benyttet som mål på klimaresiliens. Flomrisikovurderingen demonstrerte potensiale til naturbaserte trinn 1 og 2 i flomrisikoreduksjon og at de var mer effektive tiltak enn ledningsnettet, noe som antyder at det er mulig å koble seg av ledningsnettet. Resultatene illustrerte nødvendigheten av ensembler for troverdige resultater og vurderingen av robustheten til systemene, noe som styrker anbefalingen om en risiko-orientert beslutningstaking. The hybride systemet representerte den mest effektive og robuste løsningen, da det oppnådde høyest flomrisikoreduksjon og lavest varians fra ensemble simuleringene. Den relative change-factor (CF) ble vurdert som en uegnet indikator på klimaresiliens til overvannstiltak, men illustrerte de uttalte virkningene av klimaendringer og urbanisering på flomrisiko.

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 main topic of the thesis is the increased pluvial flood risk in urban catchments and nature-based solutions as tools for climate adaptation.

I would like to express my gratitude to my Associate Professor Tone Merete Muthanna for her guidance, encouragement and advice throughout the thesis. Thank you for allowing me to study a topic I am passionate about and for sharing your invaluable knowledge and insights on it.

I would also like to thank:

- PhD Candidate Vincent Pons for sharing knowledge and climate data.
- Birgitte Johannessen at the municipality of Trondheim for her interest and providing me with all the necessary information and data about the study area.
- DHI for providing me with a student license and support with MIKE+.
- Family, friends and fellow students for support and encouragement throughout the study.

Trondheim, June 9, 2023

Nadja Grozdanic

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

List of all abbreviations:

- **CA** Climate Adaptation
- **CF** Change Factor
- **DTM** Digital Terrain Model
- **F** Future
- **IPCC** International Panel for Climate Change
- **NBS** Nature Based Solutions
- **P** Past
- **RP** Return Period
- **SWM** Storm Water Management
- **3SA** 3-step Approach

CHAPTER 1: INTRODUCTION

Climate change, urbanization and exceeded stormwater systems constitute the driving forces of increased urban, pluvial flooding. The global climate is changing, and as a consequence, precipitation events are projected to become more intense and frequent (6). In combination with the effects of urbanization, which involve expansion of impervious surfaces, stormwater runoff is almost certain to increase. Traditionally, stormwater management (SWM) systems have conveyed and detained stormwater runoff through the use of grey solutions below ground, many of which are at exceeded capacity. Upgrading existing systems to manage future climate has been deemed financially infeasible (50), whilst the estimated damage costs from not adapting to the climate in Norway are in the range 45 to 100 billion [NOK] (40). The situation entails an increased flood risk accompanied by serious socio-economic and environmental consequences, and calls for reliable and robust flood risk management.

Historically, flood management has paid less attention to pluvial flooding than fluvial (river) flooding (7). The occurrence of urban, pluvial floods can be regarded a recent phenomena. The various and complex risk sources involved in such floods; climate, urbanization and comprehensive subterranean stormwater systems, make it a challenging process to assess and predict. Nonetheless, the number of occurrences are expected to increase further in line with the projected climate changes and extreme events. This realization has inspired a shift in flood management, moving from resistance-based approaches to more holistic, risk-based approaches (59; 7). A risk-based approach considers the uncertainties associated with climate change and urbanization, facilitating robust decision-making. The shift can also be linked to the recognition that absolute flood protection in unattainable, but instead, that the main objective should be risk reduction. Furthermore, it has contributed to the focus on flood and climate resilience, a concept which communicates an acceptance level for flooding and a notion of "living with water", but also emphasizes the value of pursuing climate adaptation to reduce the consequences. However, successful climate adaptation calls for effective solutions which can facilitate climate resilience to reduce the manifold consequences of increased stormwater runoff.

Nature-based solutions (NBS) have been proposed as an alternative approach for managing stormwater and increasing the resilience of the SWM system as a whole. NBS which specifically address stormwater management aim at restoring and replicating the natural hydrological cycle - a concept familiar from other well-established terms, such as BGI (Blue-Green Infrastructure), LID (Low Impact Development) and SUDS (Sustainable Urban Drainage Systems) (16). Studies have found that grey solutions might require adaptation for future climate (1) and the performance of these solutions to be effective under projected future precipitation events(3), indicating they are more resilient to climate change (33). Other studies have found that stormwater runoff is most sensitive to imperviousness than the increase in precipitation (48), suggesting NBS can increase the urban resilience and reduce runoff by introducing infiltration and retention. They can also be implemented to retrofit and aid existing SWM systems.

In Norway, NBS are mainly established in the context of the 3-step approach (3SA) for climate adaptive SWM, a strategy commonly adopted by water utilities and stakeholders. The 3SA suggests to manage daily precipitation events through infiltration, large precipitation events through infiltration and detention, and extreme precipitation events by safe floodways. Solutions are usually designed based on perceived worst-case events, which is arguably not consistent with the 3SA, as it does not entail the robustness nor resilience of the system solution (47). Recent studies argue that an ensemble approach should be followed instead to gain holistic and reliable predictions of system performance in operational and failure mode (29; 47).

Reliable predictions of flood risk, commonly considered as the combination of hazard exposure and probability, are key components in flood risk management (30). Assessment of flood risk builds upon on the numerical modeling of free surface flows, to quantify flood hazard parameters such as depths and velocities. Urban flooding is particularly complex to analyze and requires a detailed representation of both the surface, including buildings and infrastructure, as well as the network system. This has led to the development of dual-drainage models, which couple hydrodynamic 1D network models with 2D overland flow models, to better represent their interaction. However, the accuracy is challenging to model and validate. Especially the interaction between the surface and the network requires comprehensive data about the network and inlets, which is often lacking (4). The water modeling platform MIKE+, developed by DHI, offers a coupling of 1D network models to 2D surface models for running hydrodynamic simulations, and has been utilized in this study for flood risk analysis.

Applying computational models for performing scenario simulations represents a useful method for analysing and assessing the potential effects and impacts from different climate conditions, land use plans and management strategies (35). Thus, integrating scenario analysis in the flood risk management process may provide more robust decision-making. Yet, few flood assessments combine current and future scenarios to identify the need and effect of climate adaptation (19).

1.1 Research Questions and Objectives

The StopUP project (EU financed) includes a study of the potentials for retrofitting combined sewer systems with NBS in the study area Lademoen city district, in the municipality of Trondheim. This study has evaluated the hydraulic performance in flood risk reduction of two distinct climate adaptation scenarios, namely the hybrid and the blue-green system, against the conventional system scenario, also known as the "do-nothing" scenario. The conventional system comprised the existing combined sewer system, the hybrid combined nature-based step 1 and 2 solutions with the existing system and the blue-green managed all stormwater on the surface with a full scale implementation of the 3SA. The overall aim of the thesis was to demonstrate the potential effects of NBS in compliance with the 3SA on flood risk reduction, but also clarify the magnitude of the effects across a range of extreme events. The thesis specifically attends to answer three main research questions:

1. *Can nature-based step 1 and 2 solutions reduce pluvial flood risk under extreme events?*
2. *Is it feasible to transition from the conventional system to a complete blue-green solution system?*
3. *Which of the three solutions is most climate-resilient?*

To support the overall aim and efforts to answer the prepared research questions, the following objectives have been defined: 1) Explore the flooding / inundation extent using a 1D hydrodynamic systems model coupled with a 2D surface model, 2) Compare the three different systems solutions using a risk-based approach, where the risk assessment criteria will be developed as a part of the project and 3) Provide a possible retrofit solution to the existing system in complexity versus a hybrid or full blue-green system solution, evaluated based on feasibility using the selected criteria.

CHAPTER 2: BACKGROUND

This chapter represents the background of the thesis and provides elaborations of theory and research on the topics and concepts covered by the study. The contents included are selected to support the development of the method, the necessary assumptions and decisions made in the process.

2.1 Climate Change

The Intergovernmental Panel on Climate Change (IPCC) has constituted that the global climate is changing and that it has already altered and intensified the hydrological cycle (6). Their latest report warns that the evolution is accelerating and will amplify the ongoing impacts, in addition to create new ones. Precipitation patterns are becoming increasingly unfamiliar and unpredictable, in particular the occurrence of extreme precipitation events. Characterized by high intensities and short durations, they introduce challenges for SWM and impose a risk of pluvial flooding.

2.1.1 Climate Models

Different climate conditions are expected in the future than the current, but a great uncertainty is related to the specific estimates. IPCC introduces four different scenarios, called Representative Concentration Scenarios (RCP), which reflect a range of possible GHG (Green House Gas) atmospheric concentrations; RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The latter represents the worst case scenario, hence the highest emission scenario, and is the only considered in this study. The RCP scenarios form the basis of climate modelling conducted in the IPCC fifth assessment report from 2014. Global Climate Models (GCM) represent the primary source of future climates outputs, referred to as climate projections, and allow climate change to be accounted for when planning and designing the urban environment, including stormwater systems. However, GCM have a limited ability to project local climate at temporal and spatial scale. In regards to this limitation, downscaling climate data to a desired level has been a topic of interest for climate research, particularly for hydrological modeling (29; 2).

The recommendation in Norway is to account for future climate change by applying climate factors in the range 1,3 – 1,5, depending on the duration and frequency of the precipitation event to be considered. These climate factors are based on downscaled versions of six EURO-CORDEX climate projections (spatial scale for Europe), for scenario RCP8.5 (13). Downscaled values for short-term precipitation events are especially uncertain and there is ongoing work to establish a better foundation of projected events with higher intensities (20). This highlights the value of performing analysis across the climate projections. The recommended climate factors have been revised in the doctoral thesis work of Kristvik, and although the study suggested that a factor of 1,4 was sufficient for most precipitation events in the city of Bergen, it showed a greater uncertainty related to higher return periods (29).

2.1.2 Extreme Events and Cloudbursts

Extreme precipitation events, also increasingly referred to as cloudbursts (41), impose the greatest pluvial flood risk. Even as SWM has become more complex, cities still remain vulnerable to these events which can cause flash flooding (50). The impacts from pluvial flooding (flood induced by precipitation) have social, economic and environmental consequences, especially in urbanized areas where assets and values are concentrated. To reduce the manifold consequences, there is a need to build climate resilient communities, which relies on robust SWM.

The design of stormwater system solutions has historically been based on perceived worst-case events, commonly reproduced from IDF (Intensity-Duration-Frequency) curves. IDF (Intensity-Duration-Frequency) curve is a mathematical function which relates the intensity to the frequency of extreme precipitation events, commonly applied in climatology and hydrology. It provides a graphical representation of the probability, usually in terms of return periods (RP), that a precipitation event with a given intensity will occur. A RP, also known as recurrence interval, is the average time between the occurrence of precipitation events of a certain size, quantified by intensity and duration. A RP often represents the design criteria for SWM solutions. When evaluating and designing the performance of a solution, the temporal distribution of the precipitation is necessary, which is represented graphically by hyetographs. Stormwater solutions often rely on design hyetographs, which are either based on predefined shapes (Chicago, Alternate-Block etc.), or historical events. However, this event-based design approach does not study the system under failure mode, and thus does not study the robustness nor the resilience (47). In a study which revises the design of green infrastructure, Pons et al. propose an innovative framework which suggests to use an intensive sampling of local extreme events to estimate reliability and robustness of solutions, corresponding to steps 2 and 3 in the 3SA. The full range of possible responses should be covered by applying an ensemble of sampled events for studying system performance, inclusive the most conservative, which provides insight on the robustness.

2.2 Storm Water Management in Norway

Storm Water Management (SWM) are efforts and practices with the objective to manage stormwater quantity and quality, and it is increasingly recognized as a challenge to adapt to future climate and land use. Traditionally, stormwater has been managed by conveying and diverting stormwater runoff through grey solutions below ground, such as pipes and basins, which mainly make up the urban drainage system. Most of these systems are combined sewers with overflows that are activated when the amount of stormwater entering the system exceeds its capacity, finally resulting in surface flooding. Most existing SWM systems were not designed to account for the changes in climate and land use that communities are experiencing to date. The increase in precipitation intensity has already introduced difficulties within SWM, especially in urbanized areas where the fraction of impervious surfaces is increasing simultaneously (39). A report prepared by RIF concludes that the existing urban drainage system does not have sufficient capacity, nor the conditions, to manage the projected amounts of stormwater induced by climate change and urbanization (49). Updating existing systems has been deemed economically infeasible, whilst the the estimated costs of not adapting to the future climate are in a range between 45 to 100 billion NOK (40).

As a response, the three-step approach (3SA) as proposed by Lindholm (2008), has been commonly adopted by the water utilities in Norway for climate adaptive SWM. The approach proposes to manage stormwater runoff by following three different steps, which aim at coping with precipitation events of different magnitudes. Step 1 aims to manage small precipitation events, often considered as daily rain events, through infiltration. Treatment of polluted stormwater also plays an essential part of this step. Step 2 targets to manage larger precipitation events, mainly through delaying and detaining the surface runoff, preferably accompanied by the contribution of infiltration from step 1. Step 3 aims to convey stormwater through safe floodways during extreme precipitation events, which are activated when the rest of the system fails at managing. In the later years, an additional step, referred to as step 0, has been added to address the planning phase. (32)

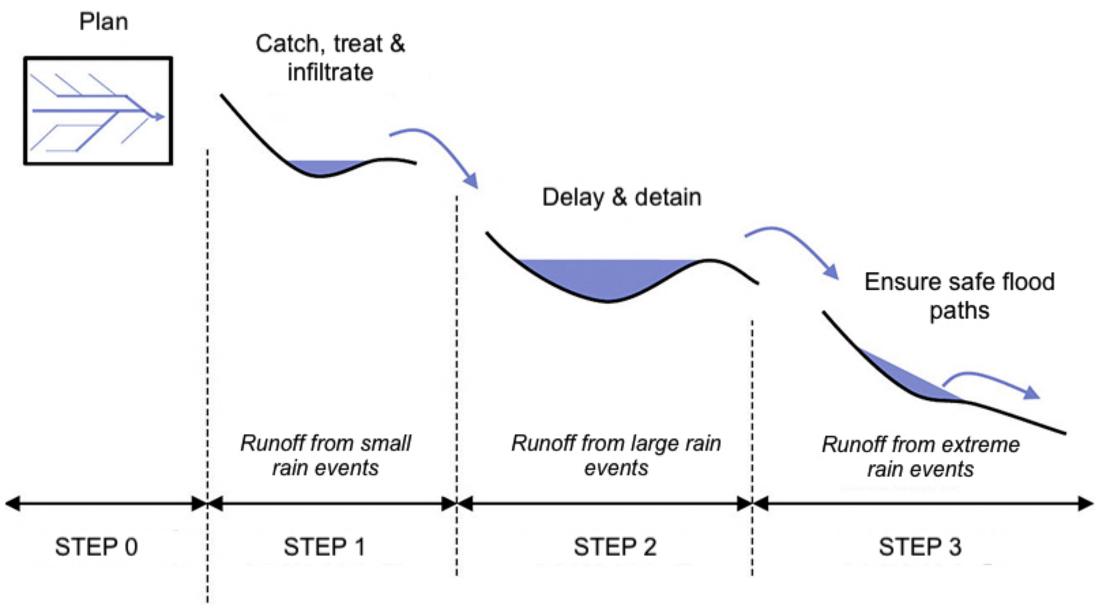


Figure 2.1: Illustration of the three-step approach for storm water management in Norway (32). Modified according to Paus (2018).

Although each step is related to a precipitation event of a certain size, there are yet no common recommendations for which RP to apply when designing solutions intended for the different steps. The recommendations vary locally and for the municipality of Trondheim they are as follows: 95 % of the yearly rain for step 1, RP = 20 years for step 2, and RP = 100 years for step 3 (28).

2.3 Climate Resilience and Adaptation Measures

Climate resilience has been formally defined by IPCC as «the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation» . The term is often used in the context of cloudbursts and climate change, where it has been interpreted that **a city resilient to cloudbursts would experience minimal disruptions when they occur and would be able to rapidly recover from any impacts they experience** (2). This interpretation will be used in this study. The process of building climate resilient cities involves climate adaptation (CA), defined as «the process of adjustment to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities» (IPCC, 2022).

