Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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Evaluating Analysis Methods for Stormwater Control Measures

Master's thesis in Civil and Environmental Engineering
Supervisor: Tone Merete Muthanna
Co-supervisor: Thea Ingeborg Skrede and Kristin Jenssen Sola
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Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU), as the final product of the course TVM4905 - Water Supply and Wastewater Systems, Master's Thesis. The thesis is written in the manuscript format, a more compact format than the traditional thesis format at NTNU. It is written according to the structure of a research article, with the goal of publishing the thesis in a scientific journal. The topic of the thesis is analysis methods of stormwater control measures, how they differ and how they can be improved.

My main supervisor was professor Tone Merete Muthanna. I would like to express my deepest gratitude for her advice, support and guidance throughout this process. Besides, i would like to thank my two co-supervisors, Thea Ingeborg Skrede and Kristin Jenssen Sola. Thea Ingeborg Skrede works for Norconsult and is a PhD candidate at NTNU, and her insights and enthusiasm provided very valuable input and continuous motivation. Kristin Jenssen Sola works for Asker municipality and holds a PhD from NMBU, and her broad experience and deep knowledge of the municipal water sector was highly valuable. I would like to especially thank her for giving me the possibility of cooperating with Asker municipality for this thesis, which has been a very positive experience. I would also like to thank my family and friends for their everlasting support.

Finally, i would like to thank all of the following, who have been willing to take time out of their busy schedules to discuss, comment, provide insights and answer questions.

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Sigurd Semb Mikkelsen

Sammendrag

Investeringsbehovet i det urbane overvannssystemet forventes å øke i løpet av de kommende årene. Kombinasjonen av hyppigere ekstremhendelser og flere tette flater krever både økt kapasitet og økt fleksibilitet i overvannssystemet. For å minimere investeringskostnadene og oppnå størst mulig effekt er det avgjørende å identifisere den best mulige kombinasjonen av overvannstiltak i hvert enkelt tilfelle. Etter hvert som forståelsen for de mangfoldige konsekvensene av både grå og blå-grønne overvannstiltak øker, øker også kompleksiteten i denne oppgaven. Den omfatter nå en vurdering av et bredt spekter av positive og negative bieffekter av tiltakene. Denne vurderingen kan blant annet gjøres ved bruk av multikriterieanalyser eller kost-nytteanalyser. Multikriterieanalyser er mindre arbeidskrevende, og tilrettelegger godt for å inkludere flere parter i vurderingene, men har også visse svakheter. De kan påvirkes av subjektive meninger, og kan resultere i langt større eller mindre implisitte monetære verdsettelser av visse aspekter enn det som var intensjonen. Kost-nytteanalyser kan langt på vei eliminere disse problemene, men er langt mer arbeidskrevende å gjennomføre. Denne masteroppgaven sammenligner disse analysemetodene, og utforsker muligheten til å bruke en kost-nytteanalyse til å kalibrere og veilede bruken av en multikriterieanalyse. Det utføres en kost-nytteanalyse av forskjellige kombinasjoner, kalt tiltakspakker, av overvannstiltak i et forstadsområde i Asker kommune. Den monetære verdien av kostnader, redusert skadepotensial, og flere positive og negative bieffekter av tiltakene blir vurdert, blant annet ved bruk av flere modellverktøy. Basert på denne framgangsmåten rangeres tiltakspakkene etter netto nåverdi. De samme tiltakspakkene vurderes i en multikriterieanalyse, og resultatene fra analysemetodene sammenlignes. Hovedfunnene er at både multikriterieanalysen og kost-nytteanalysen rangerte tiltakspakkene likt, men basert på veldig ulikt grunnlag. Multikriterieanalysen evnet ikke å identifisere selv svært store forskjeller i netto nåverdi for de ulike tiltakspakkene, men vurderte dem til å presetere nesten likt.

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Abbreviations

MCDA	Multi-Criteria Decision Analysis
CBA	Cost-Benefit Analysis
LID	Low Impact Development
NPV	Net Present Value
DEM	Digital Elevation Model
EAD	Expected Annual Damages

EVALUATING ANALYSIS METHODS FOR STORMWATER CONTROL MEASURES

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June 30, 2021

Abstract

The investment needs in urban drainage infrastructure are expected to increase worldwide over the coming years. A combination of more frequent extreme events and less impervious cover demands both increased capacity and increased flexibility in the urban drainage infrastructure. To minimize the investment need and maximize the impact, the correct identification of the optimal combination of stormwater control measures in each case is crucial. As the understanding of the diverse impacts of both grey and blue-green stormwater control measures is broadening, this task is increasingly complicated. It now involves assessment of a wide range of co-cost and co-benefits. This assessment can for instance be achieved through use of either a multi-criteria decision analysis (MCDA) or a cost-benefit analysis (CBA). MCDAs are less work-intensive and easily allow stakeholder inclusion. However, they suffer from subjective biases, and if not carefully assessed, can result in implicitly valuating certain aspects far higher or lower than intended. CBAs largely eliminates these problems but demands far more resources to perform. This study compares these analysis methods and explores the possibility of using a CBA to calibrate and guide the use of a MCDA. A CBA is performed on several combinations, or bundles, of stormwater control measures in a suburban case area in Asker, Norway. By assessing the monetary value of several co-costs and co-benefits, partly through use of several modelling tools, the bundles are ranked according to net present value. The same bundles are assessed using a MCDA, and the results of the two analysis methods are compared. The main findings were that the MCDA and the CBA concluded with the same optimal solution, however based on very different valuations. The MCDA failed to identify the wide variety in performance of the bundles.

Keywords: Urban Flood Modelling, Flooding Damages, Co-Benefits, Cost-Benefit Analysis, Multi Criteria Decision Analysis

1 Introduction

In his seminal paper ”Sustainability and Intergenerational Justice”, the British philosopher Brian Barry argued, about ”measures intended to improve the prospects of future generations”, that ”...such measures do not represent optional benevolence on our part, but are demanded by elementary considerations of justice” (Barry, 1997). Despite certain shortcomings in living up to this ideal, it remains a widely held notion that the current generations have an obligation to ensure the possibility of prosperity for future generations. This is perhaps most famously stated in the much-cited definition of sustainable development from the Brundtland Commission. ”Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1988). The pursuit of sustainable development has immense consequences for almost all aspects of society. Sustainable development of infrastructure gets at the hearth of the challenge. Infrastructure management is characterized by long planning horizons, and highly costly, slow-moving projects designed for long lifespans. The high costs and long lifespans underline the need for careful assessment of the balance between the diverse needs of current and future generations with the ability of the current generation to carry the costs. A failure to correctly strike this balance could result in implementation of sub-optimal projects, with costly and prolonged adverse consequences.

Shortcomings in sustainable development of infrastructure systems can be illustrated by assessing the field of urban stormwater management in Norway. Due to long term underinvestment and a failure to adapt to changing boundary conditions, the urban stormwater infrastructure in Norway is currently suffering from a lack of capacity (Breen, 2020; Rådgivende Ingeniørers Forening, 2019). There are considerable costs associated with investments and damages as a result of this. The costs of investments in water, wastewater and stormwater infrastructure are expected to increase by between 100 and 200 % over the next 20 years, with an investment need of 114 billion NOK for wastewater and stormwater infrastructure until 2040 (Norsk Vann, 2021). At the same time, the yearly socioeconomic cost of damages resulting from stormwater is estimated to be between 1.6 and 3.6 billion NOK and are expected to increase in the future (Skaaraas et al., 2015).

The current lack of capacity can partially be explained with changes in the boundary conditions of stormwater management. The main drivers of this change are climate change and urbanization, both of which contribute to increased amounts of stormwater for the infrastructure to handle (Skaaraas et al., 2015). Climate change leads to increased precipitation in Norway (Norsk Klimaservicesenter, 2017). Since 1900, this increase has been around 20%, most of which has occurred since 1980 (Miljøverndepartementet, 2013). The estimations that best describe the current precipitation amounts suggest an increase of up to 50% until 2100 for seasonal precipitation amounts in many parts of the country (Miljøverndepartementet, 2013). Urbanization replaces pervious area such as forests and plains with impervious cover such as rooftops and pavement, thereby reducing local infiltration and increasing the amount of area contributing to runoff. Like the rest of the world, Norway is experiencing a trend towards increased urbanization, which is expected to continue (SSB, 2020). Combined, these drivers puts the traditional stormwater infrastructure under increased pressure.

Traditionally, the goal of stormwater management has been to remove surface runoff from the urban areas as quickly as possible, utilizing gutters, drains and underground pipe systems, typically referred to as grey infrastructure. Due to the above-mentioned drivers, these systems are increasingly undersized for the current conditions (Eckart, McPhee, and Bolisetti, 2017). The costs of a sufficient up-scaling of the current system are immense (Rasmussen, 2016). As a result, a paradigm change in the approach to stormwater management is underway. This paradigm shift has been diversely framed and formulated in a wide range of published literature, as summarized by Fletcher et al., 2015. Despite differences in origins and scope, these concepts generally share the overarching approach to stormwater management. Instead of conveying stormwater away as quickly as possible, stormwater is instead managed as close to the source as possible, slowed down, detained, infiltrated and evapotranspired. By focusing on water balance, minimizing development of natural area, and utilizing local potential for detention, the existing stormwater infrastructure is provided with less water over more time, reducing the demand for peak capacity. This can partly be achieved through introduction of green infrastructure, such as green roofs and rain gardens. This approach, henceforth referred to as Low Impact Development (LID) is not considered to be an alternative to the traditional approach, but rather a supplement, achieving a more cost-effective system than either approaches on their own (Eckart, McPhee, and Bolisetti, 2017).