2.3.1 Nature-based Solutions

A recent trend in climate resilience and adaptation strategies is the implementation of nature-based solutions (NBS), which are defined as "Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions." by the EU commission (10). It is commonly interpreted as a holistic and multi-disciplinary approach towards sustainable development, which fosters synergies (42). The wide definition makes it challenging to draw connections to existing concepts, because they are often intertwined. NBS that specifically address SWM aim at restoring and replicating the natural hydrological cycle, or the pre-development conditions, which is an approach recognized from other well-known concepts, such as Blue-Green Infrastructure (BGI), Low Impact Development (LID) and Sustainable Urban Drainage Systems (SUDS). These types of solutions have taken on a range of terms across countries and coverage, and have been used interchangeably (16). Studies suggest that effects may be more eminent at bigger precipitation events, as projected in future climate, thus indicating they are more climate resilient (33; 23; 42). NBS can also be combined with conventional solutions, referred to as hybrid solutions. At exceeding design capacity, the bypass flow is either directed to the urban drainage system through underdrains, or finds its way through inlets at the surface. This approach can reduce flooding by alleviating the pressure of the drainage system, in addition to increasing the infiltration and retention capacity. Studies have shown that hybrid solutions can provide more effective results (51; 23). NBS are space-consuming compared to conventional solutions, and the attained benefits are governed by the design and extent of deployment. Available and suitable space for implementation is a scarce source in urban areas, but studies suggest that at least 5% of impervious area should be converted into NBS-measures for noticeable effects (43).

Bioretention Cells

This study has investigated the implementation bioretention cells as nature-based step 1 and 2 solutions. Bioretention cells are a type of NBS, interchangeably referred to as raingardens. They are constructed as shallow, landscaped depressions where surface runoff is retained and infiltrated through the soil layer. As they can be integrated with different shapes, dimensions and vegetation, they are regarded a flexible tool. In general, these measures are designed to manage frequent, low-intensity precipitation events through infiltration, whereas an underdrain can be connected to the urban drainage system to direct water at larger events. (60)

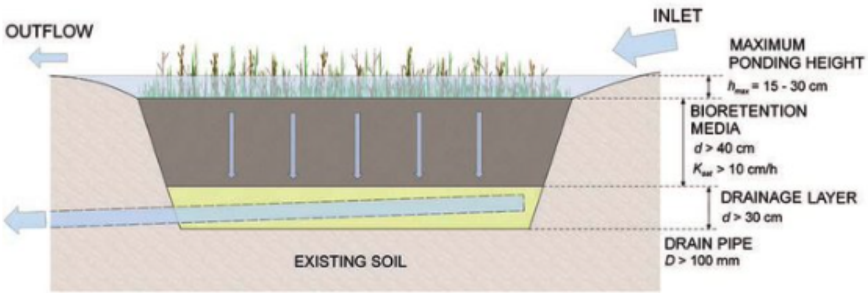


Figure 2.2: Principles of Bioretention Cell design. (45)

Bioretention cells are suitable for most catchments and will provide benefits at most scales, however the benefits can be optimized by considering parameters of the different properties. Infiltration properties of native soils, slopes and site selection can enhance the efficiency substantially and should be considered when selecting site area and design. Slope recommendations suggest $< 5\%$, according to a range of manuals (60; 22; 25). Infiltration rates of the site-specific soils should be assessed to determine whether water can infiltrate further to the ground or if it must be bypassed through an underdrain connected to the urban drainage system. In regions with cold climate, the infiltration in the bioretention media should be at minimum 100 mm/h to avoid low temperatures from constraining the infiltration capacity as a result from changes in water density and viscosity (45). Urban ground is characterized by heterogeneous infiltration properties as a result of compaction and erosion of native soils, degradation caused by organic matter and varying proportions of filling masses. Optimally, field measurements should be taken to detect the potentially heterogeneous infiltration properties (38).

2.3.2 Floodways

Floodways are measures for conveyance of stormwater that are put into action when all other parts of the SWM system are failing at managing. The application of urban streets as temporary floodways under these circumstances is a relatively new concept, and therefore, few existing guidelines are available with specific recommendations for design and site selection. Floodways have been defined by NVE (The Norwegian Water Resource and Energy Directive) as planned water courses for safe conveyance of stormwater to the recipients. Currently, their only functional criteria is to transport water safely. The recommendations suggest they should be open and that their alignment coincides with natural drainage patterns in the watershed. (46)

However, the distinction between natural flood paths and safe floodways can be unclear and

site-specific. A study by Skrede et al. proposes to distinct between flood paths and safe floodways as SWM assets, given the criteria for the latter to 1) transport stormwater to recipient and 2) under safe conditions. The second criteria requires a definition or a quantitative criteria to be interpreted properly. (57)
There is a broad agreement that the hazards which arise from urban floods can be attributed to the hydrodynamic properties depth and velocity. The high proportion of impervious area and low surface roughness in urban catchments favours both higher flood depths and velocities. A study conducted by Russo et al. proposes three different hazard levels for people in terms of velocity of urban floods and represent a possible quantitative criteria for floodways, as provided in table 2.1.

Hazard Level	**Velocity [m/s]**
High	$v \geq 1{,}88$
Moderate	$1{,}5 \leq 1{,}88$
Low	$v < 1{,}5$

Table 2.1: Hazard levels at different flow conditions for flow depths between 9 and 16 cm(53).

NVE does not provide any quantitative requirements for the velocity nor depth of flow in the safe floodways, but refers to studies done by Cox on the product of velocity and depth, vd, for different assets. The three introduces criteria may not occur at the same time due to the nature of flow which is mainly determined by slope and roughness (57). Awareness to both depth and velocity is therefore required to ensure *safe* floodways, and may require an alteration to the street alignments to attain recommended values for safety.

2.4 Flood Risk Management

The demand for flood risk management in urban areas is rising as a result from increased occurrence of urban flooding (7). Flood risk is commonly interpreted as the combination of the probability, hazard and exposure of an event (30). Hazard is normally measured by the hydrodynamic properties, velocity and depths (11), recalled from 2.3.2. Probability of a flood event is often described by the concept of RP (41). This definition can be misleading as a measure of probability, and instead, the inverse of a RP describes the probability of an event occurring at any given time more accurately.

Urban floods are especially associated with a manifold of consequences owing to the dense collection of valuable assets. The consequences from a flood event are induced by hazard exposure to the assets, which often represents the risk indicator. The risk, or hazard, indicator is evaluated against a criterion or levels of criteria. Different values have been proposed for the different hazard indicators, among them; 10 cm flood depth as a hazard level by the Copenhagen Cloudburst Plan (41) and the hazard levels for velocity presented in table 2.1. In Norway, the building acts and regulations, TEK17, provides the requirements and criteria to safeguard buildings (17). TEK17 states that buildings shall be placed, designed or safeguarded against flood such that they do not exceed the nominal probability of the RP, where the RP depends on the level of security the building classifies to. The three levels of security classes; 1, 2 and 3, are assigned a RP of 20, 200 and 1000, respectively.

Traditionally, flood risk management has aimed at absolute flood protection, which is now recognized as unattainable. This recognition has motivated a shift towards a more holistic, risk-based approach which aims at reducing the overall flood risk (59). The focus on climate resilience and an acceptance level for flooding has also encouraged this transition. It also highlights the importance of reducing the flood risk and the potential consequences (7). A risk-based approach also accounts for the uncertainties related to climate and land use changes, as oppose to a prediction-based approach, facilitating more robust decision-making (29).

The risk management process (illustrated in figure 2.3) at its core involves a flood risk assessment, which is the overall process of risk identification, risk analysis and risk evaluation (24). A risk-based approach for flood management was institutionalized by the European Flood Directive to *reduce and manage the risks posed by floods to human health, the environment, infrastructure and property*. A basic framework for flood risk management has been prepared, which requires member states to prepare a preliminary flood-risk assessment, a flood mapping and a final flood risk management plan (14).

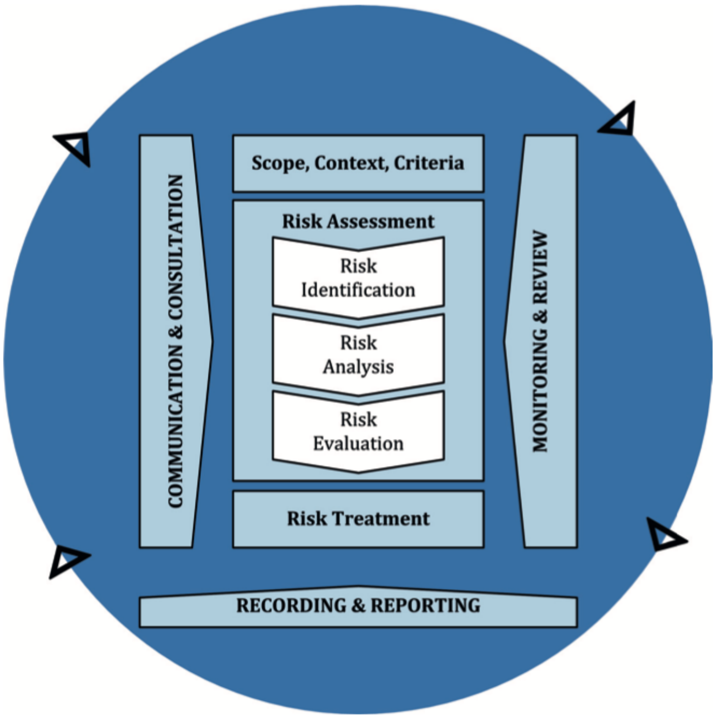


Figure 2.3: The Flood Risk Management process as proposed by ISO 31000(24).

Few flood assessments combine current and future scenarios to identify the need for and effect of CA (19). This study has undertaken a scenario analysis to assess the potential impacts on the flood risk under different CA scenarios, as well as under past climate and future climate projections. It was integrated with a flood risk assessment that comprised a risk identification (flood mapping) and risk analysis, synthesizing the different components of the risk management process and the framework for flood risk management. The flood risk assessment is described in greater detail in section 3.5. It has incorporated a quantitative assessment, which focuses on quantifying magnitude and probability of the flood risk, and a comparative assessment, which focuses on ranking and comparing the scenario risks (21).

2.5 Urban Flood Modelling

Flood risk assessment of urban areas relies on numerical modelling of free surface flows for computing the hydrodynamic parameters and mapping the extent. A hydrological model is an approximation of the hydrological system and has the objective to replicate its internal states and outputs, commonly characterized by their ability to account for spatial variation and time variability (8). Water flow is a complex process described by comprehensive mathematical equations. The Shallow Water Equations (SWE) are a set of differential equations which have been widely used to describe open-channel flows in rivers, coastal regions as well as urban areas (5; 31), and constitute the governing equations behind many numerical models. Commonly used models for urban flooding include 1D hydrodynamic models of the urban drainage systems network, 2D surface models of the terrain domain and dual-drainage models which couple the aforementioned to simulate their interaction. DHI (The Danish Hydaulic Institue) offers a 1D urban drainage module (MOUSE), a 2D flood module (MIKE 21 FM) and an integrated coupling of them within the MIKE+ water modelling platform, which has been utilized for this study. The modules offer a wide selection of methods and setups to be applied in the modelling of water flow and different sub-processes. The next sections will provide information restricted to the those applied in the study, based on DHIs documentation index and references manuals (12).

2.5.1 1D Drainage System Model

The urban drainage system is traditionally designed to convey water under a free-surface flow regime, but may tradition to pressurised flow under circumstances with heavy precipitation and flooding. Free surface flow is described mathematically by the 1D shallow water equations (SWE), also called the Saint-Venant equations, based on the conservation of mass and momentum. Calculations are carried out with a numerical solution of the SWE, and when flow transitions to a pressurized flow regime, a fictitious top slot is introduced in order for the SWE to remain valid.

2.5.2 2D Surface Flood Model

Surface flooding in urban areas is characterized by high volumes and high velocities, owing to the reduced infiltration and resistance of paved surfaces, in addition to complex flow paths around buildings and infrastructure. Accurate 2D flood modelling requires fine, spatially varying data about topography and land use to describe urban flow. In MIKE 21, the surface flow is described by the full 2D SWE, also known as the 2D depth-averaged shallow-water equations, which have shown to represent urban inundation efficiently in extensive validations (7). Manning roughness is the only empirical parameter required to be determined by the user.

A first-order explicit Euler scheme is applied for the time integration and space discretization is calculated using a finite volume method, in a triangular computational mesh. The resolution of the grid is decisive for the accuracy of the model, but also incures the computational expense.

The effect of infiltration is accounted for by a constant infiltration with capacity. It describes the infiltration process from the free surface to the unsaturated zone and to the saturated zone following the assumptions that 1) the unsaturated zone constitutes the infiltration zone with a constant porosity across the full depth of the zone, 2) a constant flow rate between the free surface and the infiltration zone, and 3) a constant leakage rate between the infiltration zone and unsaturated zone. The effects of buildings are accounted for by a topographical correction within the defined zones (polygons) of buildings. A special numerical treatment is applied to calculate the flux across faces on the borders.

2.5.3 Coupling 1D Network and 2D Surface models

Urban drainage systems can provide a significant effect on the flood volumes and distribution, when collecting runoff through and diverting discharge through flooded manholes. Therefore it may be necessary to include the urban drainage system when modelling pluvial flooding in urban areas. This has led to the development of dual-drainage-models (5). A dual-drainage model couples a 2D hydrodynamic overland flow model with a 1D network model utilising weir or orifice equations, which makes it possible to describe the interaction and flow exchange between the urban drainage system and terrain (52). However, the complexity of this interaction is challenging to model and validate, and there is often a lack of validation data and available guidance on the coefficients. This introduces a significant source of uncertainty (52). MIKE+ solves this coupling through so-called urban links. An urban link connects a node structure to the the surface domain, enabling the exchange of water flow. When the urban drainage system exceeds its capacity and the water level of a node reaches the ground level of the surface model, surcharge occurs and water flows from the node to the surface. Whereas when there is available capacity in the urban drainage system and the node level is below the surface ground level, water flows from the surface and enters node.

CHAPTER 3: METHOD AND MATERIALS

This chapter describes the data, tools and framework which have been used in the work of the thesis. The method was developed to assess the necessary flood risk indicators for evaluating the flood risk and climate resilience of three different scenarios. The method consists of four independent parts: 1) data collection, 2) development of CA scenarios, 3) hydraulic modeling and simulations, and finally a 4) flood risk assessment.

3.1 Site Description

The study area is located in Trondheim, a city in the center of Norway. It is situated by the south shore of the Trondheim fiord, where the river Nidelven enters and which serves as the water recipient. The climate classifies as subpolar oceanic climate, according to the Koppen-Geiger classification(26). Trondheim has an annual precipitation of 1050 mm, of which 100 mm falls as snow. Most of the precipitation events occur at lower intensities. However, the precipitation is expected to increase, especially in frequency and intensity (20).

The specific project area that has been examined lies in the city district Lademoen, which has been selected as a focus district by the municipality. This includes investments to the urban drainage infrastructure, among others. Today, a network of old combined sewer systems manages the wastewater and stormwater within the urban catchment. Over the coming years, the municipality plans to retrofit the system with the use of NBS, specifically bioretention cells (15). As a part of the EU financed StopUp project, modelling will be carried out to investigate the potential benefits of such a system.

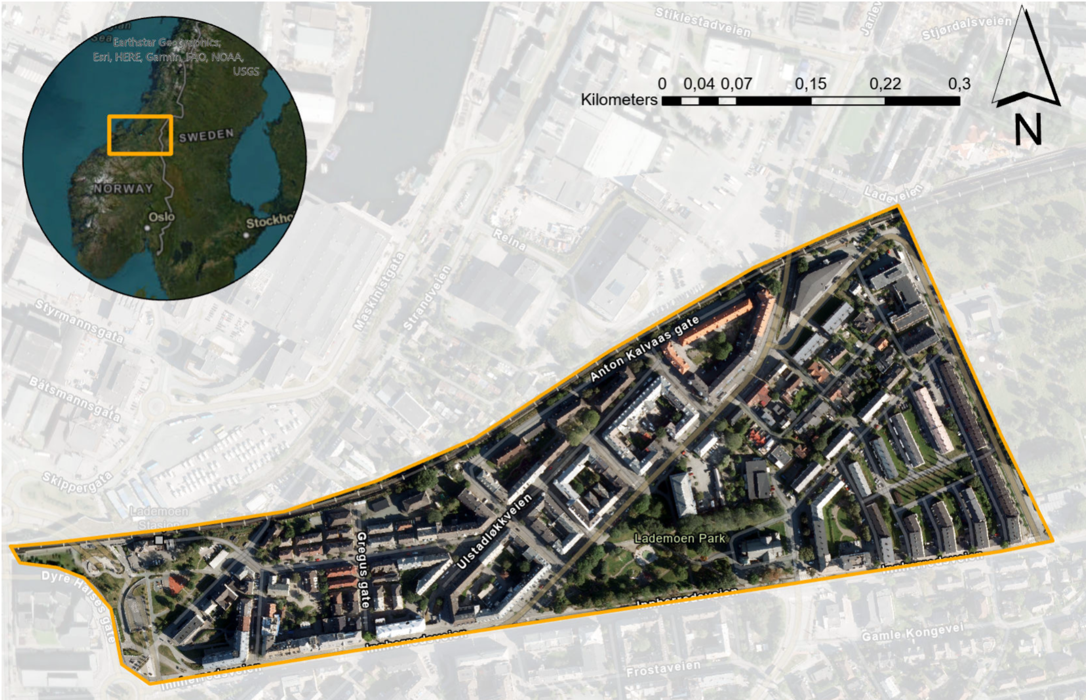


Figure 3.1: The site area of the study is outlined in orange. It is limited by Innherredsveien in the south, Lademoen cementary in the east and the rail line in the north.

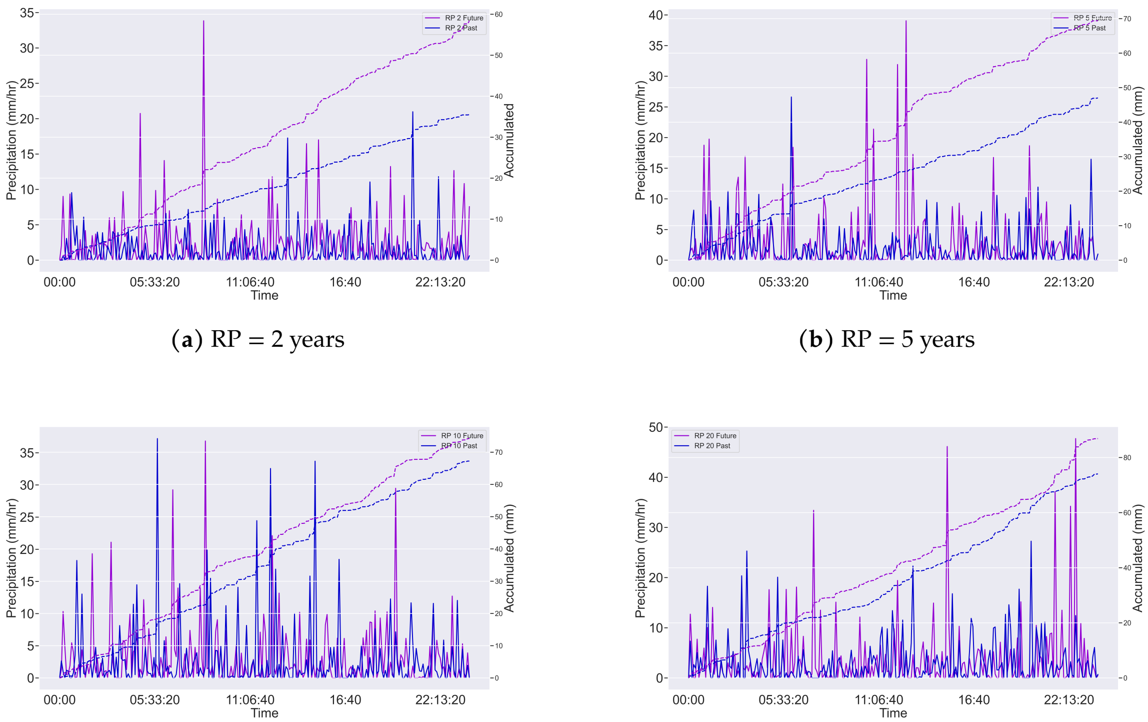
The site is semi-urbanized and covers 21 ha., where approximately 80% is impervious under current conditions. It is dominated by older residential and public buildings, of which most classify under the first first security level according to TEK17. The remaining surface consists of public and green space, yet most of is has been exposed to degradation and compaction. The ground is dominated by construction masses and the infiltration rate remains unclassified according to soil maps from NGU (Geological Survey of Norway). Through dialog with the municipality of Trondheim, it was informed that the native soils mainly consist of clay and that the infiltration is negligible. The area is relatively flat, lying on elevations ranging from 19 m to 2 m above sea level, with an average slope of 1,7%.

3.2 Data

A selection of data was collected and used for analysis and simulations. The source and applications of the data are described below.

3.2.1 Climate data

The collected precipitation data comprised an intensive sampling of local extreme events and was collected to estimate reliability and robustness of the system solutions, as an alternative to single design-events, recalled from section 2.1.2. Ensembles of temporally downscaled time-series of precipitation data was prepared and made available by PhD Candidate Vincent Pons. Prior to collecting, the data had been downscaled with a climate-change-robust model, calibrated for Trondheim, to generate random extreme events from IDF curves for different RP. A climate factor of 1.4 was applied to account for climate change and generate future events. The precipitation depth corresponding to a 24-hour event was downscaled to a 6-minute time resolution, to represent the high temporal variability of urban hydrology (34). An ensemble of 100 extreme events was collected for each of the following RP: 2, 5, 10 and 20 years, for both past and future climate.



(**a**) RP = 2 years

(**b**) RP = 5 years

(**c**) RP = 10 years

(**d**) RP = 20 years

Figure 3.2: Past (P) events are marked with blue and future (F) events are marked in purple. The data can be found available through the study *Revising green roof design methods with downscaling model of rainfall time series* (47).

The presented precipitation data was selected arbitrary among the 100 events from each ensemble and used as input data for simulations, because full ensembles were infeasible given the computational expense. The range of RP was selected to cover the design criteria set by the municipality, which is daily rain for step 1 solutions and RP = 20 year for step 2 solutions. RP = 2 year was the closest approximation to daily rain and was applied in place of long-term continuous simulations, which were omitted due to the high computational expense as well. Following the results obtained from the presented data, an ensemble limited to three events for RP_F = 10 years was applied. The ensemble included the initial event and two additional, which were selected deliberately as events with the minimum and maximum accumulated precipitation depth, in attempt to better cover the range of ensemble-uncertainty. To evaluate the safety of floodways in accordance to the design criteria set by the municipality, a time series for RP_F = 100 year event was also collected. Moreover, precipitation data was the only climate data directly applied as input, since precipitation is arguably recognized as the main driver of pluvial flooding. Based on this recognition, it was also used as an approximation of climate change effects on SWM (48) and as a climate indice. Evaporation was neglected, because significant effects normally appear over a longer period and not during extreme events (55).

3.2.2 Spatial Data

Physical properties of the urban catchment, in particular topography and land use type, provide significant implications on how stormwater runoff and pluvial flooding unfolds. The described data was used for both GIS-based analysis and in the modelling environment.

A Digitial Terrain Model (DTM) was retrieved from `https://hoydedata.no/LaserInnsyn/` and used to perform slope and hydrological analysis of the catchment with GIS software, ArcGIS Pro. The calculated slope was applied in the site selection for NBS and the identified drainage lines were used to support the selection of appropriate street segments to function as temporary safe floodways.

Publicly available land use data (FKB4) on vector format was retrieved from `GeoNorge.no`. It contained spatial information about buildings and roads in the area, which together constituted the developed area. A map of undeveloped area was prepared with ArcGIS Pro, to cover all void spaces inbetween the developed area. An additional buffer zone of 2 meters (in accordance to The Norwegian Public Roads Administration guidelines) was added around the roads to compensate for lacking spatial data about sidewalks, and thus reduce the overestimation of undeveloped area. This map was required by the adopted site detection method for NBS, described in section 3.3.1), and prepared as it was not publicly available.

3.3 The Climate Adaption Scenarios

Two CA scenarios, the hybrid system and the blue-green system, were developed in compliance with the 3SA and evaluated against the current, conventional system scenario. They are described as follows:

1. *Conventional*: The conventional system scenario, also considered as the "do-nothing" scenario, consists of the existing urban drainage system exclusively. The existing system mainly comprises a combined sewer with overflows that are activated when the pipe-network surpasses its capacity.
2. *Hybrid*: The hybrid system scenario implements NBS solutions to manage step 1 and step 2 according to the 3SA, in combination with the existing urban drainage system. At capacity, the NBS alleviate the existing network and when they reach failure-mode, the exceeding flow is directed to the urban drainage system.

3. *Full Blue-Green*: The full blue-green system scenario relies on NBS exclusively. The system implements the same NBS solutions as the hybrid solution, but is disconnected from the urban drainage system. Instead, this system relies on safe floodways under failure mode. The flow is directed to appropriate streets and depressions where the damage potential is considered low, for temporary conveyance and detention.

An overview of the implemented CA measures is illustrated in figure 3.3. The development is described in the following.

3.3.1 NBS Site Selection

A GIS-based method for NBS site detection was adopted from a guideline developed by the Centre for Research-based Innovation (SFI), KLIMA 2050, and modified to select suitable sites for improved NBS efficiency (27). The method follows a simple procedure and only requires commonly available data. Thus, the method automates the process and ensures reproducible results. Land use maps of undeveloped areas were coupled with a slope analysis based on DTM. Suitable sites were identified in areas which met the criteria of being 1) undeveloped and 2) having slope < 5%, based on recommendations from a range of manuals and guidelines (56; 44; 22). The method yielded 40 % area coverage and NBS were established for maximal feasible deployment as follows to evaluate the potentials of a full scale installation. It should be noted that full method includes field measurements of infiltration rates to detect heterogeneous properties of the soils, typically present in urban areas, and might apply for the study area (38). However, field measurements were omitted due to time-restriction and weather conditions, and for this reason, infiltration properties of the native soils were considered instead. As addressed earlier, the infiltration properties were negligible, and consequently, the criteria related to infiltration was excluded. The process is available and illustrated in Appendix A - NBS Site Detection Method.

3.3.2 NBS Design

Bioretention cells were established as a flexible NBS and designed to manage step 1 and 2 in the 3SA. The design parameters were adopted from literature and guidelines, but were adjusted so they could be transferred to the required inputs of the model environment. The values are presented in table 3.1. Storage depth was assigned a value in the higher range to increase the detention capacity and meet the requirements of a step 2 solution. Infiltration on the other hand was assigned a conservative criteria to account for weather conditions present in Nordic climate.

Layer	Parameter	Design Value
Surface	Storage Depth [mm]	200 *
	Surface Roughness [Manning (M)]	10 **
Soil	Infiltration Rate [mm/h]	100 *
Storage	Height [mm]	800 *
	Porosity	0,5 **

Table 3.1: Parameter values of implemented bioretention cells. Values adopted from (44) and (9) are respectively denoted with $*$ and $**$.

3.3.3 Floodways

Open floodways were placed in street segments that coincide with existing drainage lines in the catchment, identified by the hydrological analysis according to recommendations. One floodway was established in the streets Strandveien and Østersunds gate, which intersect one each other. Another floodway was established in Mellomveien, connected to Nidarholms gate. Both floodways lead to a local depression with low damage potential where the flooded water is intended to be detained temporary, before eventually reaching the recipient through individual existing drainage lines. Prior to selecting the urban streets as floodways, the functionality and geometry was evaluated. Neither of them were considered to be important access roads during extreme flood events, and thus regarded appropriate. The geometry was characterized as wide and straight, and expected to provide better transportation capacity.

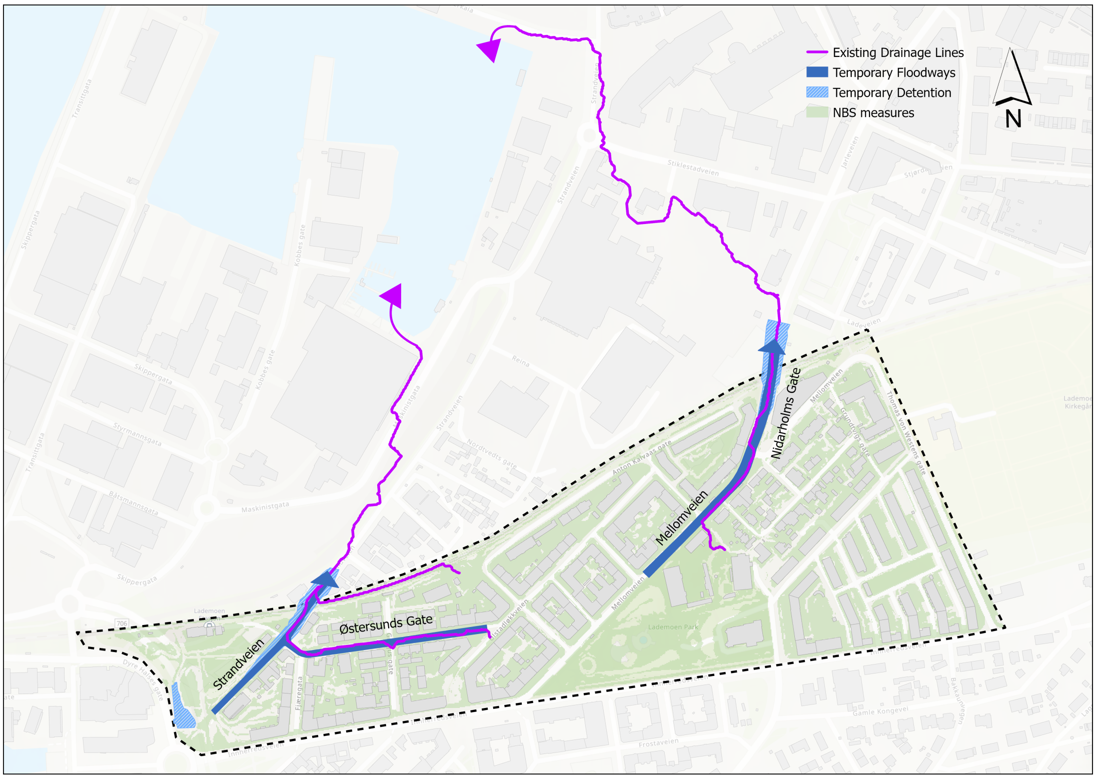


Figure 3.3: Overview of the implemented climate adaptation measures in the hybrid and blue-green system: Local NBS are implemented in areas marked with darker green and illustrate a max feasible deployment of measures based on an automated site-selection analysis. The temporary safe floodways are marked in darker blue and temporary detention in medium blue.

3.4 Modelling Environment

The three system scenarios were modelled in the water modelling platform MIKE+ as coupled 1D-2D dual drainage models (objective 1). The hydraulic efficiency was assessed by running simulations with the presented precipitation data as input. Details and graphic representations of the modeling environment can be found in Appendix B - Modeling Environment.

3.4.1 1D Network Model

The municipality of Trondheim maintains a calibrated 1D-model for the urban drainage network system of Trondheim within the MIKE URBAN Modeling Environment. The model of the Lademoen catchment was obtained and converted to be set up in the MIKE+ modeling platform, which offers integrated coupling of different water systems, including the urban drainage network system and surface. The model consists of 56 sub-catchments described by area and imperviousness, which direct generated runoff to the network system using the time-area method and Horton infiltration. In the obtained model, each sub-catchment was initially assigned the same precipitation load and a unique wastewater load, accounting for the dry weather flow. The precipitation load was removed in the coupled model, because it was allocated to the 2D surface domain. New sub-catchments were modelled to describe the area covered by buildings and connected to the closest node belonging to the combined sewer system. Precipitation load was assigned to these sub-catchments instead to account for the runoff from rooftops directed via downspout connections. A so called "hotstart"-file was applied to represent initial conditions of a dry weather flow, which was generated by running a simulation without precipitation (12).

3.4.2 2D Surface Model

A 2D surface model was built and used to simulate the surface flood inundation. The surface domain was described by a triangular mesh which covered the same area as the 1D-model. The mesh was delineated by a polygon file describing the area and the elevation was interpolated from a DTM. Buildings were included to account for their effect on flow paths. The spatial extent of the buildings was defined by polygons in the 2D Infrastructure module within the modelling platform and assigned a height of 5 meters for topographical correction. Infiltration and surface roughness was also defined by polygons describing buildings and roads. Infiltration was omitted, due to the negligible infiltration properties of the native soils. Surface roughness was set to Mannings numbers (M $[m^{1/3}/s]$) 35 and 40 for the roads and buildings respectively, and 20 for the remaining area, based on recommendations from DHIs reference manual (12). The described model was used for the conventional system scenario and as baseline model for the CA scenarios.