Despite the maturity of LID as a paradigm, there is a significant gap between the guiding principles as stated in published literature, and operational plans on the municipal level (Palazzo, 2019). To fill this gap, several frameworks for the practical implementation of these approaches have been suggested (La Loggia, Puleo, and Freni, 2020; Fratini et al., 2012; among others). The emphasis and nuances vary across the frameworks, but some key themes are recurring. Managing the watershed as a whole, stakeholder involvement, appreciation of complexity/system interactions, utilizing local potential, and creating robust systems that can function during or shortly after flood events is common in these frameworks. This moves the goal from fail-safe systems that are designed to convey all water, to safe-to-fail systems that can be flooded without excessive damages (Kim et al., 2017, among others). In Norway, LID has mainly been operationalized through an approach commonly referred to as the Three Step Approach (O. Lindholm et al., 2008). This approach suggests different management practices for different sizes of rainfall events, where small events are to be infiltrated, medium events should be detained, and safe flood-ways should be provided for the largest events. The Three Step Approach has become the industry standard for implementing LID in practice in Norway.

LID entails an increased utilization of urban surface area for stormwater management. Since such areas are at a premium, it is often not feasible to design large single-purpose open stormwater infrastructure in urban areas. The areas must be multi-functional, providing benefits to the urban environment during the time it is not actively functioning as stormwater infrastructure. The design of urban areas for stormwater management thus demands a multidisciplinary approach. Urban areas are highly complex, and stormwater professionals must work together with professionals from other disciplines, such as city planners, landscape architects and biologists. Additionally, as the distribution of risk, ownership and responsibilities of land and stormwater infrastructure is severely fragmented, complex legal questions regularly arise in stormwater management, requiring close cooperation with legal professionals (Miljøverndepartementet, 2010). This increasingly multidisciplinary approach puts stormwater professionals in a new position to both solve a problem that would otherwise be a constant resistance to development, and actively create more livable, safe, resilient urban areas. Thereby, the work of stormwater professionals can both help advancing intergenerational equity, as well as the progress towards several of the UN sustainable development goals (Bent C Braskerud and Paus, 2020).

Despite the new possibilities this presents, the increased multi-functionality in stormwater management complicates the assessment methodology used to evaluate the the measures involved. Multi-functional measures introduce a wide variety of costs and benefits beyond the main goal of the project (Alves, Gersonius, Kapelan, et al., 2019). A rain garden implemented to reduce peak flow can for instance provide improved air quality and aesthetic values, but also lead to increased greenhouse gas emissions. These costs and benefits are referred to as co-costs and co-benefits, and the correct prioritization between different measures requires careful consideration of these factors.

When including co-costs and co-benefits in the assessment, prioritization of measures is often done through multi-criteria decision analysis (MCDA) (Alves, Gersonius, Sanchez, et al., 2018). In a MCDA, measures are compared by assessing each measures performance according to several criteria. MCDA is a qualitative approach, wherein each measure is given a score to represent its performance within each criterion. Additionally, criteria are weighted according to their respective importance to the overall assessment. The assessment is commonly done in groups, which opens the possibility for including several stakeholders with different backgrounds: both professional and otherwise. Based on the scores and weights, a total score of each measure is obtained. The measure with the highest total score will then be the measure which performance is most in line with the stated prioritization of the stakeholders. Despite its widespread use, MCDA has significant weaknesses. As the scoring is not directly tied to any performance indicators, the approach is inherently subjective. This opens the door for subjective biases to influence the outcome of the analysis (Marttunen, Belton, and Lienert, 2018).

An alternative approach to assessment of measures is a cost-benefit analysis (CBA). In a CBA, all costs and benefits of the measures are assessed in monetary terms. However, for several cost and benefits, no exact monetary value exists, as there is no market where the costs and benefits are traded. These values are referred to as non-market values, and they can be estimated using non-market valuation methods (Wise et al., 2010). When all values are estimated, the net present value (NPV) of each measure is calculated, using a discount rate to account for the time-value of money. Measures with a positive NPV are considered socio-economically profitable, and the measure with the highest NPV is the most profitable measure. As all values are derived based on existing data and valuation studies, the CBA approach can potentially lead to a less biased assessment than the MCDA approach. However, there is a lack of non-market valuation studies for several co-costs and co-benefits provided by stormwater infrastructure, therefore this approach cannot paint a complete picture of the costs and benefits of stormwater control measures (Wise et al., 2010). Still, as CBA offers a more accurate estimation than MCDA for the costs and benefits for which monetary valuation has been sufficiently documented, there could be merit to using a CBA to evaluate and improve existing MCDA approaches. Since MCDAs use weighting and scoring of criteria to determine the best measures but lack objective data to assess the validity of the determined values, CBAs could potentially fill this gap and provide calibration of MCDAs. No research has been found which uses this approach, and this study aims to help fill this research gap. In this study, the approach was tested by performing both a CBA and a MCDA on several stormwater control measures in a case area in Asker municipality. The goal of the study was to determine differences in the results of the analysis methods, explore the possibility of using a CBA to calibrate a MCDA, and evaluate the data needs for providing better CBAs in the future. Based on these goals, the following research questions were formulated:

- How does the valuations and optimal solution in the CBA and the MCDA differ?
- How can a CBA be used to calibrate a MCDA?
- What data does Asker municipality need to perform more accurate CBAs?

2 Method

To compare the assessments made by a MCDA and a CBA, both methods were applied to potential stormwater control measures in a case area in Asker municipality. Figure 1 displays a flow chart of the methodology.

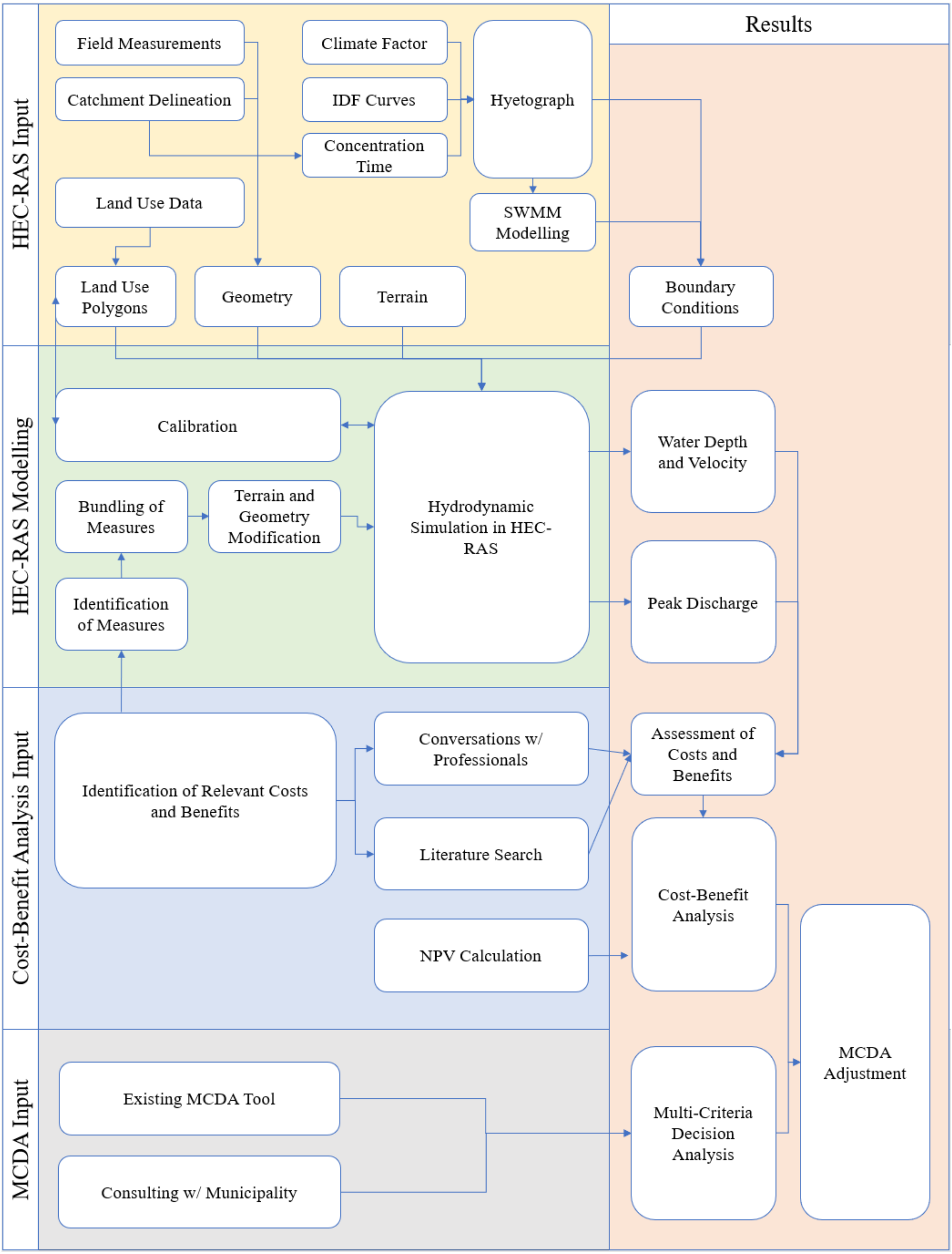


Fig. 1: Methodology flow chart. The two sided arrows between "Hydrodynamic Simulation in HEC-RAS", "Calibration" and "Land Use Polygons" represents the iterative process of calibrating the model through changing the land use data.

To provide context, a description of the case area is included. The following description was written as a part of a previous project work and is reproduced in a condensed and slightly altered form here. The original can be found in the project work, Attachment 1.

2.1 Description of Case Area

The Hvalstad district was selected as the case area for this study. Located 10 km west of Oslo and spanning roughly 1km^2, the area is long and narrow, defined by the catchment area of a local stream. From a small dam in the uppermost part of the case area, the stream runs partly open and partly closed through a suburban area characterized by single housing, large open spaces, and small suburban roads. Halfway through the area, the stream runs through a small field, just upstream of a railway embankment. Downstream of the embankment there is another suburban housing area, where the stream runs along a small road, before entering a large field. Then, the stream enters an industrial area. This area is right next to E18, the main westward highway from Oslo, and contains a large vegetated natural depression. Downstream of this area the stream runs closed. This pipe meets another piped stream from further south, where the pipe capacity regularly have been exceeded during large rain events. Figure 2 and 3 displays the location and an overview of the area.