Because MIKE+ does not offer an explicit LID-module for the 2D surface model, the bioretention cells were modelled in the 2D Infiltration module by using the infiltration type "Constant Infiltration with Capacity" varying in the domain, as an approximation. The spatial extent of the bioretention cells was described by polygons attained from the site-selection method described above. The infiltration and retention properties were described by the following parameters: Infiltration rate, leakage rate, porosity and depth. The design values of the parameters presented above in table 3.1 were transferred to fit the required inputs. Infiltration and porosity were assigned the same values as presented in the table. Leakage rate was assigned 0 mm/h, representing the properties of the native soils. Depth was defined to be 1 m, accounting for both storage depth in the surface layer and storage height in the soil layer as presented in the table. The surface roughness was modified in the same areas and assigned a Manning's number (M) 10 from the table.

3.4.3 1D - 2D Coupling

The 1D and 2D model were coupled through 1D-2D couplings in the MIKE+ platform. Couplings were defined between node structures and the 2D terrain domain. Because inlets did not constitute a part of the modeled drainage system, the connection was made to the nodes in closest proximity to the location of the inlets. The default parameter set was applied, as the efficiency of the inlets was unknown. The couplings were applied in the modelling of the conventional and hybrid scenario, which employ the urban drainage network.

3.5 Flood Risk Assessment

The flood risk assessment comprised a risk identification, risk analysis and risk evaluation, based on the results obtained from running hydraulic simulations with the described model (objective 2). The risk identification includes a flood hazard mapping of the flood depths in the study area and velocity in the floodways, while the flood risk analysis and risk evaluation quantifies the flood risk and compares the different system scenarios.

3.5.1 Flood Risk Identification

Risk indicators were identified and described as a part of the flood risk identification. The risk indicator was described in terms of flood hazards measured by the hydrodynamic properties, velocity and depth, and hazard criteria. The flood hazards were identified and quantified from the hydrological simulations. The simulations produced map result files with information about the flood extent, including the spatial variety of velocities and depths. A specific map result file which contained statistical results from single time steps was used to retrieve maximum values over the simulation period. The maximum values for flood depth were used to evaluate the flood hazard exposure in the area. Flood hazard was identified where flood depths were above 10 cm, which constituted the main hazard criterion. This criterion was developed according to the Copenhagen Cloudburst Management plan, because it addresses a flat region, alike the study area (41). The hazard exposure to buildings was assessed for a RP_F = 20 year, responding to TEK17 criteria to safeguard buildings and the municipality's design criteria for step 1 and 2 solutions. The identified flood hazards were used further to carry out the flood risk analysis. The risk identification also assessed the flood hazard in the floodways of the blue-green system during a RP_F = 100 year event and was evaluated against the velocity criteria presented in 2.1, to verify whether the safe floodways meet their functioning criteria. The product of velocity and depth, vd, nor the duration of the hazards could be efficiently assessed due to limitations of the output data.

3.5.2 Flood Risk Analysis

The flood risk analysis was carried out to quantify the risk considering the probability of the events and the magnitude of the risk indicator. The probability was calculated as the inverse of the RP of the simulated extreme events and the magnitude of the risk indicator was quantified by the hazard exposure, calculated as the area percentage of flooded area. The analysis applied an automated process in ArcGIS Pro and included a number of steps to retrieve the ultimate results. Firstly, the flooded area was classified in depth ranges < 5 cm, 5 - 10 cm, and > 10 cm. Secondly, the percentage of area covered by depths above 10 cm was calculated and used as the main risk indicator relating to the hazard exposure. The process can be found in Appendix D - Post-processing results. A risk plot was finally produced to combine the flood hazard exposure and probability for the three different system scenarios. The CA scenarios were also evaluated against the conventional to evaluate the flood risk reduction. The $RP_F = 10$ year ensemble allowed implications of uncertainty to be considered.

3.6 Delta Change-Factor

A Delta Change-Factor (CF), commonly used in urban drainage modeling, was estimated as the relative difference between future and present conditions across a range of return periods (61). It was applied in this study as an indicator of climate resilience, but also to evaluate the impacts of climate change and urbanization on flood risk. The CF calculated the relative change in system performance, measured by the flood risk, with the relation:

$$CF = \frac{X_F - X_R}{X_R} \tag{3.1}$$

Where X refers to the risk indicator, R refers to the reference value and F refers to the future value.

As a climate resilience indicator, the CF was calculated with X_F set equal to the results obtained from future events and X_R to those obtained by the past events, for all system scenarios and RP. The same calculation was used to evaluate the impacts of climate change on the flood risk. CF was also calculated for a climate indice (CI), measured by the accumulated precipitation, to assess the relation between the estimated changes in climate and flood risk.

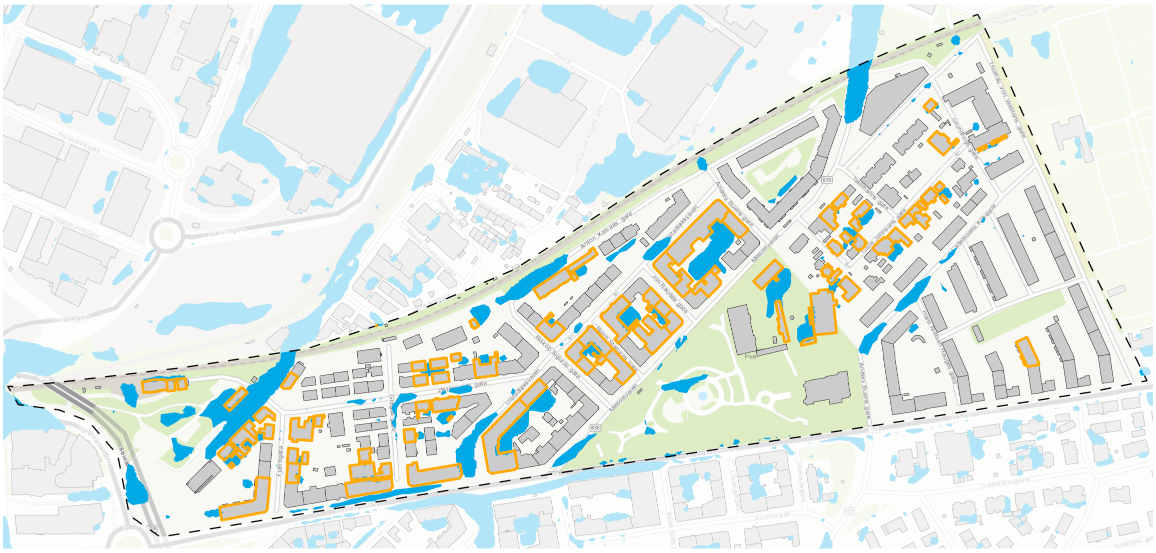
To evaluate impacts of urbanization, X_F was set equal to the results obtained by the conventional system and X_R to the results obtained by the hybrid system during the same precipitation events. The calculated CF estimated changes in flood risk caused by decreasing the imperviousness. To avoid confusion, the conventional system represented the current scenario and the hybrid system a potential future scenario, but were interchanged to embody the typical impacts of urbanization. Recall that the hybrid and conventional only differ in imperviousness.

CHAPTER 4: RESULTS

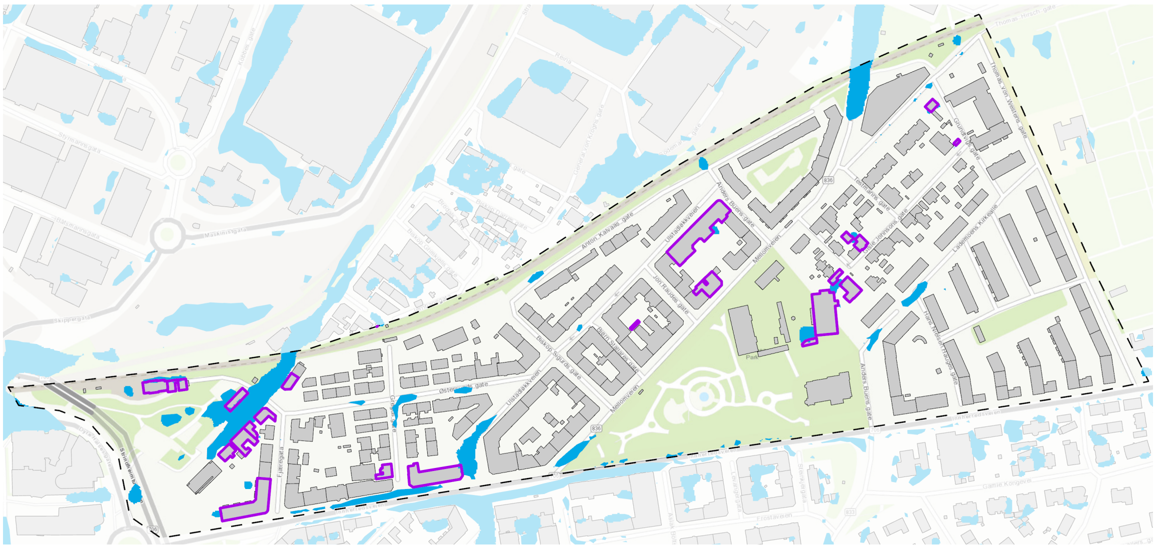
This chapter presents and describes the main results attained from the methodology, primarily the flood risk assessment. It is structured in a chronological order in accordance to section 3.5; flood risk identification followed by the flood risk analysis. Finally, the calculated delta change-factors are presented. The results are derived from hydraulic simulations and illustrate the potential effects from increasing infiltration and retention capacities through nature-based step 1 and 2 solutions, but also some of the limitations at higher return periods and in future climate.

4.1 Flood Risk Identification

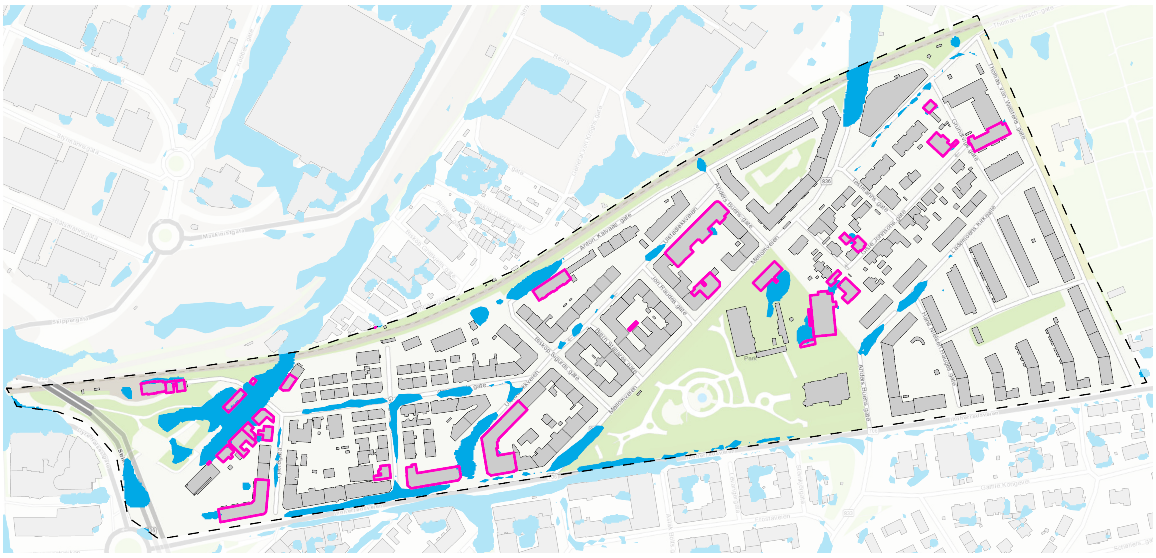
Flood hazards were represented by the hydrodynamic parameters depth and velocity, and used as risk indicators. Mapping of the flood hazards was prepared as a part of the flood risk identification to assess the exposure of the identified flooded area and visualize it. Figure 4.1 shows the flood hazard maps for the conventional, hybrid and blue-green system scenario as a result of a $RP_F = 20$ year event. The surface flood is marked with blue and covers areas where flood depths were calculated to be above the criterion, hence flood depths > 10 cm. The presented results respond to the requirement stated in TEK17 for buildings, which is to withstand RP = 20 year event. Buildings which were exposed to the flooded hazard are highlighted in colors. A total of 94, 25 and 35 buildings were flooded in the conventional, hybrid and blue-green scenario, respectively. The presented flood hazard maps also illustrate differences in both the extent and the distribution of flooded area between the different scenarios. By comparing the conventional and blue-green scenario, it is especially evident that the flood distributed differently, while the hybrid scenario managed the combination.



(**a**) Conventional Scenario



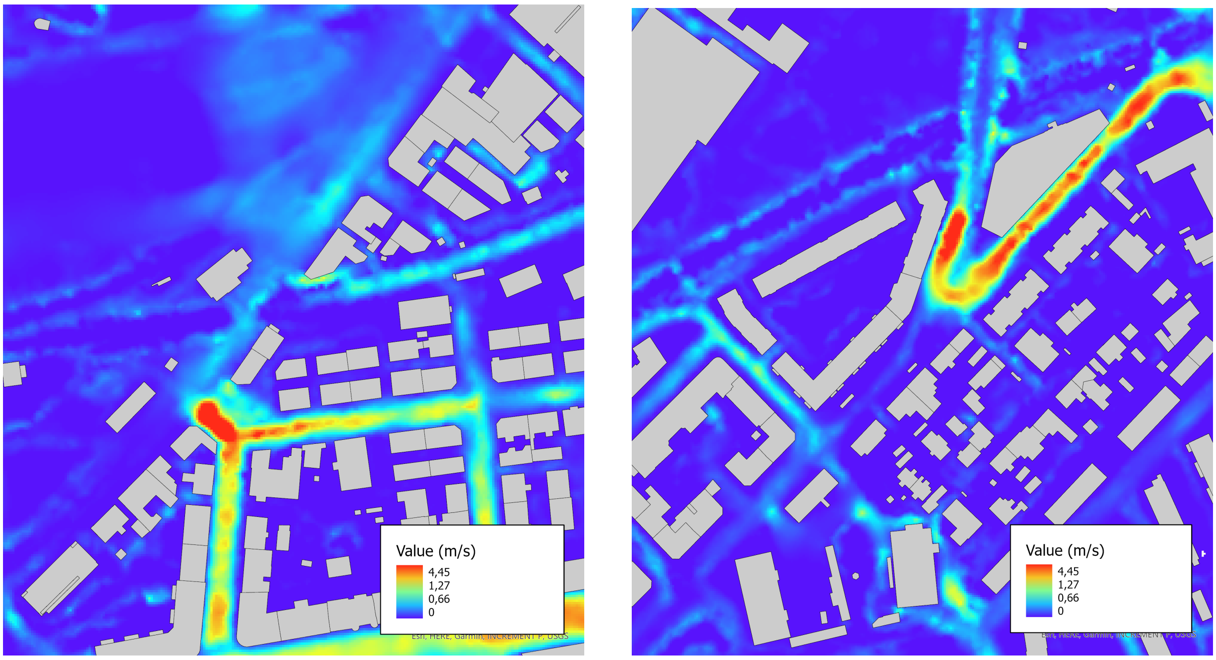
(**b**) Hybrid Scenario



(**c**) Blue-Green Scenario

Figure 4.1: Flood hazard maps show hazard exposure during RP_F = 20 year event. Flooded area is marked in blue and flooded buildings are highlighted in colors.

Maximum velocities were used to represent the hazard exposure to pedestrians in the application of the urban street segments as floodways under extreme events. The hazard exposure is presented in figure 4.2 for a $RP_F = 100$ year event, which is the design criteria for safe floodways. The presented results belong the blue-green system, which was the only system to intentionally implement safe floodways as a measure. Maximum hazard conditions were found above the upper boundary of the hazard levels presented in section 2.3.2. The highest velocities are concentrated in the middle of the roads and decrease towards the sidewalks. Some street sections which were not intended to operate as floodways also experienced higher velocities, whilst parts of the sections which were intended to function as floodways experienced lower velocities than expected. This applies particularly at sharp turns.



(**a**) Strandveien and Østersunds Gate (**b**) Mellomveien and Nidarholms gate

Figure 4.2: Flood hazard present in floodways represented with maximum velocity during a $RP_F = 100$ year event.

4.2 Flood Risk Analysis

The results of the flood risk analysis are presented in figure 4.3. The flood risk was represented as the combination of hazard exposure and the probability of the event. The flood risk was the lowest for the hybrid scenario, median for the blue-green and highest for the conventional scenario. The same order applied at all probabilities and in both past and future climate. The general trend was that the hazard exposure, represented as percentage flooded area, increased with a similar order of magnitude with lower probabilities (higher RP) for all three system scenarios. A notable result was that the flood risk attained by the hybrid system was lower in future climate than the flood risk attained by the conventional system in past climate. The same was observed for the blue-green system at the probabilities 50 % (RP = 2 years) and 10 % (RP = 10 years).

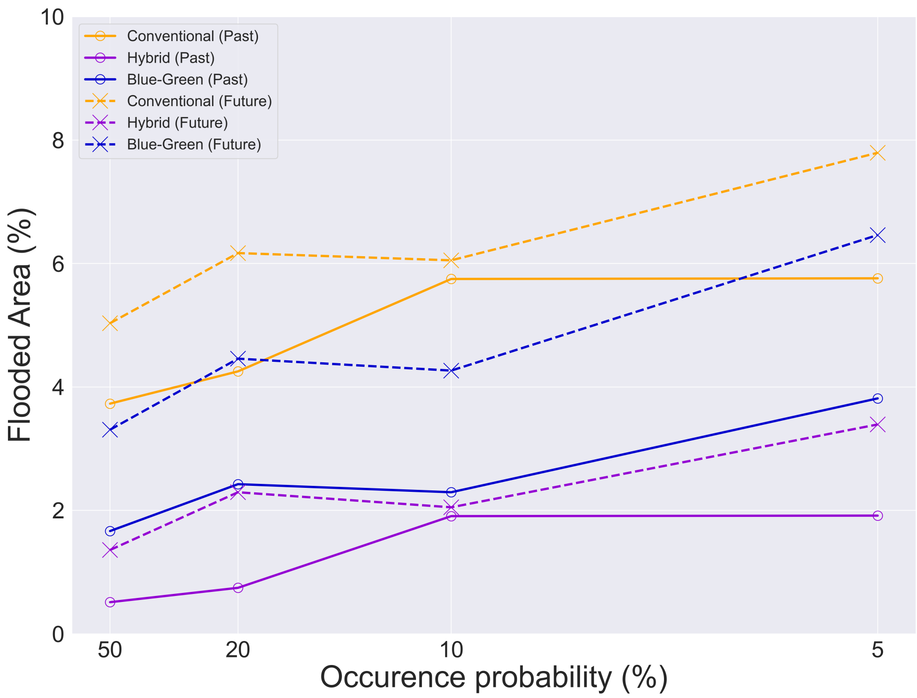


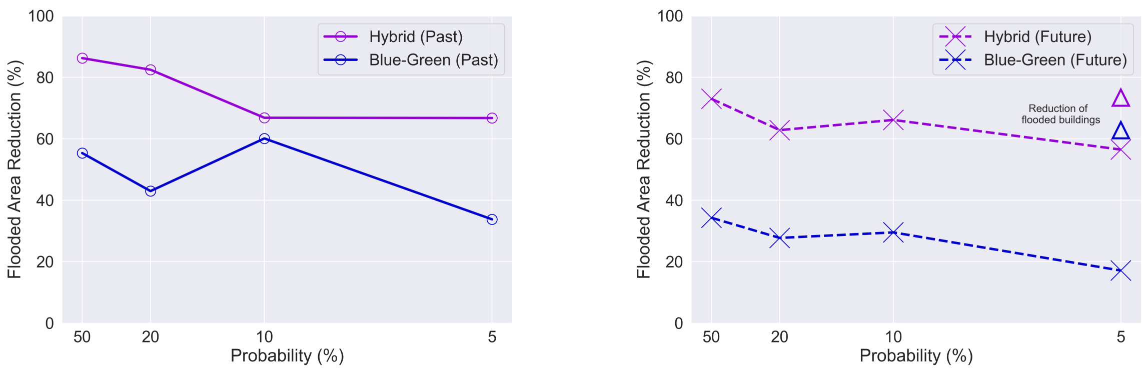
Figure 4.3: The flood risk plot presents the flood risk as the combination of the hazard exposure, measured by the flooded area (%) and the probability expressed in term of the inverse return period (%). Conventional is marked with orange, hybrid with purple and blue-green with blue color. Results from past climate are presented with a solid line and future climate with a dashed line.

Another notable result was that the hazard exposure from a $RP_F = 5$ year event was higher than for the $RP_F = 10$, as can be seen in the numerical values presented below.

	Past			**Future**		
RP	**C**	**H**	**BG**	**C**	**H**	**BG**
2	3.72	0.51	1.66	5.02	1.36	3.31
5	4.25	0.74	2.42	6.17	2.29	4.46
10	5.75	1.91	2.29	6.05	2.05	4.26
20	5.76	1.92	3.81	7.79	3.39	6.46

Table 4.1: Numeric results of flooded area (%). Values in red are from the $RP_F = 10$ year event, which included an ensemble of two more events.

Figure 4.4 presents the flood risk reduction achieved from pursuing CA with a retrofit to a hybrid and blue-green system, in both past and future climate. The flood risk reduction was calculated for the hybrid and the blue-green scenario, relative to the conventional scenario, as the current situation. A risk reduction was achieved by both CA system scenarios, but was found to be higher for the hybrid. Up to 80 % reduction was achieved by the hybrid and up to 60 % by the blue-green. The risk reduction was higher at smaller events, hence events in past climate and with higher probability, and decreased with bigger events. The reduction in flooded buildings is presented in the same figure for $RP_F = 20$ year event and was calculated with the results presented above from in flood hazard maps. The hybrid system also attained the highest reduction in flooded buildings, but the difference compared to the blue-green system was significantly smaller than the observed difference in the reduction of flooded area.

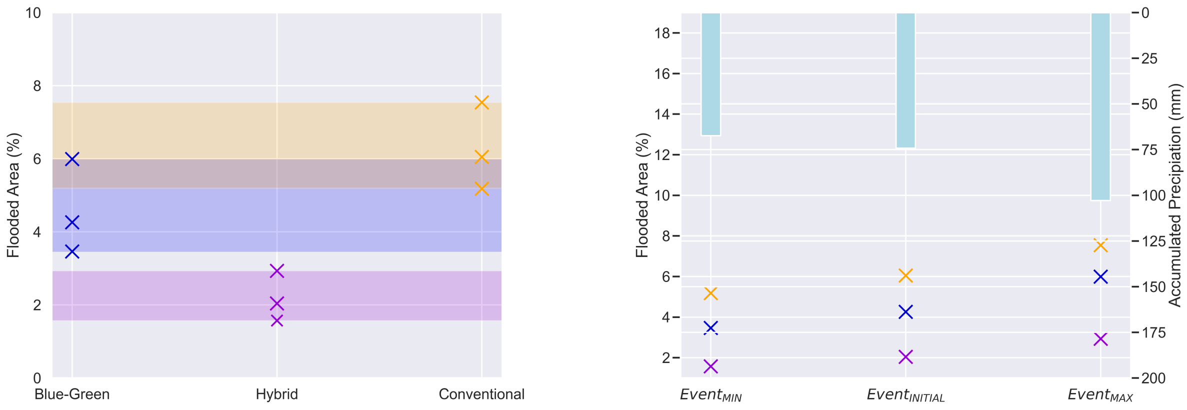


(**a**) Past climate

(**b**) Future climate

Figure 4.4: The flood risk reduction attained from climate adaptation measures, for both hybrid (in purple) and blue-green systems (in blue), compared to the conventional (current) system. Reduction in flooded buildings for the $RP_F = 20$ year is also presented for future climate and marked with triangles.

For $RP_F = 10$ year, an ensemble limited to three precipitation events was simulated under all three system scenarios and resulted in a wide range of flood response outcomes for the same RP. The results are presented in figure 4.5.



(a) Values with shaded ensemble-uncertainty bounds.

(b) Values related to the accumulated depth of the precipitation event.

Figure 4.5: Results from an ensemble of three events for RP_F = 10 year.

The blue-green yielded the widest range (3,45 - 5,99) and the values were found to overlap with the range for the conventional (5,19 - 7,54). The hybrid yielded the lowest values and the smallest range (1,57 - 2,93). The magnitude of the flood response was associated with the accumulated precipitation depth of the event. Higher accumulated precipitation depth resulted in a higher flood hazard exposure.

4.3 Delta-Change Factor

CF was applied as an indicator of the climate resilience (CR) of each system, calculated as the relative change in system performance due to impacts climate change. CF was also calculated for a climate indice (CI) as the relative change in accumulated precipitation. The results are presented on the left side of figure 4.6. To evaluate the impacts of urbanization, a CF was calculated as the relative change in system performance due to decreased imperviousness (IMP) and is presented on the right side of 4.6. A low CF value signifies low relative change in system performance, hence low performance impairment, while the opposite is true for a high CF value.

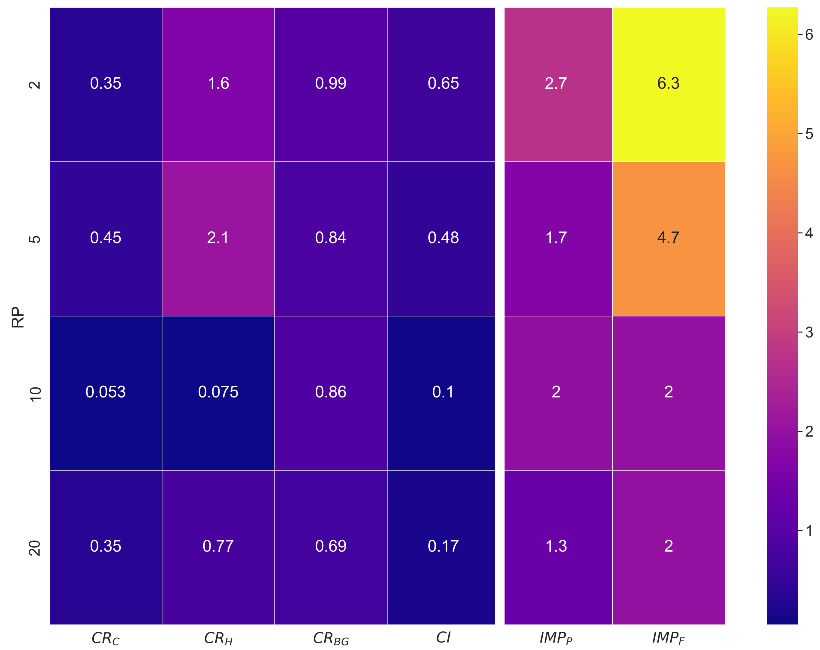


Figure 4.6: Calculated CF values illustrate the relative change in performance, due to climate change (on the left side) and due to changes in imperviousness (right side). Where CR is the climate resilience indice, CI is the climate indice and IMP is the imperviousness indice. C, H and BG denotes the conventional, hybrid and blue-green scenario, respectively.

The conventional scenario obtained CF values on the lowest range (0,053 - 0,45) and the blue-green obtained CF values on the higher range (0,69 - 0,99). The hybrid obtained values across the widest range (0,075 - 2,1), from the second lowest to the highest value. The CF for imperviousness was found on the higher range (1,3 - 6,3) and varies substantially across the different RP. Higher values were found for smaller events and in future climate. It should be noted that the calculations were done on different scales and are not directly comparable, and therefore separated in the figure.

CHAPTER 5: DISCUSSION

This chapter provides a discussion of the main results, limitations and venues for further work. It is structured in accordance with the research questions as defined in section 1.1: 1) Can nature-based step 1 and 2 solutions reduce pluvial flood risk under extreme events?, 2) Is it feasible to transition from the conventional system to a complete blue-green solution system?, and 3) Which of the three solutions is most climate-resilient? Moreover, it provides remarks about the limitations and uncertainties in section, and finally recommendations for further work 5.4.

5.1 Flood Risk Reduction from Nature-Based Step 1 and 2 Solutions

To address the potentials of nature-based step 1 and 2 solutions in compliance with the 3SA for flood risk reduction, a flood risk assessment was carried out based on the results attained from hydrodynamic simulations of dual-drainage models (objectives 1. and 2.). The flood risk assessment comprised a risk identification analysis, followed by a flood risk analysis, and had the aim to compare the performance of the three different system solutions scenarios. All results are pointing to that flood risk reduction can be achieved by establishing NBS as step 1 and 2 solution of the 3SA. They are discussed in in the follwing.

The flood hazard maps for the three system solutions showed noticeable differences in the distribution and the extents of the flooded area. The difference in the distribution of the flooded area was most evident between the conventional and blue-green scenario, whilst the hybrid scenario yielded the combined effects. A probable explanation for this effect is the location of the SWM measures of the systems. The curb inlets in the conventional system and the NBS in the blue-green system were placed at different locations and the results imply that both types of measures provide a local effect at reducing flooding. This effect is also reflected in the number of buildings which are exposed to the hazard. As seen in figure 4.4, the reduction in the number of flooded buildings is not proportional to, but higher than, the reduction of the flood risk attained by the blue-green scenario. This suggests that the majority of the flooded area in the blue-green scenario was intentionally flooded, as flow was directed where damage potential was considered to be low. These results illustrate the potentials of NBS as useful tools in local flood reduction and as an alternative solution for protecting older buildings (or other assets) which are not located, designed or safeguarded according to TEK17 or other guidelines and recommendations. It also suggests that the full implementation of the 3SA functioned as intended, even if not reflected in the total flooded area percentage. The extent of the total flooded area was different between all three systems solutions and can be considered an indicator for their capacity to reduce floods, which is also illustrated in the flood risk plot in figure 4.3. The hybrid system attained the lowest extent of flooded area, followed by the blue-green and finally the conventional. The flood reduction can be attributed to the increased infiltration and retention introduced by the implemented NBS within the urban catchment, and ultimately suggests that nature-based step 1 and 2 solutions can manage to reduce the pluvial flood risk. A comparison of the flood risk in the conventional and blue-green scenario, implies that NBS perform better at flood risk reduction than traditional, grey solutions. However, the observed gap between the flood risk in the hybrid and blue-green scenario also suggests that the effects from the network are pronounced. As expected, the hybrid scenario performs best at overall flood reduction. It can be argued that NBS covered an unrealistically large area, which would be infeasible due to practical and economic aspects, but the observed local effects are suggesting that smaller scales also provide significant benefits. The NBS-area was selected based on an automated process which could be reproduced.

The main findings of the flood risk analysis is that the hybrid system imposes the lowest flood risk, the blue-green median and the conventional imposes the highest, which aligns with the results from the flood hazard maps. The same order applies with all probabilities, for both future and past climate, suggesting the hybrid system is the preferable solution under all of the simulated events. As expected, the flood risk increased with lower probabilities (higher RP) and from past to future climate, which can be explained by the size of the precipitation events. A notable result from the flood risk analysis is that $RP_F = 2$ year yields a flood risk closer to the $RP_P = 20$ year than $RP_P = 2$ year, for all scenarios. In other words, what we recognize as a RP = 20 year flood event in today's climate, resembles more a RP = 2 year event in the projected future climate (RCP 8.5). This finding amplifies the need for flood risk assessment on future climate scenarios, but also the need for CA. On the other side, the flood risk attained by the hybrid scenario in future climate is lower than the flood risk attained by the conventional scenario in past climate at all probabilities, which indicates that NBS can potentially counteract the impacts from climate change on flood risk. A similar effect was found for the blue-green scenario in two RP events, but at a lower magnitude.

Contrary to the expected values, RP_F = 10 years event attained a lower flood risk than RP_F = 5 years. This can be explained by the pattern of the generated precipitation events and the range of ensemble-uncertainty. Because the simulated events were selected arbitrary amongst each ensemble, it is likely that some lie closer to the lower boundary of the range, whilst other closer to the upper boundary. This amplifies the value of the ensemble-approach. Following these results, an ensemble limited to three events of RP_F = 10 was simulated for all scenarios and resulted in a wide range of outcomes for all scenarios, closely associated to the accumulated precipitation depths. The ranges were also found to be overlapping for the conventional and blue-green scenario, while the range for the hybrid was found well below. This suggests that consequences from selecting the conventional system over the blue-green system, or vice versa, may be lower than from discarding the hybrid solution. Moreover, the hybrid solution attains a smaller uncertainty-range, which signifies that the performance is more stable across different events and represents a more robust solution. A similar range would be expected for other RP if the full ensemble was simulated. Altogether, these results support the common understanding in research that an ensemble approach is necessary to gain reliable information about the performance of systems solutions and to design more robust systems, which in this case would be the hybrid solution system. The full range of outcomes provides implications about the consequences from choosing the "wrong" solution, by comparing the gaps or overlaps between the bounds of flood risk for the different solutions, as exemplified above with the overlaps between the conventional and blue-green system solution. It would also provide the opportunity to decide where on the range it would be necessary to design solutions for, depending on the concentration and value of different assets to be considered. E.g., it would be desirable to be on the conservative side of the range for critical infrastructure.