The area is quite steep, with an elevation difference of about 165 meters from the highest point upstream of the dam to the lowest point at the stream intake upstream of the highway.

Historically, there have been significant stormwater problems in the area, especially due to basement flooding. Basement flooding has been reported both as a result of stream flooding and as a result of pluvial flooding (Sweco, 2017), and the houses north of the stream, downstream of the railway embankment have been especially vulnerable. Stream flooding has been particularly prevalent when intakes have been blocked. The area has been identified as one of the priority areas in the municipality's stormwater management plan (Asker Kommune, 2020)

2.2 Stormwater control measures

In a previous project work, a list of potential stormwater control measures in the area was synthesized. The following measures were to be assessed:

- Expansion of culverts
- Construction of detention area upstream of the railway embankment (Detention Basin 1)
- Construction of detention area in the natural depression within the industrial area (Detention Basin 2)
- Disconnection of downspouts
- Construction of green roofs and rain gardens in the industrial area
- Construction of safe floodway downstream of the railway embankment (Floodway 1)
- Construction of safe floodway upstream of the industrial area (Floodway 2)

An overview of the measures is provided in Figure 4.

Fig. 2: Location of case area.

Fig. 3: Overview of case area.

Fig. 4: Overview of stormwater control measures measures. Downspout disconnections not included here. For downspout disconnections, see Table 3

2.3 Bundling of Measures

Based on conversations with the municipality, it was assumed that no single measure would be enough to sufficiently reduce the flood risk in the area. Additionally, as the effects of the measures were to be modelled, simulation time in the model limited the amount of simulations that could be performed. Measures were therefore combined into three different combinations, or bundles. The flood modelling assessed the performance of the bundles, and not of the individual measures. The bundles were therefore designed with enough diversity to still allow for identification of each measure's individual contribution to the overall performance of the bundle. Further, the bundles were designed to be actionable for the municipality, with each bundle aiming to provide holistic stormwater management for the entire area. The following bundles were designed:

Bundle 0:

- Current situation - No measures

Bundle 1:

- Construction of detention area upstream of railway embankment
- Construction of detention area in the natural depression within the industrial area
- Disconnection of downspouts
- Construction of green roofs and rain gardens in the industrial area

Bundle 2:

- Expansion of culverts
- Construction of detention area upstream of railway embankment

- Construction of detention area in the natural depression within the industrial area
- Disconnection of downspouts
- Construction of green roofs and rain gardens in the industrial area
- Construction of safe floodway downstream of the railway embankment
- Construction of safe floodway upstream of the industrial area

Bundle 3:

- Construction of detention area in the natural depression within the industrial area
- Construction of safe floodway downstream of the railway embankment
- Construction of safe floodway upstream of the industrial area

2.4 Costs and Benefits

To perform the CBA, all relevant costs and benefits were defined. Based on a previous project work, a list of relevant costs and benefits which realistically could be valued monetarily was synthesised. The following costs and benefits were chosen:

- Flood damage reduction
- Peak flow reduction
- Investment cost
- Operation/maintenance cost
- Net CO_2 emissions
- Improved air quality
- Increased roof longevity

All costs and benefits of each measure were assessed in monetary terms. The assessment methodology was highly diverse. For some costs and benefits, monetary valuation was readily available, while for others, the monetary value was estimated based on modelling, literature review, interviews with experienced professionals, or a combination of these. An overview of the assessment method for each identified cost and benefit is provided in Table 1.

2.5 Multi-Criteria Decision Analysis

Based on the identified measures, a MCDA was performed. The MCDA was performed using an existing tool, currently in use by Asker municipality. In the MCDA tool, relevant costs and benefits are defined within five categories. The categories are: "Values", "Society", "Environment", "Financial" and "Social". Additionally, the monetary costs of the measures are entered as a separate input. Finally, the estimated risk reduction for each measure is entered, and the tool calculates a total risk reduction for each bundle. Each measure is given a score from -5 to 5 within each identified value for each of the categories. Each identified value is given a weight between 1 and 5, to reflect the importance of that value to the overall score of the category. The contribution of each measure to the performance of the bundle is weighted according to the share of the costs of the bundle that measure represents. Additionally each category is given a weight of 0.0 to 1.0, to reflect the importance of the category to the overall performance of the measure. Thus, the overall score of each bundle is defined by the score of the measures within each value, weighted according to share of the bundle costs, the weight of each value within the category, and the weight of the category within the overall assessment.

The scores and weights were determined over the course of a 3 hour video conference, together with four representatives from the Department of Water and Aquatic Environment in Asker municipality. The analysis was done without any detailed modelling or calculation, and was largely based on discussion between the participants. However, to provide a some insight into the expected effects of the measures, some rough estimations were done during the meeting. The category "Financial" was excluded, as the input of costs was considered a sufficient assessment of the financial aspects of the measures.

Tab. 1: Overview of assessment methods for costs and benefits

	Detention Basin 1	Detention Basin 2	Green Roofs	Rain Gardens	Floodway 1	Floodway 2	Downspouts	Culvert Expansion
Flood Damage Reduction	Modelling, Threshold Values and Damage Costs	Modelling, Threshold Values and Damage Costs	Modelling, Threshold Values and Damage Costs	Modelling, Threshold Values and Damage Costs	Modelling, Threshold Values and Damage Costs	Modelling, Threshold Values and Damage Costs	Modelling, Threshold Values and Damage Costs	Modelling, Threshold Values and Damage Costs
Peak Flow Reduction	Modelling Downstream Capacity Up-scaling Cost	Modelling Downstream Capacity Up-scaling Cost	Modelling Downstream Capacity Up-scaling Cost	Modelling Downstream Capacity Up-scaling Cost	Modelling Downstream Capacity Up-scaling Cost	Modelling Downstream Capacity Up-scaling Cost	Modelling Downstream Capacity Up-scaling Cost	Modelling Downstream Capacity Up-scaling Cost
Investment Cost	Municipality	Municipality	Green Roof Provider	Literature	Literature	Literature	Literature	Municipality
Operation/Maintenance Cost	Literature	Literature	Green Roof Provider	Literature	Literature	Literature	Literature	-
CO_2 Emissions	Carbon Footprint Tool	Carbon Footprint Tool	Literature	Literature	Literature	Literature	Carbon Footprint Tool	-
Improved Air Quality	-	-	Literature	-	-	-	-	-
Increased Roof Longevity	-	-	Literature	-	-	-	-	-

2.6 Modelling

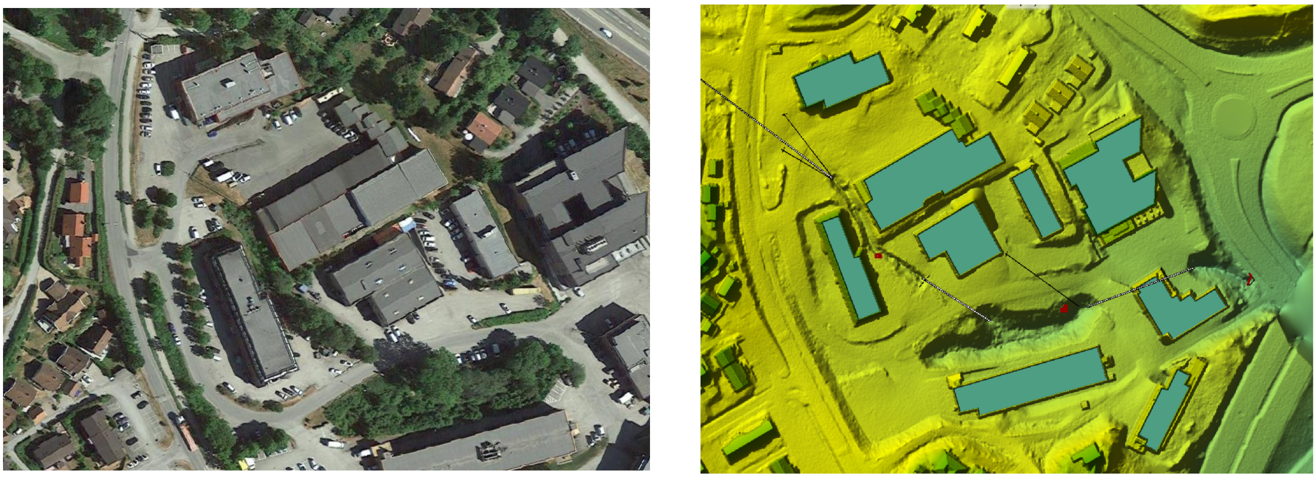
To assess flood damage reduction and peak flow reduction resulting from each measure, a hydrodynamic 2D flood model was created in HEC-RAS 6.0.0 Beta. A Digital Elevation Model (DEM) with a resolution of 0.25*0.25 meters was rasterized from LIDAR data using ArcMap 10.8. The raster was created using the last returns from the LIDAR data, to remove vegetation. The LIDAR data were provided by the Norwegian Mapping Authority. The extent of the catchment was determined using the Fill, Flow Accumulation and Watershed tools in ArcMap. The resulting catchment was exported as a SHP file to HEC-RAS, and tested with preliminary model runs. A trial-and-error procedure ensued, assessing the extent of the area that would influence the model, as the catchment boundaries in HEC-RAS differed slightly from the results of the GIS analysis. After the catchment boundaries were found to be sufficiently accurate, culverts were added to the model, based on data from Gemini VA, a digital water infrastructure mapping tool used by Asker municipality. As the culvert data were incomplete, field measurements were performed in the area, measuring culvert sizes and assessing their placement. Using the terrain modification tool in HEC-RAS, some modifications were made to the terrain data, as the last returns did not always accurately capture the terrain, especially in the stream. Break lines were used to avoid water being conveyed across physical boundaries within cells such as curbs, since HEC-RAS only records topography at the cell face. Other simulation settings are provided in Appendix E.

Land use polygons were retrieved from Geonorge. The land use data were clipped and converted to SHP files in ArcMap 10.8, before being imported to the HEC-RAS model. To fill gaps in the data set, additional land use polygons were drawn manually, using the classification polygons feature in HEC-RAS. Land-Use Polygons are displayed in Appendix D. The polygons were characterized individually using Manning's n values, percent impervious cover, and infiltration capacities. Percent impervious cover and Manning's n values were collected from NVE, 1998. Infiltration capacities were defined using the Deficit Constant method in HEC-RAS. As no infiltration data were available for the catchment, the infiltration capacities had to be estimated. Becker, Tone M Muthanna, and Bent C. Braskerud, 2016 did field measurements of infiltration capacities at 12 different locations in Ekeberg, Oslo, for varying soil types. Using this data, the infiltration capacity at Hvalstad was estimated by averaging the Ksat values of the soil types similar to the soil type at Hvalstad (Norges geologiske undersøkelse, 2020).

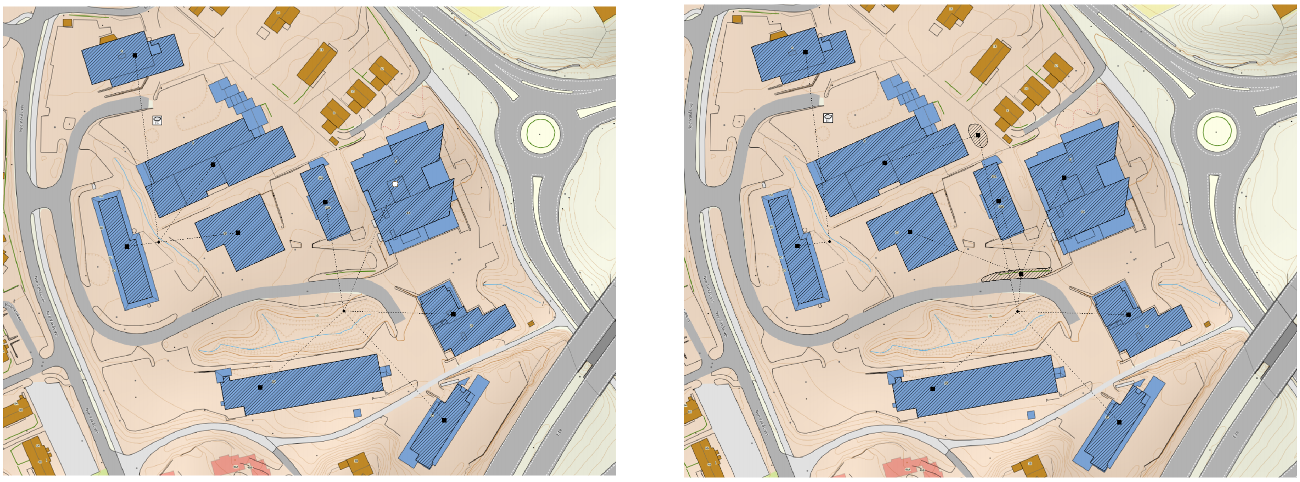
Concentration time of rainfall events in the catchment area was determined using the empirical methods proposed by Kirpich for channel flow and Kerby for overland flow, resulting in a concentration time of 44 minutes (Lawrence Dingman, 2015; Kerby, 1959). To calculate flood damages, it was necessary to provide data on a wide range of events. The 10-, 50- and 200-year events were chosen. The 10-year event was chosen because this event is expected to be handled by the stormwater system. The 50-year event was chosen because the municipal stormwater plan in Asker states that the 50-year event should be handled without significant damages (Norconsult, 2017). The 50-year event was of particular interest, as the 50-year event with a climate factor closely resembled a recent 200-year event. There were photos and local knowledge available for the 200-year event that the model could be calibrated against. The IDF curves for the 45-minute event with 10-, 50- and 200-year recurrence interval was retrieved from Klimaservicesenteret, using a 1.5 climate factor in accordance with both the municipal stormwater plan and national guidelines (Norconsult, 2017). Based on the IDF curves, symmetrical hyetographs were constructed according to the methodology proposed by the Norwegian Water Resources and Energy Directorate. However, as 45 minutes is not conveniently divisible by 2, the tail ends of the events were set to 7.5 minutes, while the rest of the time intervals were set to 5 minutes. The hyetographs were added as precipitation in HEC-RAS. This resulted in a total of twelve model runs, as three rainfall events were modelled for four bundles of measures.

The field measurements also introduced the possibility of talking with local residents about the effects of past flooding events. Conversations with several local residents provided insights into the depths and extents of past floods, and some also provided pictures of a recent flood event. The information from local residents on historic water levels, along with the pictures of a recent extreme event, were used for calibration of the model. These data are expected to have higher degree of uncertainty compared to most measured data. However, no measured data were available for the catchment, so these were the best calibration data available. The calibration was performed by adjusting the percent impervious cover in the land use polygons.

The effects of the green roofs and rain gardens were examined using the Storm Water Management Model (SWMM). Input files can be found in Attachment 3. To avoid adding the precipitation twice (once in HEC-RAS, once in SWMM), the roofs were effectively removed from the HEC-RAS model by redefining the terrain elevation of the roof area to zero. Thereby all precipitation falling on the roofs in the HEC-RAS model was detained there, preventing it from influencing the model results. The same precipitation was added in the SWMM model, and the resulting hydrographs from the SWMM model were added to the HEC-RAS model as boundary conditions. The SWMM model was run for two setups: One representing the existing roofs, and one representing the situation with green roofs and rain gardens. The area in SWMM and HEC-RAS is shown in Figure 5.



(a) Photo of Industrial Area (b) HEC-RAS Industrial Area



(c) SWMM Industrial Area, current situation (d) SWMM Industrial Area, Green Roofs and Rain Gardens

Fig. 5: The Industrial Area in SWMM and HEC-RAS. The resulting output hydrographs from the SWMM model were added as boundary conditions in HEC-RAS. To avoid accounting for the precipitation twice, the area of the roofs was redefined to an elevation of 0 in the HEC-RAS model, thereby detaining the water on the roofs in the HEC-RAS model. This explains the abrupt colour change in the HEC-RAS model.

The model provided two main results: Flood maps, with inundation depth and velocities throughout the rainfall events, and peak flow to the downstream system.

Using the inundation depths and velocities, the monetary cost of flooding was determined by using a system of threshold values. When the threshold depth or velocity for the asset in question was exceeded, damage was considered to occur, with associated damage cost. The threshold values, as well as the damage costs, were collected from a report by the consulting firm Rambøll, written for Oslo municipality (Rambøll, 2019). The damage cost were converted to the current day case for Asker municipality by accounting for inflation. The costs were dependent on type of asset. Using this method, the total cost of damages to private houses, garages, commercial buildings, roads and parking lots was assessed. The total cost of each of the flood events was determined with and without measures. By assessing the differences in the flooding costs, the monetary value of the flood risk reduction for each rainfall event was obtained. Based on the reduced damages for each measure, the reduction in Expected Annual Damages (EAD), was calculated using the trapezoidal method as detailed in Olsen et al., 2015.

The monetary value of runoff volume reduction was determined based on the effect the applied measures had on peak discharge into the downstream stormwater pipe. The valuation was done based on the reduction in the 50-year event, as the municipal plans state that the 50-year event should be handled without excessive damages. Since there has been significant flooding problems further downstream in the stormwater drainage network, and the goal was to determine whether the applied measures could alleviate the drainage network enough to avoid investment in up-scaling of the downstream network. The necessary peak flow reduction was determined based on the pipe capacity, and peak flow from the other stream draining to the same network. However, the necessary reduction in peak flow totaled more than the entire flow from the case area, since the peak flow from the other stream already exceeded the downstream pipe capacity. Therefore, the value of the reduced peak flow was determined based on the percentage reduction towards downstream capacity, assuming that measures taken in both the case area and in the catchment area of the stream to the south could ultimately achieve the necessary reduction. The total area of the case area was 1.02 km^2. The total area of the other contributing area was 1.33 km^2. The pipe capacity was determined by the municipality to be 1.5 m^3/s. By distributing the capacity according to size of the catchment area, this left a downstream capacity of 0.65 m^3/s for the case area, and the value of reduced peak flow was determined based on the percentage reduction towards this capacity. Due to the large dimensions, opening the stream was considered more viable than an up-scaling of the downstream pipe. The costs of opening the stream were based on data from Oslo municipality (Vann- og avløpsetaten, 2020). The estimated price per meter was 92 710 NOK. For the Hvalstad case, this would result in a total cost of 72 313 800 NOK. This project would be so expensive that it was not considered a realistic comparison basis for the measures at Hvalstad. Therefore, an alternative approach was utilized. Based on discussions with the municipality, a more realistic comparison basis was developed. By considering implementation of safe floodways in the most vulnerable areas, as well as flood-proofing of vulnerable buildings, a total budget of 5 000 000 NOK was deemed a realistic basis for comparison.

2.7 Carbon Footprint Tool

For culvert expansions and detention basins, the CO$_2$ emissions were estimated using the greenhouse gas accounting tool developed by Norwegian Water, an association representing Norway's water industry. The tool was developed for estimating greenhouse gas emissions associated with common projects in the Norwegian municipal water sector, and is amongst other based on emissions from transportation, material use and construction efforts. The cost associated with CO$_2$ emissions is determined based on the Social Cost of Carbon, according to the US. Environmental Protection Agency.

2.8 Meetings with Industry Professionals

To help determine cost of measures, and to provide input for the discussion, several industry professionals were contacted. For the costs, the availability and quality of data was variable and often limited, resulting in a more diverse determination methodology, ranging from exact values from previous projects to estimations based on experience. No structured interviews were conducted, and the conversations took place over the course of five months. Table 2 displays the organizations and companies who provided input for this study.

Tab. 2: Contributing organizations and companies

Norconsult AS	Consulting Firm
Oslo	Municipality
Bærum	Municipality
Asker	Municipality
Bergknapp AS	Green Roof Supplier
Blomstertak AS	Green Roof Supplier
Nortekk AS	Roof Supplier
Finans Norge	Industry Organization

2.9 Assessment of Individual Costs and Benefits

The following is a description of the assessed measures, as well as the assessment method for their respective costs and benefits. None of the measures are implemented in real life in the case area; the description concerns how they theoretically would be implemented.