The observed reduction in flood risk was higher for the hybrid system than for the blue-green, although both yielded substantial results. This supports the understanding of NBS as effective adaptation measures, but again implies that contributing effects from the network remain pronounced. The flood risk reduction was more eminent at lower RP and in past climate, suggesting that NBS are most effective at lower intensities. The same results were found in the calculated CF_{IMP} values, which were higher at smaller events. This is not surprising, as they normally are intended and designed to cope with smaller events.

5.2 Complete Transition from Conventional to a full Blue-Green system

To evaluate whether it is feasible to transition completely away from the conventional system to a full blue-green system, the flood risk analysis was combined with a hazard analysis of the urban streets which were intended to serve as safe floodways during a RP_F = 100 year event.

The results for the floodways show that maximum velocities were found above the upper boundary of the recommended hazard levels for pedestrians, and thus do not meet the criteria to be considered safe. However, the highest values (in the range of 1,27 - 4,45 m/s) are centered in the middle of the roads and decrease towards the sidewalks. The safety of the floodways can be elevated by altering the streets, for example by curb stones and drainage slopes on the sidewalks, to support a potential transition to a complete blue-green system. It should also be mentioned that very high velocities can lead to erosion. Moreover, it was demonstrated that higher velocities occur in other street sections than the intended floodways, and the opposite, lower velocities in the planned floodways. An explanation for this, is that the selection of urban streets was based on a GIS-based hydrological analysis, which is common practice, but it only considers the slope and not the dynamic properties of water flow. The findings confirms that hydrodynamic analysis should be conducted to examine the safety of floodways because the likelihood of a temporary floodway to complete a hairpin turn decreases with an increasing velocity, as was found in the study by Skrede et al. (58).

Due to computational cost, the RP_F = 100 year event was only simulated for the blue-green scenario. With the underlying assumption that more flooding favours higher velocities, it can be presumed that the conventional scenario would yield even higher velocities in the same streets under the same event. Based on this presumption, the blue-green system represents a more favourable solution than the conventional, based on the flood risk assessment. The same presumption implies that the hybrid would yield the lowest velocities.

5.3 Climate Resilience of the Systems Solutions

To evaluate the climate resilience of the three system solutions, a CF was calculated to provide implications on the relative change in performance in future events relative to past events. The CF measures the systems *ability to minimize disruptions from the occurrence of an event* and does not encompass the entire interpretation of climate resilience, as stated in 2.3. While there is a general consensus that NBS are more climate resilient than grey solutions, the contrary was reflected in the calculated CF values. The conventional scenario attained the lowest CF values, which reflects that the performance of the system was less impaired due to climate change and thus more climate resilient, than the hybrid and blue-green. Comparison of CF_{CR} and CF_{CI} illustrates a relatively linear relationship between changes in flood risk and climate change, meaning the flood risk increased with the same magnitude as the changes in climate.

A CF factor was also calculated for the change in imperviousness between the hybrid and conventional scenario, to assess the impacts urbanization has on flood risk. The calculated CF_{IMP} is substantial, which supports findings from former studies that imperviousness is a driving factor for the increase in stormwater runoff. Values are higher at lower RP and in future climate, indicating the effects of NBS are more prominent at smaller events and in future climate. These findings contradict the implications of the CF_{CR}, because they imply that the established NBS in the hybrid scenario would perform better in the predicted future climate conditions. While the CF_{IMP} values are higher than the CF_{CR} values, they cannot be compared directly because the values are linked to different factors and consequently different scales. Nevertheless, CF_{CR} values are still pronounced, indicating climate change will have impacts on flood risk in all scenarios and supports the recognition for an acceptance level for flooding and the notion of "living with water". It also encourages CA to reduce consequences.

Although the CF is a common approach, several shortcomings were found in this application. Firstly, the CF factor was calculated with values from single events and not with an ensemble-mean. This might have resulted in some over- or under-exaggerated values for different RP, depending on where in the range of the ensemble that the compared events lie on. The full ensemble would possibly provide different, but more representative, results. Secondly, the relation evaluates the change in performance against the reference value (the denominator in the relation), and consequently a poor reference value, that is a higher flood risk, will favour a lower CF. This relation explains why the conventional system attained the lowest values, which should reflect it is climate resilience, even though the contrary was demonstrated in the other results. This suggests that the relative CF was not a suitable indicator of climate resilience. The evaluation of climate resilience should instead turn to the comparative flood risk analysis in this study, which suggests that both the blue-green and hybrid system perform better in future climate. The absolute performance is more compatible with the purpose of climate resilience and adaptation than the relative change.

5.4 Limitations and Further Work

The overall aim of this thesis has been to investigate the potentials of NBS to reduce pluvial flood risk and build climate resilience. While results suggest that NBS are indeed useful and effective tools for this, there are some uncertainties related to the limitations of the study and suggestions for further investigations.

A full ensemble approach was not carried out due to computational expense and consequently the presented flood risk results do not provide the full uncertainty space. By simulating the full ensemble for all RP, more reliable results can be attained with additional information on uncertainty ranges. A sensitivity analysis could also provide valuable information on the overall uncertainty of the model, by studying how different values for the independent parameters (e.g. roughness and infiltration) affect the simulated flood.

No calibration nor validation techniques were used for the model due to lack of data, which introduces an uncertainty. Validation and calibration of hydraulic models is crucial for reliable, site-specific results. This can be performed following techniques from literature, for example those based on floodwater marks (36) and use of private amateur recordings of floods(18). However, calibration of 2D models remains a complicated task and sometimes provides geophysical parameter values outside table values, which do not make physically sense. This was demonstrated in the thesis work of Mikkelsen (37).

The output files from the hydraulic simulations provided information on maximum values of the hydraulic parameters, but the duration of the values was not assessed because of limitations to the output data. The duration of the hazard exposure is an important factor for the actual risk, and thus the risk might be smaller in reality in locations where the duration is negligible.

The study was limited to the risk of surface flooding, which is only one of multiple variables to be considered in a decision-analysis for the optimal retrofit solution. Some of the key benefits of NBS include improved water quality, reduced CSO-activity, groundwater recharge, increased biodiversity and improved air quality. On the other side, NBS can also be costly to implement and maintain. Deciding on the optimal solution should be based on a multi-criteria analysis, which considers cost-efficiency, maintenance aspects, social and environmental impacts, and amenity reasons. Because the attained results are attributed to a large coverage of NBS, the required area for significant effects should also be addressed in such an analysis.

Because inlets do not constitute a part of the obtained 1D network model, the coupling of the 1D and 2D model was implemented between nodes and the surface. The inlet efficiency is also unknown and to date there is a lack of efficient tools and guidelines to determine the inlet efficiency at the scale of this study. A study by Russo et al. proposes a formula to calculate the hydraulic efficiency of grated inlets, related to the flood depth, flow and empirical parameters from experiments (54). However, as the variables change during an event, it was not feasible for the scale of this study. Another method is to subtract the estimated capacity of the network in terms of mm/hr from the precipitation, but this approach would not provide the same results on the distribution of the flood.

The study focused on surface flooding, which is induced by large precipitation events. Therefore the hydraulic modelling was limited to extreme events, while continuous long-term simulations were omitted. Hence, the initial state of the system prior to the extreme events was not taken into consideration, and neither was the systems performance to manage step 1. A continuous long-term simulations has a high computational cost for 2D models, but may provide important information about the influence that initial conditions have on the response of an extreme event. It would also provide valuable information on the other aspect of climate resilience, which is the systems *response and ability to recover rapidly after the impacts of an event*.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This study has explored the potentials of NBS to reduce the pluvial flood risk and build resilience in an urban catchment. A scenario analysis was performed to evaluate and compare the flood risk from three different system scenarios, namely the conventional, the hybrid and the blue-green system solution. NBS were established for maximal feasible deployment and to function as step 1 and 2 solutions in compliance with the 3SA, in the hybrid and blue-green system. The hydraulic performance of each scenario was evaluated across a range of extreme events, in both past and future climate, through coupled 1D/2D flood modeling. The flood modeling also investigated the effects of simulating ensembles to identify the range of uncertainty of the systems response. A risk-based approach was followed to quantify the magnitude of the flood risk, as a combination of the flood hazard exposure as a risk indicator and the probability of the event, where the flood hazard was identified in areas where flood depths were above 10 cm and its exposure was quantified by percentage area. The results of the flood hazard exposure were further used to assess and evaluate the flood risk reduction attained from transitioning to a hybrid and blue-green system. A delta change-factor was applied to the calculated risk indicators to evaluate the climate resilience and the impacts from climate change and urbanization on the flood risk.

The flood risk assessment has demonstrated that NBS can reduce the flood risk and build resilience, by introducing higher infiltration and retention capacities. The hybrid system attained the greatest flood reduction at 80 % , but a substantial flood reduction was also attained by the blue-green system, with up to 60 % reduction. The hybrid yielded a lower flood risk in future climate than the conventional in past climate, which showed that NBS can counteract the impacts of climate change when established at a large scale. Comparison of the conventional and blue-green system showed that NBS exclusively managed the flooding more efficiently than the grey solutions, and that effects appear locally. The transition from a conventional to a full blue-green system, which entails a complete disconnection from the existing network and full employment of the 3SA, was found to function successfully and represents a more attainable system than the current situation. However, the most effective and robust retrofit solution (objective 3.) based on the flood risk assessment and ensemble-uncertainty was the hybrid system, and it is arguably more sustainable as it takes advantage of the existing network. As discussed, it is acknowledged that the CF did not represent a suitable indicator for climate resilience. Nevertheless, the CF did illustrate substantial changes in flood risk due to impacts from urbanization (i.e. increased surface imperviousness) and climate change (i.e. increased precipitation), highlighting the need for climate adaptation. It also showed that the effects of NBS were more prominent in future climate, which encourages the use for building resilience.

The risk-based approach was undertaken to provide a more well-founded and reliable basis for decision-making in the flood management process. Events from ensembles identified and demonstrated a wide range of possible outcomes for the same RP. It can be concluded that an ensemble-approach is necessary to gain insight in the robustness and reliability of the systems performance.

In light of these findings, the overall conclusion is that climate change and urbanization will increase the pluvial flood risk, but that NBS are efficient tools for mitigation and that the 3SA facilitates an effective implementation. Adding to this, countless of other benefits have been associated to NBS, including but not limited to; flood risk reduction, CSO-reductions, increased evaporation and infiltration, groundwater recharge, amenity and biodiversity.

BIBLIOGRAPHY

[1] I. Andrés-Doménech, A. Montanari, and J. B. Marco. Efficiency of Storm Detention Tanks for Urban Drainage Systems under Climate Variability. *Journal of Water Resources Planning and Management*, 138(1):36–46, 2012. doi:10.1061/(ASCE)WR.1943-5452.0000144.

[2] K. Arnbjerg-Nielsen, L. Leonardsen, and H. Madsen. Evaluating adaptation options for urban flooding based on new high-end emission scenario regional climate model simulations. *Climate Research*, 64, 2015. doi:10.3354/cr01299.

[3] C. Bae and D. Kun Lee. Effects of low-impact development practices for flood events at the catchment scale in a highly developed urban area. *International Journal of Disaster Risk Reduction*, 44:101412, 2020. doi:https://doi.org/10.1016/j.ijdrr.2019.101412.

[4] R. Bertsch, V. Glenis, and C. Kilsby. Urban flood simulation using synthetic storm drain networks. *Water*, 9:925, 2017. doi:http://dx.doi.org/10.3390/w9120925.

[5] B. Boliang Dong, Xia J., Zhou M., Li Q., Ahmadian R., and Falconer R.A. Integrated modeling of 2D urban surface and 1D sewer hydrodynamic processes and flood risk assessment of people and vehicles. *Science of The Total Environment*, 827, 2022. doi:https://doi.org/10.1016/j.scitotenv.2022.154098.

[6] M.A. Caretta, A. Mukherji, M. Arfanuzzaman, R.A Betts, Gelfan, A., Y. Hirabayashi, T.K. Lissner, J. Liu, E. Lopez Gunn, R. Morgan, S. Mwanga, and S. Supratid. 2022: Water. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. pages 551–712, 2022. doi:10.1017/9781009325844.006.

[7] L. Cea and P. Costabile. Flood Risk in Urban Areas: Modelling, Management and Adaptation to Climate Change. A review. *Hydrology*, 9:50, 2022. doi:https://doi.org/10.1016/j.envsci.2019.05.020.

[8] V. T. Chow, D. R. Maidment, and L. W. Mays. *Applied Hydrology*. 2012.

[9] T. Chui, X. Liu, and W. Zhan. Assessing cost-effectiveness of specific LID practice designs in response to large storm events. *Journal of Hydrology*, 2016. doi:https://doi.org/10.1016/j.jhydrol.2015.12.011.

[10] European Commission. Towards an EU Research and Innovation policy agenda for Nature-Based Solutions Re-Naturing Cities. Final Report of the Horizon 2020 Expert Group on "Nature-Based Solutions and Re-Naturing Cities" (full version). Brussels. 2015. doi:https://doi.org/10.2777/765301.

[11] H. De Moel, J. Van Alphen, and J.C.J.H. Aerts. Flood maps in Europe—Methods, availability and use. *Natural Hazards Earth Systems, Sci.*, 9(2):289–301, 2009. doi:https://doi.org/10.5194/nhess-9-289-2009.

[12] Danish Hydraulic Institute (DHI). *MIKE+ Collection System User Guide*. DHI, 2023.

[13] A. V. Dyrrdal and E. Førland. Klimapåslag for kortidsnedbør. [Climate factors for short-duration rainfall]. *NCCS Report nr. 5*, 2019.

[14] Belgium EU, Brussels. European Parliament and the Council Directive 2007/60/EC on the Assessment and Management of Flood risk. 2007.

[15] StopUp EU. Protecting the aquatic environment from urban runoff pollution: StopUP, 2022. URL: https://stopup.eu/trondheim/.

[16] T. D. Fletcher, W. Shuster, W. F. Hunt, R. Ashley, D. Butler, S. Arthur, S. Trowsdale, S. Barraud, A. Semadeni-Davies, J. Bertrand-Krajewski, P. S. Mikkelsen, G. Rivard, M. Uhl, D. Dagenais, and M. Viklander. SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7):525–543, 2015. doi:https://doi.org/10.1080/1573062X.2014.916314.

[17] Direktoratet for byggkvalitet [D]. Byggteknisk forskrift (tek17) med veiledning [regulations on technical requirements for construction works], 2017. URL: https://dibk.no/regelverk/byggteknisk-forskrift-tek17/7/7-2.

[18] N. Guillen, A. Patalano, C. García, and J. Bertoni. Use of LSPIV in assessing urban flash flood vulnerability. *Natural Hazards*, 87(1):383–394.

[19] S.F. Hailemariam and K. Alfredssen. Quantitative flood risk assessment in Drammenselva River, Norway. *Water*, 15(5):920, 2023. doi:https://doi.org/10.3390/w15050920.

[20] I. Hanssen-Bauer, E.J. Førland, I. Hadeland, H. Hisdal, S. Mayer, A. Nesje, J.E.Ø. Nilsen, S. Sandven, A. B. Sandø, A. Sortenberg, and B. Ådlandsvik. Klima i Norge 2100 [climate in Norway 2100]. 2015.

[21] R.M. Harrison and R.E Hester. *Risk Assessment and Risk Management*. Royal Society of Chemistry, 1998.

[22] Belinda Hatt, Peter Morison, Tim Fletcher, and Ana Deletic. *Adoption Guidelines for Stormwater Biofiltration Systems*. 01 2009.

[23] R. Hernes, A. Gragne, E. Abdalla, B. Braskerud, K. Alfredsen, and T. Muthanna. Assessing the effects of four SUDS scenarios on combined sewer overflows in Oslo, Norway: Evaluating the low-impact development module of the Mike Urban model. *Hydrology Research*, 51, 2020. doi:10.2166/nh.2020.070.