Detention Basin 1

The area upstream of the railway embankment was converted to a detention basin by narrowing the downstream pipe inlet and adding a second pipe inlet at a higher elevation. This allows the water to accumulate and rise before overflowing into the second pipe when the storage capacity is reached. The embankment was assumed sufficiently stable to withhold the water without implementation of additional measures. The measure was implemented in the model reducing the inlet dimensions of the existing culvert from 1000 mm to 400 mm, and adding a separate overflow culvert with diameter of 1000 mm, 2.07 m above the original culvert. The flow in the culvert was assessed for each model run, to ensure that the flow through the two culverts in the model did not exceed the capacity of the original pipe. Investment costs were estimated based on data from the municipality, by assuming that the costs per culvert (the downscaled and the overflow) would be twice those of normal culvert expansions. The CO$_2$ emissions were estimated using the Norwegian Water greenhouse gas accounting tool. Operation and maintenance demands were assumed to be equal to the minimum required maintenance for rain gardens, without infiltration testing. For a more detailed description, see the section on rain gardens below.

Detention Basin 2

The natural depression in the industrial area was converted to a detention basin by the same method as for Detention Basin 1, reducing the dimension of the existing culvert from 1000 mm to 400 mm, and adding a separate culvert of 1000 mm, 2.4 meters above the existing culvert. The soils surrounding the depression were assumed to be stable and capable of withholding the detained water, as analysis of this was beyond the scope of this work. Investment costs, CO_2 emissions and operation/maintenance costs were assumed to be the same as for Detention Basin 1.

Green Roofs

Green roofs were installed on all large commercial buildings in the downstream area. Across nine buildings, the total roof area was 11 850 m^2. To allow space for roof installations and excluding smaller building extensions, the total installed green roof area was assumed to be 10 000 m^2. Since the roofs are retrofitted, it was assumed that the buildings could not support intensive green roofs. Therefore extensive sedum roofs with a depth of 3 cm were installed. The green roofs were implemented in the SWMM model using calibrated model parameters for a green roof i Trondheim, Norway (Hamouz and Tone Merete Muthanna, 2019). The green roofs were connected to two rain gardens (see below). The resulting output hydrograph from the rain gardens was added into the HEC-RAS model as a boundary condition, conveyed directly into the natural depressions in the commercial area. Investment costs were determined based on meetings with Norwegian green roofs suppliers, as well as the project work done by Ragni Hernes, where average costs for green roofs were found by both surveying several Norwegian suppliers and by collecting offers for a hypothetical project (Hernes, 2018). The results of this work are summarized in Attachment 2, however the project work itself is only available at request. Based on these sources, a price of 330 NOK per square meter was used. Maintenance cost were determined based on conversations with green roof suppliers, and a yearly cost of 11.8 NOK per square meter was used. Since the green roof was installed on existing roofs, it was assumed that the roofs would need to be rehabilitated first. The rehabilitation costs were determined through conversations with a Norwegian roof supplier, Nortekk. A detailed description can be found in Appendix F. Operation and maintenance costs were determined in an interview with Bergknapp, a Norwegian green roof supplier.

Green roofs are shown to prolong roof longevity, due to protection from temperature fluctuations and UV-radiation, as shown by Teemusk and Mander, 2009. The effect on roof longevity was determined based on the work done by Björk, 2004. The costs of roof rehabilitation and expected lifetime of the roof prior to green roof installation was based on a meeting with the Norwegian roofing supplier Nortekk. The resulting expected lifetime for the green roofs were 59 years.

Green roofs can have a positive impact on the local air quality, as particulate matter can be intercepted by the plant surface and harmful gases can be absorbed by the plants (Wise et al., 2010). Quantification was based on three relevant papers (Currie, 2005; Yang, Yu, and Gong, 2008; Speak et al., 2012). Using the pollutant capture information from these papers, the value was estimated using reports on the socioeconomic cost of different pollutants, from the Norwegian Institute of Transport Economics and The Norwegian Public Roads Administration (Transportøkonomisk Institutt, 1999; Transportøkonomisk Institutt, 2014; StatensVegvesen, 2018).

As CO_2 is emitted during construction, but sequestered as the substrate grows, the net CO_2 emissions were assessed. This has been studied in Kavehei et al., 2018, and the net emissions from this paper were used.

Rain Gardens

Two rain gardens were constructed in the industrial area. Both were constructed in existing green space, with areas of 75 m^2 and 140 m^2. The rain gardens were included in the SWMM using default parameters for Bio-Retention Cells. Investment costs were determined based on Hernes, 2018 and data from the municipality, and an average of these costs were used, since the investment costs of rain gardens are highly variable. Operation and maintenance costs were estimated based on the stated hours of yearly maintenance of a large rain garden in Trondheim, Norway (Bent C Braskerud, Paus, and Ekle, 2013). Based on conversations with personnel with detailed knowledge of the rain garden in question, the minimum yearly maintenance was determined to be significantly less than the number of hours reported. As the rain gardens are situated in an area where the visual quality of the gardens is of little consequence, the visual maintenance was eliminated, resulting in an estimated yearly maintenance of ten hours, regardless of size of the rain garden. This maintenance consists of an estimated two hours for yearly removal of sediments from the outlet, as well as eight hours for infiltration testing. Cost per hour of labour was determined based on costs for similar work in Asker municipality, at a cost of 775 NOK per hour. Net CO_2 emissions were assumed to be zero, based on Kavehei et al., 2018, who found that the sequestration of carbon in the plant substrate makes up for the emissions during construction. In fact, the article suggests that rain gardens could provide net removal of carbon, however as the sequestration rate for carbon in rain gardens was based on only two studies, which differed significantly, a net zero carbon footprint was assumed as a conservative estimate.

Culvert Expansion

Culverts with known historical capacity issues during extreme events were expanded in the model. The dimensions were expanded from 600 mm to 1000 mm for the culverts downstream of the railway embankment, and from 800mm to 1200mm for the culvert upstream of the industrial area. The shorter culverts downstream of the railway embankment were assumed to be fully replaced, while the other culverts were assumed expanded for the first two meters, as the inlet capacity is commonly the limiting factor for culvert capacity. Investment costs were estimated based on data from similar projects in the municipality, at a cost of 75 000 NOK per culvert. It was assumed that the inlet expansion had no effect on the operation and maintenance costs. The CO_2 emissions were estimated using the Norwegian Water greenhouse gas accounting tool.

Safe Floodway 1

A safe floodway was established on the road along the stream downstream of the railway embankment. The road is shown as ”Safe floodway” in Figure 1, and an overview of the layout is provided in Appendix B. The goal was to convey excess water from the stream without causing flood damages. By containing the flood within the existing road, uncontrolled flooding of vulnerable areas could potentially be avoided. The current condition of the road required new asphalt to achieve a continuous and durable cover, in order to limit erosion during flooding. The road was designed with a 3% one-sided fall towards the stream, in accordance with the maximum one-sided fall allowed by the Norwegian Road Authority (Statens Vegvesen, n.d.).

The floodway conveyed water for up to 160 meters, utilizing an elevation difference of 4 meters. The measure was implemented in the model by utilizing the terrain modification tools, defining a channel along the road with a 3% sideways fall and a width of 4 meters. Investment and operation/maintenance costs were determined based on a report which collected costs from municipal road authorities (Norsk Kommunalteknisk Forening, 2006). CO_2 emissions were determined based on an average of national estimates for emissions resulting from investments in road construction (Zero, 2018).

Safe Floodway 2

A safe floodway was established between the inlet upstream of the industrial area, and the first outlet within the industrial area. An overview of the layout is provided in Appendix C. The safe floodway was designed by constructing a system of two rounded curbs, partial lowering of a parking lot, and two speed bumps. The resulting system conveyed excess stream water across 122 m of overland area, utilizing an elevation difference of 2 meters. The measure was implemented in the model by drawing a system of polygons with heights corresponding to the height of the respective curbs and speed bumps, and a polygon with a 10 cm reduction in the terrain elevation where the parking lot was to be lowered. Investment costs, operation and maintenance costs and CO_2 emissions were determined using the same procedures as for Safe Floodway 1.

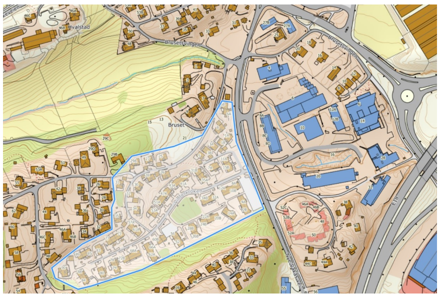
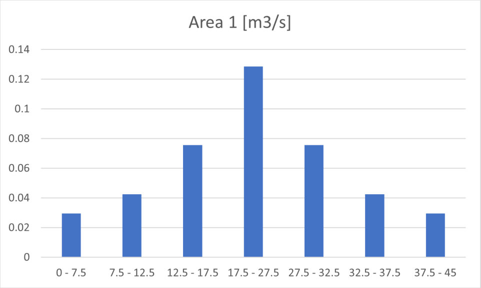
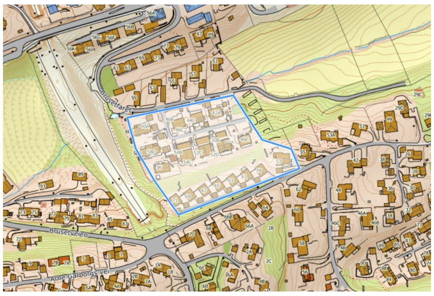
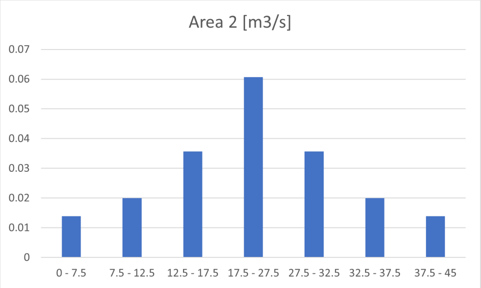
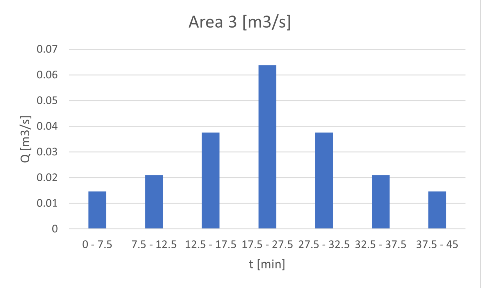
Downspout Disconnection

Several buildings in the area have downspouts directly connected to the stormwater drainage system. As the drainage system uses the local stream as a recipient, all precipitation falling on buildings with connected downspouts will lead to increased flow in the stream. The currently connected downspouts were represented in the model by input hydrographs, developed using the rational method. The connected areas and resulting hydrographs are summarized in Table 3, while more detailed description is provided in Appendix A. To prevent the precipitation falling on the roofs connected to the drainage system from interfering with the surface runoff, the concerned roofs were redefined with an elevation of 0 in HEC-RAS, detaining the water on the roofs by the same methodology as for the green roofs. The number of buildings with connected downspouts was assessed by inspection during the field measurements, where downspouts leading into the ground were noted. As there was no way of confirming that downspouts leading into the ground were in fact connected directly to the drainage system, it was assumed that this was the case for 50% of the concerned downspouts. Removal of the directly connected downspouts was implemented in the model by removing the input hydrographs, and removing terrain modifications on the roofs, reintroducing the roof runoff as surface runoff in the model. The investment costs were based on municipal reimbursement rates for similar measures in the nearby municipality of Fredrikstad (Bent C Braskerud and Skallebakke, 2013). Operation and maintenance costs, as well as CO2 emissions, were assumed negligible.

2.10 Cost-Benefit Analysis

Based on the monetarily assessed costs and benefits, the cost-benefit analysis was performed. As some costs and benefits are arising continuously, while others are one-time costs, a time frame for the analysis was defined. The time frame was set to 100 years, as this is the expected lifetime of most stormwater infrastructure. For measure with shorter lifetime, reinvestment was assumed. This was the case for green roofs and safe floodways. However, as the safe floodways were constructed in existing roads, it was assumed not to influence the reinvestments occurring later, and was therefore ignored. Reinvestment in green roofs were considered to occur after the expected lifetime

Tab. 3: Overview of the areas with downspouts connected to directly to the stream, and resulting hydrographs added in the HEC-RAS model

Overview	Area	200-year Hydrograph
	40 buildings 20 assumed to contribute totaling 2894 m^2	
	18 buildings 9 assumed to contribute totaling 1366 m^2	
	15 buildings 8 assumed to contribute totaling 1436 m^2	

of 59 years. The analysis did not consider remaining values of the measures after 100 years. For future costs and benefits, the Net Present Value (NPV) was calculated using a discount rate of 4%, which is the standard discount rate for public projects in Norway(Finansdepartementet, 2005). NPV was calculated for operation/maintenance costs, expected annual damages, improved air quality and increased roof longevity.

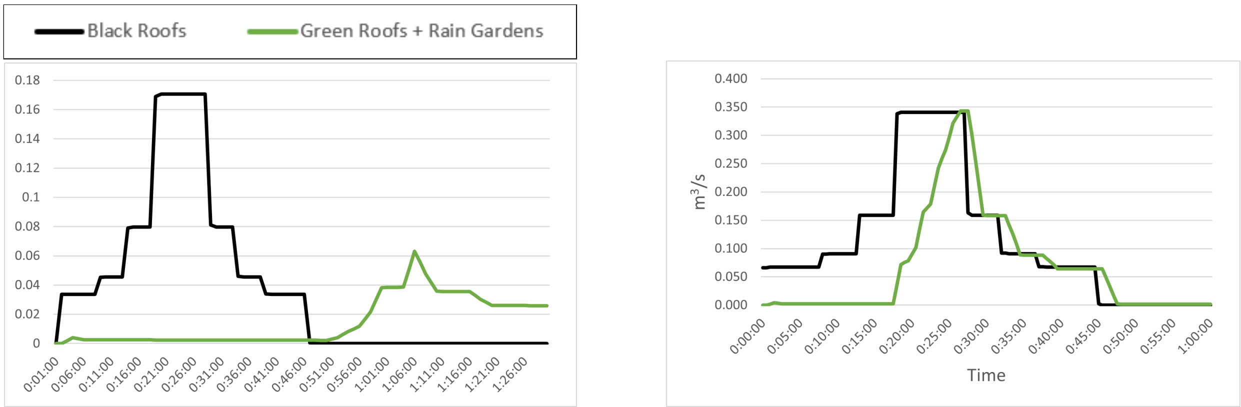
2.11 Comparison of MCDA and CBA

To compare the results from the MCDA and the CBA, the implicit monetary valuation resulting from the MCDA was determined. By assessing the contribution of "Costs" towards overall score for the cheapest and most expensive bundle, the implicit monetary value of each point in the MCDA was obtained. The monetary value of the points in the MCDA were then used to derive the implicit monetary valuation of the costs and benefits assessed in the MCDA.

3 Results

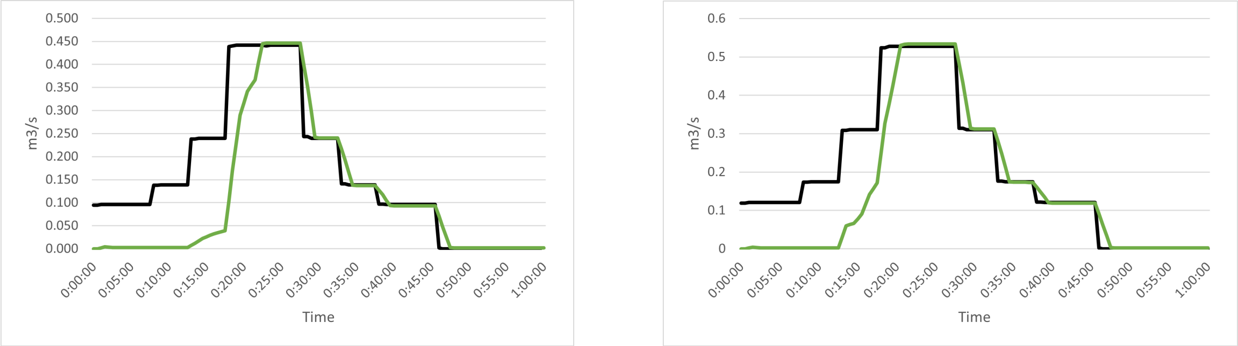
3.1 SWMM Results - Hydrograph from Green Roofs and Rain Gardens

The results of the SWMM modelling are summarized in Figure 6. The green roofs and rain gardens did not achieve a reduction in peak flow for any of the rain events. Time to peak was increased with 8 minutes for the 10-year event, 4 minutes for the 50-year event and 2.5 minutes for the 200-year event. The green roofs and rain gardens reduced the total flow for all events, however the flow rate in the later part of the events was larger, due to the detention effect of the roof and rain garden substrates. As peak flow out of the HEC-RAS model occurred late in the event, the contribution from green roofs and rain gardens towards reduced peak flow was determined to be zero. Figure 6 also includes the results of the SWMM models, run for a 5-year event without climate factor. The results show that the green roofs in fact have a large impact on both peak flow and time to peak for smaller rain events than those used in this analysis.



(a) 5-year event without climate factor

(b) 10-year event



(c) 50-year event

(d) 200-year event

Fig. 6: Output hydrographs from the SWMM model, which were used as input in the HEC-RAS model. The current day condition is labeled "black roofs". The 5-year event without climate factor was included to provide some context: The green roofs and rain gardens performs well for smaller events.

3.2 HEC-RAS Results - Calibrated Values, Flood Maps and Peak Flow

The calibrated values for percent impervious cover are displayed in Table 4. After the calibration, the model was significantly improved, and deemed sufficiently accurate to be used for the analysis. However some discrepancies between the model results and the calibration data were still present.

Tab. 4: Calibrated values for percent impervious cover according to land use

Land Use	Percent Impervious
Developed - High Intensity	70
Developed - Low Intensity	20
Green Area	15
Fields	10
Forested Area	5
Stream	100

Flood maps of the 10-year event for the residential area downstream of the railway embankment are shown in Figure 7. Inundation depths of less than 10cm were filtered out of the map to provide a clearer, less cluttered picture of the effects. Due to a bug, the flood map of Bundle 2 displays large inundation depths at some parts of the roofs in the area, however this did not affect the computations. The effects of the measures can clearly be seen by examining the inundated area in the gardens to the north of stream. Additionally, the increased inundation of the road as a result of being used as a safe floodway can be seen especially well for Bundle 3.

Flood maps of the 200-year event for the industrial area are displayed in Figure 8. Inundation depths under 20 cm were filtered out. The inundated area, and depth in the detention basin was very similar for all bundles, as the basin overtopped for all bundles in the 200-year event. The overtopping was especially significant for Bundle 3, which can be seen by a slightly larger inundated area downstream of the basin. The effects of the increased culvert capacity can clearly be seen for Bundle 2, resulting in a much smaller inundated area in the upper left side of the picture. Again, the effects of the safe floodway are particularly clear for Bundle 3: here the inundated area closely follows the floodway.

The peak flow for each bundle was determined by assessing the peak flow in the original culvert, the overflow culvert, as well as any flow resulting from overtopping. The results are displayed in Table 5. For the 10-year event, all measures achieved a reduction in peak flow, with Bundle 1 achieving the greatest reduction. For the 50-year event, Bundle 1 and 2 achieved a reduction in peak flow, with Bundle 1 achieving the greatest reduction, while Bundle 3 led to an increased peak flow. Bundle 3 also caused an increased peak flow in the 200-year event. In the 200-year event, Bundle 2 achieved the greatest reduction.