[24] ISO. ISO 31000:2018 Risk Management - Guidelines.

[25] Switzerland IUCN, Gland. IUCN (2020). Global standard for nature-based solutions. A user-friendly framework for the verification, design and scaling up of NbS. First edition. Gland, Switzerland: IUCN. URL: https://portals.iucn.org/library/sites/library/files/documents/2020-020-En.pdf.

[26] B. G. Johannessen, T. M. Muthanna, and B. C. Braskerud. Detention and retention behavior of four extensive green roofs in three nordic climate zones. *Water*, 10:671, 2018. doi:https://doi.org/10.3390/w10060671.

[27] D.P. Kliewer and E. Sivertsen. *Sustainable urban drainage systems (SUDS) area detection using GIS. Guideline. Version 1.0.* SINTEF Community, 2018.

[28] Trondheim Kommune. VA-norm vedlegg 5. Beregning av overvannsmengde. Dimensjonering av ledning og fordrøyningsvolum [Water and Wastewater Norm. Attachment 5. Calculation of stormwater flows. Design of pipes and detention basins]. URL: https://www.va-norm.no/trondheim/.

[29] E. Kristvik. *Climate-Informed Planning and Design of Urban Water Systems*. PhD thesis, Norwegian University of Science and Technology (NTNU), 2018.

[30] W. Kron. Flood Risk = Hazard • Values • Vulnerability. *Water International*, 30:58–68, 2005. doi:https://doi.org/10.1080/02508060508691837.

[31] Y.G. Lau. Two-dimensional depth-averaged flow modeling with an unstructured hybrid mesh. *Journal of Hydraulic Engineering*, 136, 2010.

[32] O. Lindholm, S. Endresen, S. Thorolfsson, S. Sægrov, G. Jakobsen, and L. Aaby. Veiledning i klimatilpasset overvannshåndtering [Guidelines for climate adapted stormwater management.]. *Norsk Vann Report nr. 162-2008.*, 2008.

[33] C. Lucas Williams and J. Sample David. Reducing combined sewer overflows by using outlet controls for green stormwater infrastructure: Case study in Richmond, Virginia. *Journal of Hydrology*, 520:473–488, 2015. doi:10.1016/j.jhydrol.2014.10.029.

[34] H. Lyu, G. Ni, X. Cao, Y. Ma, and F. Tian. Effect of temporal resolution of rainfall on simulation of urban flood processes. *Water 2018, 10, 880*, 2018. URL: https://doi.org/10.3390/w10070880.

[35] IPCC TGICA Expert Meeting. Integrating analysis of regional climate change and response options meeting report, 2007. URL: https://archive.ipcc.ch/pdf/supporting-material/tgica_reg-meet-fiji-2007.pdf.

[36] E. Mignot, A. Paqiuer, and A. Haider. Modeling floods in a dense urban area using 2d shallow water equations. *Journal of Hydrology*, 321(1-2):186–199, 2006. URL: https://doi.org/10.1016/j.jhydrol.2005.11.026.

[37] S. S. Mikkelsen. Evaluating analysis methods for stormwater control measures. Master's thesis, Norwegian University of Science and Technology (NTNU), 2022.

[38] T. Muthanna, E. Sivertsen, D. Kliewer, and L. Jotta. Coupling field observations and geographical information system (GIS)-based analysis for improved sustainable urban drainage systems (SUDS) performance. *Sustainability*, 10:4683, 2018. doi:https://doi.org/10.3390/su10124683.

[39] L. Nie, O. Lindholm, G. Lindholm, and E. Syversen. Impact of climate change on urban drainage systems – a case study in fredrikstad norway. *Urban Water J. 6 (4), 1-10*, 2011.

[40] NOU. 2015: 16. Overvann i byer og tettsteder. URL: https://www.regjeringen.no/no/dokumenter/nou-2015-16/id2465332/?ch=1.

[41] The City of Copenhagen. Cloudburst Management Plan 2012. page 6, 2012.

[42] H. V. Oral, P. Carvalho, M. Gajewska, N. Ursino, F. Masi, E. D. van Hullebusch, J. K. Kazak, A. Exposito, G. Cipolletta, T. R. Andersen, D.F. Finger, L. Simperler, M. Regelsberger,

V. Rous, M. Radinja, G. Buttiglieri, P. Krzeminski, A. Rizzo, K. Dehghanian, M. Nikolova, and M. Zimmermann. A review of nature-based solutions for urban water management in European circular cities: A critical assessment based on case studies and literature. *Blue-Green Systems 1*, 2(1):112–136, 2020.

[43] A. Palla and I. Gnecco. Hydrologic modeling of Low Impact Development systems at the urban catchment scale. *Journal of Hydrology*, 538:361 – 368.

[44] K. Paus and B. C. Braskerud. Forslag til dimensjonering og utforming av regnbed for norske forhold [recommendations for design of raingardens for Norwegian climate]. *Vann*, 1(48):54–67, 2013.

[45] K. Paus, T. Muthanna, and B. Braskerud. The hydrological performance of bioretention cells in regions with cold climates: Seasonal variation and implications for design. *Hydrology Research*, 2015.

[46] T.B. Pedersen, R. Bratlie, I.J. Verbaan, B. Sandal, S.T. Solbrå, A. M. Hagerup, T.G. Alexandra Marietta Röttorp, A. Fleig, M. Stickler, P. E. Sommer-Erichson, E. V. Dalen, I.C. Storteig, K. Tvedalen, L. W. Dören, and S. J. Sigrid Johanne Langsjøvold. NVE: Rettleiar for handtering av overvatn i arealplanar [The Norwegian Water Resources and Energy Directorate: Guidelines on stormwater management in municipality plans-]. 2022.

[47] V. Pons, T. Muthanna, E. Sivertsen, R. Benestad, and J. Bertrand-Krajewski. Revising green roof design methods with downscaling model of rainfall time series. *Water Science and Technology*, 85(5):1363–1371, 2022. `doi:10.2166/wst.2022.023`.

[48] C. Pyke, M. P. Warren, T. Johnson, J. LaGro, J. Scharfenberg, P. Groth, R. Freed, W. Schroeer, and E. Main. Assessment of low impact development for managing stormwater with changing precipitation due to climate change. *Landscape and Urban Planning, Volume 103, Issue 2, 2011, Pages 166-173,0*, 2011. URL: `https://doi.org/10.1016/j.landurbplan.2011.07.006`.

[49] RIF. State of the Nation. 2015.

[50] B. Rosenzweig, B. Ruddell, L. McPhillips, R. Hobbins, T. McPhearson, Z. Cheng, H. Chang, and Y. Kim. Developing knowledge systems for urban resilience to cloudburst rain events. *Environmental Science Policy*, 99:150–159, 2019. `doi:https://doi.org/10.1016/j.envsci.2019.05.020`.

[51] L. Ruangpan, Z. Vojinovic, S. Di Sabatino, L. Leo, V. Capobianco, A. M. P. Oen, M. E. McClain, and E. Lopez-Gunn. Nature-based solutions for hydro-meteorological risk reduction: A state-of-the-art review of the research area. *Nat. Hazards Earth Syst. Sci., 20, 243–270*, 2022. URL: `https://doi.org/10.5194/nhess-20-243-2020`.

[52] M. Rubinato, Martins. R, G. Keserwani, J. Leandro, S. Djordjević, and J. Shucksmith. Experimental calibration and validation of sewer/surface flow exchange equations in steady and unsteady flow conditions. *Journal of Hydrology, Volume 552*, 2017.

[53] B. Russo, M. Gómez, and F. Macchione. Pedestrian hazard criteria for flooded urban areas. *Natural Hazards*, 69(1):251–265, 2013.

[54] B. Russo, M.G. Valentín, and J. Tellez-Álvarez. The relevance of grated inlets within surface drainage systems in the field of urban flood resilience. *Sustainability*, 13(13):7189, 2021. `doi:https://doi.org/10.3390/su13137189`.

[55] Spraakman S., J-L. Martel, and J. Drake. How much water can bioretention retain, and where does it go? *Blue-Green Systems 1*, 4(2):89–107, 2022. `doi:https://doi.org/10.2166/bgs.2022.002`.

[56] L. Shoemaker, Jr.J. Riverson, K. Alvi, J. X. Zhen, S. Paul, and T. Rafi. Sustain - a framework for placement of best management practices in urban watersheds to protect water quality. *No. EPA/600/R09/095). Cincinnati (U.S.): U.S. Environmental Protection Agency.*, 2009.

[57] T. Skrede, T. Muthanna, and K. Alfredsen. Challenges with identification and management of floodways as stormwater infrastructure assets. 2021.

[58] T. Skrede, T. Muthanna, and K. Alfredsen. Comparison of tools for mapping floodways in urban planning. 2022. From the 12th Urban Drainage Modeling Conference, California. URL: `https://udm2022.org/wp-content/uploads/2021/11/1247_Skrede_REV-97c3f4e9.pdf`.

[59] C. Vitale. Understanding the shift toward a risk-based approach in flood risk management, a comparative case study of three Italian rivers. *Environmental Science Policy*, 146:13–23, 2023. `doi:https://doi.org/10.1016/j.envsci.2023.04.015`.

[60] B. Woods, B. Wilson, H. Udal-Clarke, S. Ilman, T. Scott, and R. 2015 Ashley. The SUDS Manual, CIRIA, London, UK.

[61] Q. Zhou, G. Leng, J Su, and J. Ren. Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation. *Science of The Total Environment*, 658(13):24–33, 2019. doi:10.1016/j.scitotenv.2018.12.184.

A - NBS SITE DETECTION METHOD

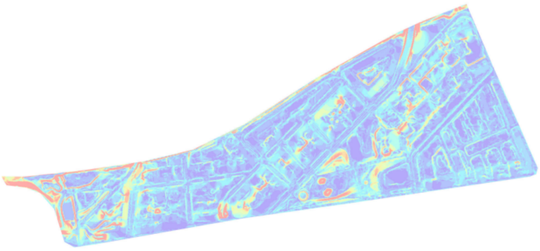
```python
import arcpy

def Model():  # Model

    # To allow overwriting outputs change overwriteOutput option to True.
    arcpy.env.overwriteOutput = False

    ProjectArea = "ProjectArea"
    Roads = "Roads"
    Buildings = "Buildings"
    dtm1_33_124_141_tif = arcpy.Raster("dtm1_33_124_141.tif")

    # Process: Erase Roads
    Output_Feature_Class = "C:\\Users\\NGC\\OneDrive - NTNU\\01. GIS\\
    Lademoen_NBS\\Lademoen_NBS.gdb\\ProjectArea_Erase"
    arcpy.analysis.Erase(in_features=ProjectArea, erase_features=Roads,
    out_feature_class=Output_Feature_Class, cluster_tolerance="")

    # Process: Erase Buildings
    Undeveloped_Area = "C:\\Users\\NGC\\OneDrive - NTNU\\01. GIS\\Lademoen_NBS\\
    Lademoen_NBS.gdb\\Undeveloped_Area"
    arcpy.analysis.Erase(in_features=Output_Feature_Class, erase_features=
    Buildings, out_feature_class=Undeveloped_Area, cluster_tolerance="")

    # Process: Slope Analysis
    Slope_2_ = "C:\\Users\\NGC\\OneDrive - NTNU\\01. GIS\\Lademoen_NBS\\
    Lademoen_NBS.gdb\\Slope"
    Slope = Slope_2_
    Slope_2_ = arcpy.sa.Slope(in_raster=dtm1_33_124_141_tif, output_measurement=
    "DEGREE", z_factor=1, method="PLANAR", z_unit="METER")
    Slope_2_.save(Slope)


    # Process: Reclassify to =< 5 % slope
```

```
    Slope_5_perc = "C:\\Users\\NGC\\OneDrive - NTNU\\01. GIS\\Lademoen_NBS\\
Lademoen_NBS.gdb\\Slope_5_perc"
    Reclassify = Slope_5_perc
    Slope_5_perc = arcpy.sa.Reclassify(in_raster=Slope_2_, reclass_field="VALUE"
, remap="0 5 1", missing_values="DATA")
    Slope_5_perc.save(Reclassify)


    # Process: Combine slope and undeveloped area
    NBS_Suitability = "C:\\Users\\NGC\\OneDrive - NTNU\\01. GIS\\Lademoen_NBS\\
Lademoen_NBS.gdb\\NBS_Suitability"
    Combine = NBS_Suitability
    NBS_Suitability = arcpy.sa.Combine(in_rasters=[Undeveloped_Area,
Slope_5_perc])
    NBS_Suitability.save(Combine)


if __name__ == '__main__':
    # Global Environment settings
    with arcpy.EnvManager(scratchWorkspace=r"C:\Users\NGC\OneDrive - NTNU\01.
GIS\Lademoen_NBS\Lademoen_NBS.gdb", workspace=r"C:\Users\NGC\OneDrive - NTNU
\01. GIS\Lademoen_NBS\Lademoen_NBS.gdb"):
        Model()
```

Listing 1: NBS Site Detection Analysis - conducted in ArcGIS Pro

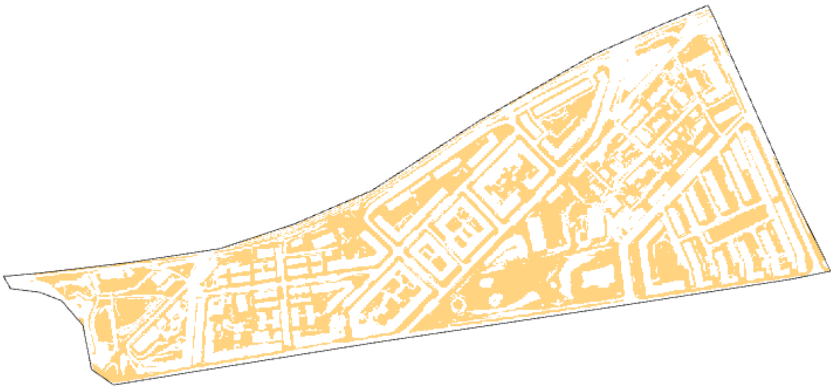
(**a**) DTM. ↓

(**b**) Developed Area. ↓



(**c**) Slope Analysis. ↘

(**d**) Undeveloped Area. ↙



(**e**) NbS Area from GIS Analysis.

Figure 1: GIS Analysis for NbS Area Detection illustrated. Slope Analysis was based on DTM, and map of undeveloped area was made from erasing developed area. Combining slope and undeveloped area provided the suitable NbS area.