Tab. 5: Peak flow, in cubic meters per second

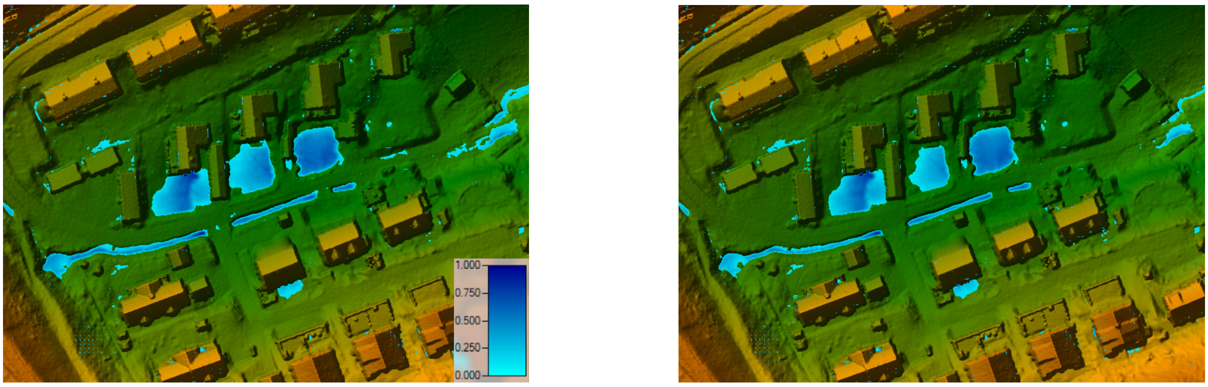
	Bundle 0	Bundle 1	Bundle 2	Bundle 3
10-Year Event	1.23	0.65	0.69	1.01
50-Year Event	2.54	1.82	1.97	2.73
200-Year Event	4.26	3.73	3.59	5.23
Percentage of necessary 50-Year reduction	0%	38%	30%	-10%

3.3 Damage Costs and Expected Annual Damages

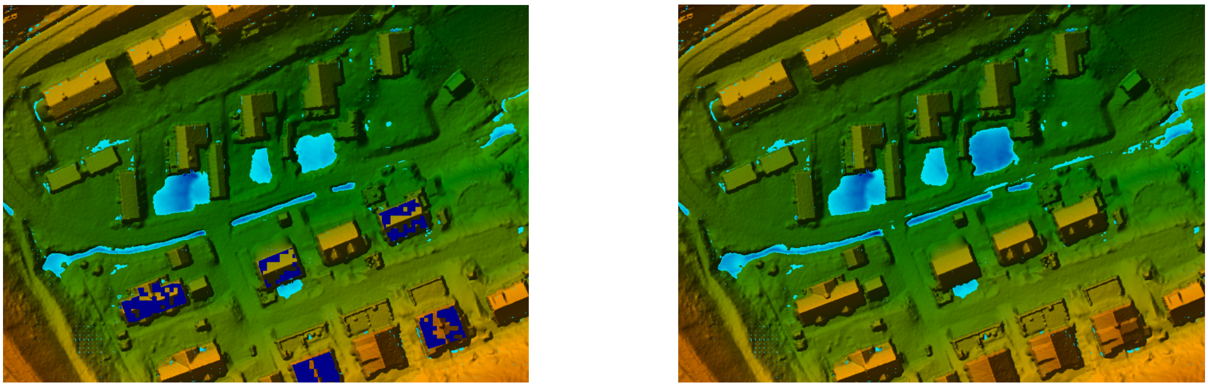
The damage costs for each bundle in each event are displayed in Table 6. Based on the damage costs, the expected annual damages (EAD) for each bundle were calculated. For bundle 0 and 3, there was little increase in the damage costs from the 50- to the 200-year event, as most of the damage potential in the area was already reached at the 50-year event. The damage costs of the 200-year event are very similar for all bundles, including the current day situation, for the same reason. In terms of EAD, Bundle 2 achieved the greatest reduction, followed by Bundle 1. Bundle 3 did achieve a reduction in EAD, albeit much smaller than Bundle 1 and 2. This was mainly due to the fact that the upstream detention basin proved were important for damage reduction. Compared to the other bundles, Bundle 2 performed particularly well in the 50-year event, as the culverts dramatically reduced damages to the road downstream of the railway embankment.

Tab. 6: Damage costs for each event and the resulting expected annual damages, in 1000 NOK

	Bundle 0	Bundle 1	Bundle 2	Bundle 3
10-Year Event	277	159	149	150
50-Year Event	4 305	1 749	529	4 865
200-Year Event	5 072	5 026	4 885	5 108
Expected Annual Damages	388	209	145	353

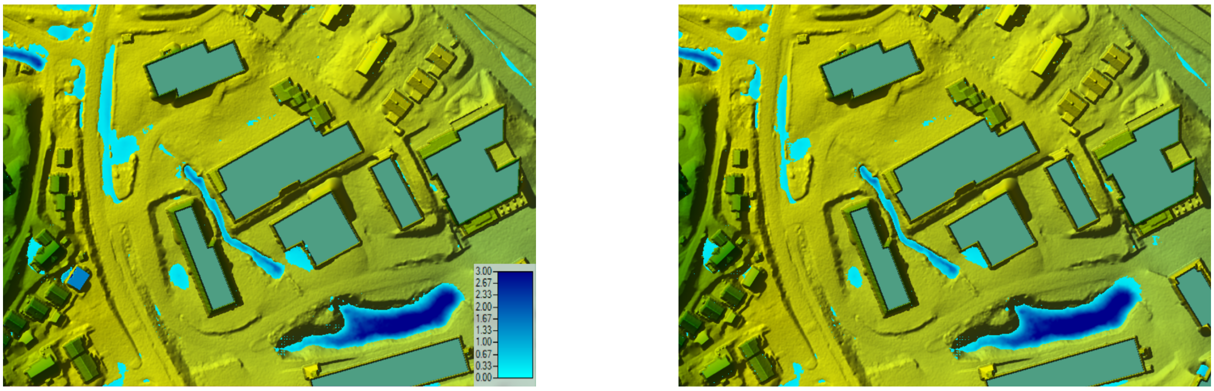


(a) Bundle 0 (b) Bundle 1

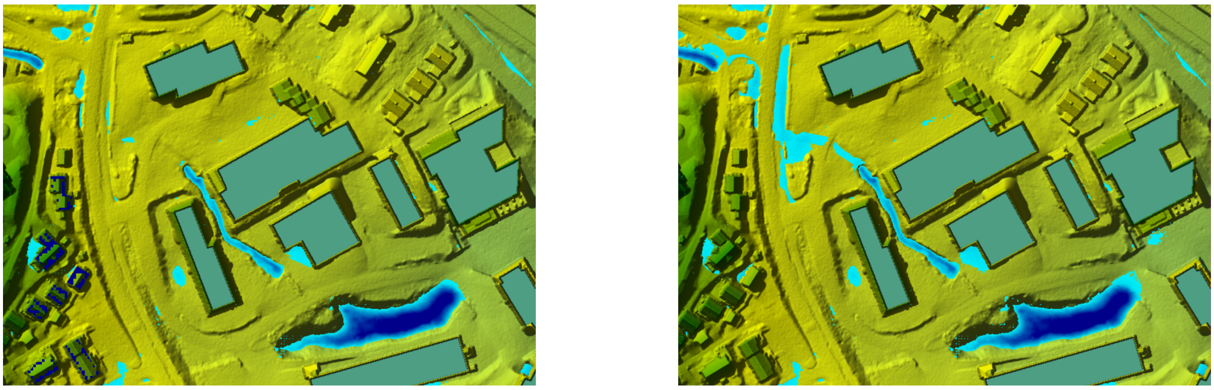


(c) Bundle 2 (d) Bundle 3

Fig. 7: 10-year event flood map, downstream of railway embankment.



(a) Bundle 0 (b) Bundle 1



(c) Bundle 2 (d) Bundle 3

Fig. 8: 200-year event flood map, industrial area. The deep inundation depths at the roofs in Bundle 2 are the results of a bug, and did not influence model output.

3.4 Assessment of Costs and Benefits

Individual costs and benefits for each measure are displayed in Table 8. Values which were not assessed are represented by a dash (-). Values which were assessed, but found to be zero, are represented with a zero. By comparing local damages between bundles, the contribution of each measure towards reduced flood damages were estimated. Due to its placement at the downstream end of the case area, Detention Basin 2 did not contribute towards reduced flood damages.

3.5 Cost-Benefit Analysis

The results of the cost-benefit analysis for each bundle are shown in Table 9. According to the cost-benefit analysis, Bundle 1 has by far the highest net present value. Bundle 3 has the second highest net present value, followed relatively closely by Bundle 2. None of the measures achieved a positive net present value, and are therefore considered unprofitable investments according to the analysis. As the green roofs and rain gardens did not contribute towards reduced flood damages or reduced peak flow, another combination of measures was assessed, by removing green roofs and rain gardens from Bundle 1. This bundle is referred to as Bundle 1a. The results of the cost-benefit analysis for this new bundle are included in Table 9. This new bundle achieved a high positive net present value, which means that this would by far be the best bundle to invest in according to the analysis, and the only bundle representing a profitable investment.

3.6 MCDA Results

The results of the multi-criteria decision analysis are displayed in Table 7. The resulting implicit monetary value of each point in the MCDA was 7 489 000 NOK. All bundles achieved a positive score, however this does not indicate that the bundles are considered profitable investments. The tool can strictly be used for comparison of measures, and does not provide an immediate answer as to whether or not to invest. According to the analysis, Bundle 1 performed the best, followed by Bundle 3 and lastly, Bundle 2. Bundle 1 and 2 had generally similar performance in the analysis, but Bundle 1 achieved a higher score due to the lower cost of the bundle.

Tab. 7: MCDA Results, of scoring each measure within each bundle. Maximum score for each category is +5, and minimum score is -5.