B - MODELING ENVIRONMENT

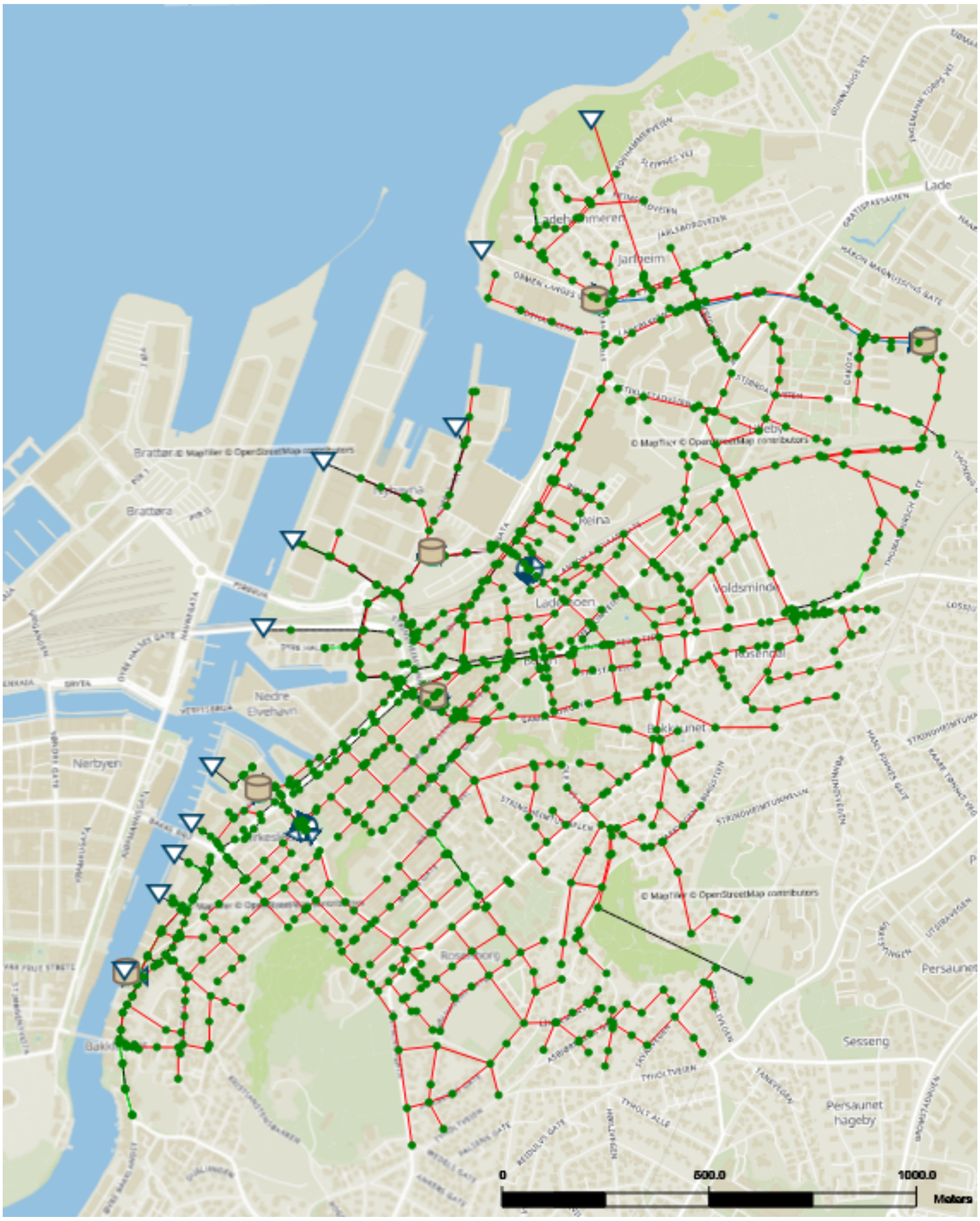


Figure 2: 1D Urban Drainage System Model.

2D-model

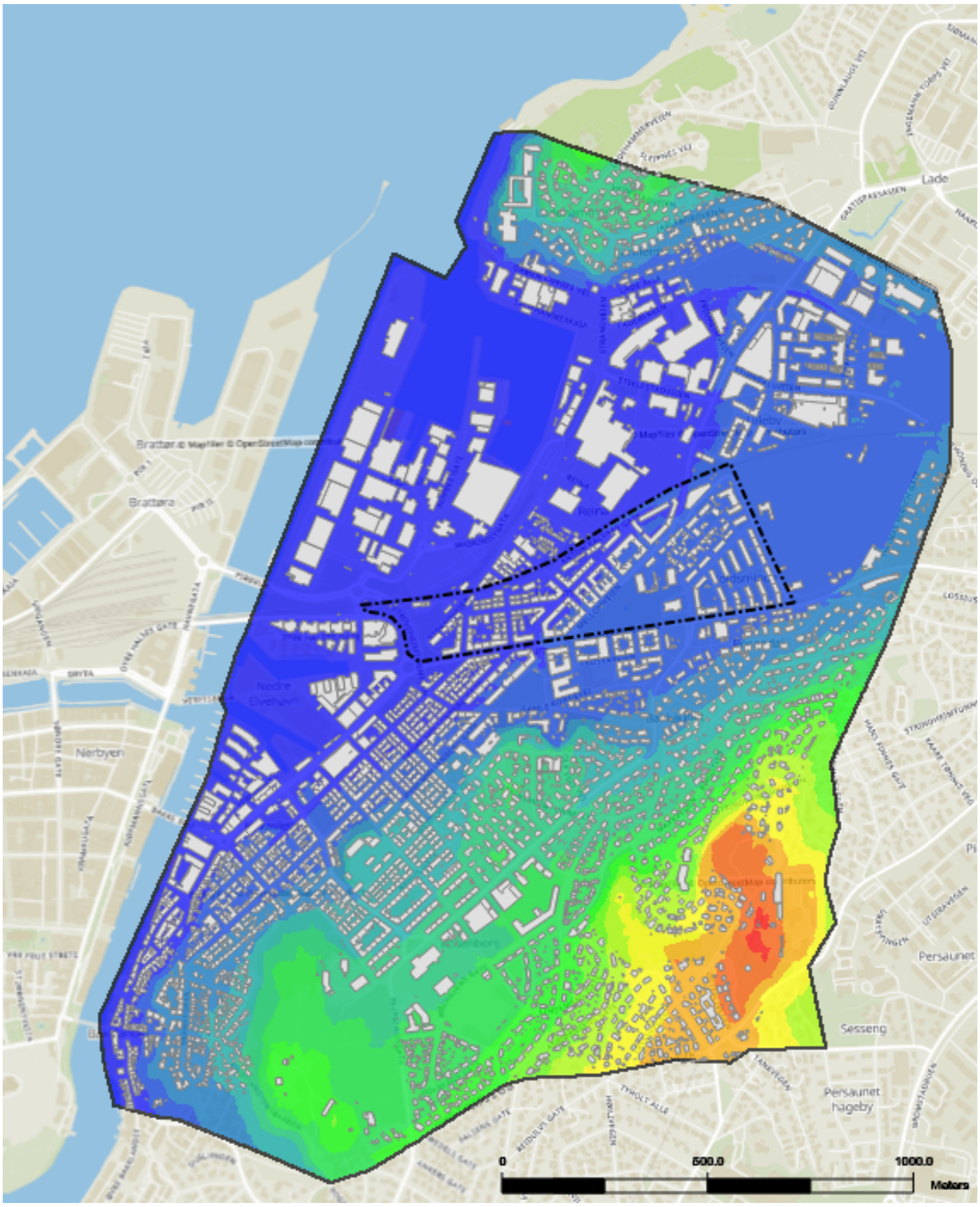
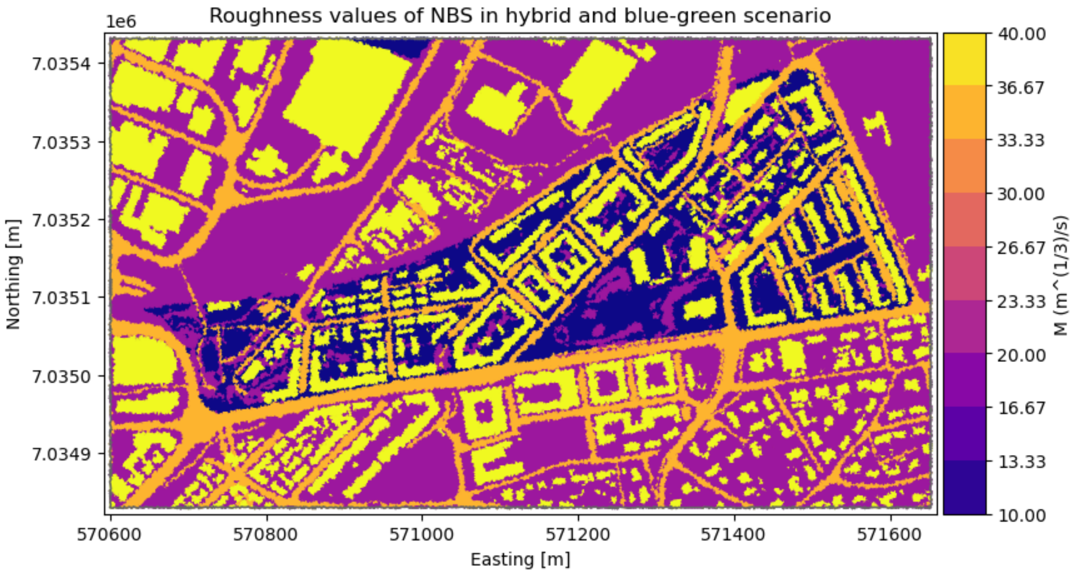


Figure 3: 2D Surface Model - Project area is outlined with dashed line lines.

(**a**) Roughness values for existing conditions.



(**b**) Roughness values with NBS implemented.

Figure 4: Manning roughness values.

RP	Climate	Scenario
2, 5, 10, 20	Past	Conventional
2, 5, 10, 20	Future	Conventional
2, 5, 10, 20	Past	Hybrid
2, 5, 10, 20	Future	Hybrid
2, 5, 10, 20	Past	Blue-Green
2, 5, 10 (ensemble), 20, 100	Future	Blue-Green

Table 1: Simulations overview

Simulation Setup	
Simulation Period	01.01.2020 - 01.02.2020
Simulation Type	Catchments, Collection system network, 2D Overland
Modules	Rainfall-runoff, Catchment Discharge, Hydrodynamic
Time Step	Min: 0,01 s
	Max: 3 s
Max CFL Factor	0,8

Table 2: Simulation Setup

D - POST-PROCESSING RESULTS

```
def Model():
    arcpy.env.overwriteOutput = False

    arcpy.ImportToolbox(r"c:\program files\arcgis\pro\Resources\ArcToolbox\
toolboxes\Data Management Tools.tbx")
    Flood_statistics_asc = arcpy.Raster("Flood_statistics.asc")
    ProjectArea = "ProjectArea"

    #Process: Reclassify (Reclassify) (sa)
    Reclass = "C:\\Users\\NGC\\OneDrive - NTNU\\Documents\\ArcGIS\\Projects\\
MyProject\\MyProject.gdb\\Reclass"
    Reclassify = Reclass
    Reclass = arcpy.sa.Reclassify(in_raster = Hybrid_2RP_Past0_asc,
reclass_field="VALUE", remap="0 0,049000 1;0,049000 0,099000 2;0,099000 20 3
", missing_values="DATA")
    Reclass.save(Reclassify)


    #Process: Clip Raster (Clip Raster) (management)
    Reclass_Clip1 = "C:\\Users\\NGC\\OneDrive - NTNU\\Documents\\ArcGIS\\
Projects\\MyProject\\MyProject.gdb\\Reclass_Clip1"
    arcpy.management.Clip(in_raster=Reclass, rectangle="570600,429900001
7034948,15630388 571652,0999 7035430,9354053", out_raster=Reclass_Clip1,
in_template_dataset=ProjectArea, nodata_value="", clipping_geometry="
ClippingGeometry", maintain_clipping_extent="NO_MAINTAIN_EXTENT")
    Reclass_Clip1 = arcpy.Raster(Reclass_Clip1)

    #Process: Raster to Polygon (Raster to Polygon) (conversion)
    RasterT_Reclas11 = "C:\\Users\\NGC\\OneDrive - NTNU\\Documents\\ArcGIS\\
Projects\\MyProject\\MyProject.gdb\\RasterT_Reclas11"
    with arcpy.EnvManager(outputMFlag="Disabled", outputZFlag="Disabled"):
        arcpy.conversion.RasterToPolygon(in_raster=Reclass_Clip1,
out_polygon_features=RasterT_Reclas11, simplify="SIMPLIFY", raster_field="",
 create_multipart_features="SINGLE_OUTER_PART", max_vertices_per_feature=
```

```
None)

    #Process: Add Field (Add Field) (management)
    RasterT_Reclas11_2_ = arcpy.management.AddField(in_table=RasterT_Reclas11, field_name="Area", field_type="LONG", field_precision=None, field_scale=None, field_length=None, field_alias="", field_is_nullable="NULLABLE", field_is_required="NON_REQUIRED", field_domain="")[0]

    #Process: Calculate Geometry Attributes (Calculate Geometry Attributes) (management)
    RasterT_Reclas11_3_ = arcpy.management.CalculateGeometryAttributes(in_features=RasterT_Reclas11_2_, geometry_property=[["Area", "AREA"]], length_unit="", area_unit="SQUARE_METERS", coordinate_system="PROJCS[\"ETRS_1989_UTM_Zone_32N\",GEOGCS[\"GCS_ETRS_1989\",DATUM[\"D_ETRS_1989\",SPHEROID[\"GRS_1980\",6378137.0,298.257222101]],PRIMEM[\"Greenwich\",0.0],UNIT[\"Degree\",0.0174532925199433]],PROJECTION[\"Transverse_Mercator\"],PARAMETER[\"False_Easting\",500000.0],PARAMETER[\"False_Northing\",0.0],PARAMETER[\"Central_Meridian\",9.0],PARAMETER[\"Scale_Factor\",0.9996],PARAMETER[\"Latitude_Of_Origin\",0.0],UNIT[\"Meter\",1.0]],VERTCS[\"NN2000_height\",VDATUM[\"Norway_Normal_Null_2000\"],PARAMETER[\"Vertical_Shift\",0.0],PARAMETER[\"Direction\",1.0],UNIT[\"Meter\",1.0]]", coordinate_format="SAME_AS_INPUT")[0]

if __name__ == '__main__':
    #Global Environment settings
    with arcpy.EnvManager(scratchWorkspace=r"C:\Users\NGC\OneDrive - NTNU\Documents\ArcGIS\Projects\MyProject\MyProject.gdb", workspace=r"C:\Users\NGC\OneDrive - NTNU\Documents\ArcGIS\Projects\MyProject\MyProject.gdb"):
        Model()
```

Listing 2: Processing raster flood data in ArcGIS PRO

```

import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
import itertools

file_path_p = r"/Users/nadjagrozdanic/Library/CloudStorage/OneDrive-NTNU/04.Script/Results_Past.xlsx"
file_path_f = r"/Users/nadjagrozdanic/Library/CloudStorage/OneDrive-NTNU/04.Script/Results_Future.xlsx"
```

```
results_past = pd.read_excel(file_path_p, sheet_name = "Results", index_col=[0])
results_future = pd.read_excel(file_path_f, sheet_name = "Results", index_col
    =[0])

total_area = 214500  # Total area, used for percentage calculations

RP = [2, 5, 10, 20]  # List of all return periods
SC = ['C', 'H', 'BG']  # List of all scenarios

def flooded_area(df):
    under_five = df.loc[df['gridcode'] == 1, 'Area'].sum() / total_area * 100
    five_to_ten = df.loc[df['gridcode'] == 2, 'Area'].sum() / total_area * 100
    above_ten = df.loc[df['gridcode'] == 3, 'Area'].sum() / total_area * 100
    return above_ten

def SC_RP(SC,RP):  # SC refers to acronym of scenario (letter), RP to return
    period (number)
    sheet = SC + '_'+ str(RP) + 'RP'   # Excel sheet
    results_p = pd.read_excel(file_path_p, sheet_name=sheet)
    results_past.loc[RP,SC] = flooded_area(results_p)
    results_f = pd.read_excel(file_path_f, sheet_name=sheet)
    results_future.loc[RP,SC] = flooded_area(results_f)

for r in itertools.product(SC, RP):
    SC_RP((r[0]), (r[1]))


# Change Factor:
sns.set(font_scale=1.8)

fig, ax = plt.subplots(figsize=(20, 15))
CF = (results_future - results_past) / results_past
CF.rename(columns = {"C": "$CR_{C}$", "H": "$CR_{H}$", "BG": "$CR_{BG}$"},
    inplace = True)

CF["$IMP_{P}$"] = (results_future['C'] - results_future['H']) / results_future['
    H']
CF["$IMP_{F}$"] = (results_past['C'] - results_past['H']) / results_past['H']

ax = sns.heatmap(CF, cmap='plasma', linewidth = 0.3, annot = True)
ax.set(ylabel='RP')
```

```

plt.savefig('Heatmap.png', dpi=300)
plt.show()

# Flood Risk Plot

results_past.rename(columns = {"C": "Conventional (Past)", "H": "Hybrid (Past)",
    "BG": "Blue-Green (Past)"}, inplace = True)
results_future.rename(columns = {"C": "Conventional (Future)", "H": "Hybrid (
    Future)", "BG": "Blue-Green (Future)"}, inplace = True)



ax1 = results_past.plot(figsize=(20,15),style='-', linewidth = 3, label= "C",
    color = ['orange', 'darkviolet', 'mediumblue'], marker = '.',markerfacecolor
    ='none', markersize = 25)
results_future.plot(ax=ax1, style='--', linewidth = 3, label ='BG', color = ['
    orange', 'darkviolet', 'mediumblue'], marker = 'x', markersize = 20)
plt.xticks(results_past.index,['50', '20', '10', '5'])
plt.ylim(0,10)

ax1.set(ylabel='Flooded Area (%)', xlabel = 'Occurence probability (%)')
plt.savefig('Flood_Risk.png', dpi=300)
plt.show()
```

Listing 3: Python Script for Flood Risk Calculations

NTNU

Norwegian University of
Science and Technology