	Weight	Bundle 1	Bundle 2	Bundle 3
Costs	2	3.37	2.54	4.09
Values	0.25	3.91	3.89	3.63
Society	0.05	-2.05	-1.95	-2.4
Environment	0.025	2.1	1.1	-0.8
Social	0.05	2.85	3.25	3.75
Risk Reduction	1	3	4	1.5
Total Score	-	10.81	10.14	10.64

Tab. 8: Overview of costs and benefits for each measure, in 1000 NOK

	Detention Basin 1	Detention Basin 2	Green Roofs	Rain Gardens	Floodway 1	Floodway 2	Downspouts	Culvert Expansion
Flood Damage Reduction	3 921	0	0	0	781	121	654	737
Investment Cost	-300	-300	-6 754	-787	-3 733	-2 846	-22	-300
Operation/Maintenance Cost	-40	-40	-3 010	-395	-276	-210	-	-
CO_2 Emissions	-0.3	-0.3	-104	0	-45	-35	-	-1
Improved Air Quality	-	-	1 908	-	-	-	-	-
Increased Roof Longevity	-	-	418	-	-	-	-	-

Tab. 9: Overview of costs and benefits for each bundle, and the resulting net present value from the cost-benefit analysis, in 1000 NOK. Bundle 1a consists of Bundle 1 without green roofs and rain gardens.

	Bundle 1	Bundle 2	Bundle 3	Bundle 1a
Flood Damage Reduction	4 575	6 213	901	4 575
Peak Flow Reduction	1 905	1 508	-503	1 905
Investment Cost	-8 163	-15 042	-6 879	-622
Operation/Maintenance Cost	-3 484	-3 970	-525	-79
Net CO_2 Emissions	-104	-185	-80	-0.6
Improved Air Quality	1 908	1 908	0	0
Increased Roof Longevity	418	418	0	0
Net Present Value	-2 947	-9 150	-7 085	5 777

4 Discussion

4.1 SWMM Results

For the rain events used in the analysis, the SWMM model showed little effect of the green roofs and rain gardens. The rain events used in this analysis included a climate factor of 1.5, resulting in very large events. The 10-, 50-, and 200-year events with a climate factor of 1.5 roughly equals the current 50-, 200- and 800-year events. For rain events of these sizes, extensive green roofs and rain gardens have limited impact, resulting in very unfavourable outcomes in the cost-benefit analysis. This does not imply that green roofs and rain gardens are without merit in stormwater management. The results of the SWMM model for the 5-year event without climate factor shows a significant potential for detaining smaller events. In areas with combined sewer systems, this can be beneficial for reducing combined sewer overflow and basement flooding. Additionally, for especially vulnerable areas, green roofs and rain gardens can have damage reduction potential for smaller rain events. This highlights the need for careful consideration of what we want to achieve by implementing stormwater control measures. In the case of the Norwegian Three Step Model, we should assess what step the measure is targeting. Green roofs and rain gardens implemented as a part of Step 1 and 2 should not be expected to contribute towards reduced damages in the most extreme events: for this, other measures are needed.

4.2 HEC-RAS Calibration

The HEC-RAS model was calibrated by changing the percent impervious cover in the land use data. Physically, the percent impervious cover is entirely decided by the land use, and should therefore not be expected to vary significantly from established table values. However, HEC-RAS is a conceptual, not a physical model. It does not aim to accurately capture all physical processes influencing runoff, but rather to provide a sufficiently accurate approximation using a simplified methodology. In this context, a calibration using percent impervious cover is justified. Besides, some deviations from table values are expected, as the permeability of i.e. asphalt roads is dependant on the condition of the road. However, in order to not differ too much from the physical processes, both the ranking and order of magnitude of impervious cover for each land use was maintained. Additionally, the percent impervious cover of the stream was kept at 100.

4.3 Peak Flow Reduction

All measures achieved a reduction in peak flow for the 10-year event. This shows that Detention Basin 2 had an effect on the peak flow for this event, as it was the only measure contributing towards reduced flow in Bundle 3. However, the inclusion of other measures, such as Detention Basin 1 and Downspout Disconnections, clearly provided additional peak flow reduction, as both Bundle 1 and 2 performed better than Bundle 3. For the 10- and 50-year event, Bundle 1 performed better than Bundle 2, since inclusion of culvert expansions and safe floodways increased the peak flow, by increasing the amount of water being transported downstream. The increased transportation of water downstream explains why Bundle 3 performed worse than Bundle 0 (no measures) for the 50- and 200-year event. In these events, Detention Basin 2 overtopped, effectively neutralizing its effect on peak flow, leaving the floodways to have a large negative impact on peak flow.

4.4 Expected Annual Damages

All bundles achieved a reduction in expected annual damages (with the exception of Bundle 0, which represents the current condition). Bundle 2 outperformed the other bundles, mainly due to significantly lower damages in the 50-year event. The combination of detention basins, downspout disconnections and safe floodways led to a great reduction in the damages done to the road downstream of the railway embankment. For the 10-year event, all bundles performed similarly, most notably caused by a good performance of the floodways in Bundle 3, which managed to convey excess water without being damaged in the process. This caused Bundle 3 to achieve an overall reduction in EAD, despite actually increasing the damages for the 50- and 200-year event. In those events, Bundle 3 performed poorly, as the capacity of Floodway 1 was exceeded, resulting in large damages to the road and to the surrounding assets. For Bundle 0 and 3, there was little additional damage in the 200-year event compared to the 50-year event. This was due to the fact that most of the damage potential in the area was already realized, and additional inundation mostly did not cause additional damage in the analysis. The damages in the 200-year events were very similar for all bundles, for the same reason. The use of threshold values thus made it difficult to differentiate between bundles for the largest events, as all events essentially caused the same damage, despite differences in inundation depths. This underlines one of the weaknesses of threshold values compared to depth-damage curves for damage assessment of flooding events, and indicates that depth-damage curves should be used when assessing damages for large rain events. Alternatively, the threshold method could be improved by introduction of additional, higher thresholds, causing additional damage to assets after the threshold is reached.

The damages resulting from the 200-year event also highlight another important point. Stormwater control measures need considerable capacity in order to handle the largest rain events, especially when applying a climate factor. However, the reduction of damages in the 200-year event has limited impact on EAD, as the event occurs very infrequently. In this analysis, a complete elimination of the damages of the 200-year event would have a NPV of around 1 200 000 NOK, which is not enough to make any of the bundles profitable. However, the costs of achieving this would have been immense, as it would require far more radical measures than those assessed in this analysis. This is an important concept to keep in mind as we decide what events we should design our stormwater systems to handle. Due to the high costs of designing measures for large events, and the infrequency of the events themselves, for a certain size of event it becomes more cost-effective to cover the damages than to prevent them. This concept was explored by Phan, Samyo, and O. G. Lindholm, 2019, whose findings suggested that it was not necessarily more cost-efficient to design for events with climate factors, than for events without. However, the public opinion on a stated policy of accepting damages might be a barrier for implementing such an approach.

4.5 Assessment of Costs and Benefits

Detention Basin 1 proved to be the most important measure for flood damage reduction. This was partly due to its upstream location: All damages occurred downstream of the basin, so the basin had a positive impact on all damages. Floodway 1 achieved a greater damage reduction than Floodway 2, as the damage potential along Floodway 1 was significantly greater than that of Floodway 2. This highlights the need for careful assessment of local need for safe floodways according to the local damage potential.

The investment costs for green roofs are very high in the analysis. This is partially due to the assumption that the roofs need to be rehabilitated before green roof installation. The rehabilitation costs represent about half of the total investment costs. The assumption that rehabilitation was needed was based on conversations with Bergknapp, Blomstertak and Nortekk, and is partly a result of liability conditions in building codes. According to Bergknapp and Blomstertak, the market for green roofs in Norway is dominated by roof provided for new buildings, designed for green roofs. This indicates that the costs for the necessary roof rehabilitation before installing green roofs on existing buildings are often prohibitive. However, this also underlines the need for planning for green roofs when new buildings are constructed, as retrofitting is much more expensive.

The value of improved air quality resulting from green roofs was found to be substantial, covering nearly half of the operation and maintenance costs of the green roofs, and equaling the maximum achieved value of reduced peak flow. On a square meter basis, the value of improved air quality was found to be 7.5 NOK per m^2 per year. However, this is a socioeconomic value that will not directly influence investment decisions in green roofs. As the values are still relevant for the society at large, this could be used as an argument for introduction of financial incentives for green roof construction, especially in areas with poor air quality.

The investment costs of rain gardens are highly variable. The data used for valuation in this analysis varied by a factor of ten. Whether or not the rain garden is constructed as a part of a larger construction project can have a large impact on the costs. This points to the need for planning for stormwater management as a part of other construction projects, and to utilize possibilities for cheap construction that may arise.

The discount rate used in the analysis was the same for all future costs and benefits, both the directly monetary values and the valued non-monetary values. The use of discount rates for future costs and benefits is partially seen as problematic (Hagen, 2011). The resulting NPV of values realized in the future is small compared to the cost occurring today. Thereby, the analysis weights the costs to current generations high compared to the values realized by future generations. In terms of intergenerational equity, this can be problematic. However, there are also problematic consequences of not using a discount rate, as this implies that it is always profitable to delay investments (Keeler and Cretin, 1983). Due to the counterintuitive consequences of not discounting future costs and benefits, this analysis was performed using a discount rate.

The cost of CO_2 emissions was determined based on the social cost of carbon. In some cases, the cost of carbon credits in the EU Emissions Trading System could be more applicable. In those cases, the prices for CO_2 Emissions can be swapped with the price of carbon credits.

4.6 Performance of Bundles

Bundle 1a performed far better than any other bundle, and had it not been included, none of the bundles would have been considered profitable, even though a theoretically very profitable bundle existed. This highlights the importance of reviewing the effects of the measures during the analysis, to assess whether a more optimal bundle can be created.

Among the bundles originally included in the analysis, Bundle 1 performed the best, having the highest peak flow reduction, substantial damage reduction, and far lower investment costs than Bundle 2. Bundle 2 and 3 display an important aspect of floodways and culvert expansions. By introducing measures that convey water away from vulnerable areas, damage in downstream areas might increase. In essence, damages are partially reduced, but also partially moved. Complex legal problems may arise as a result of this. This also highlights the need for holistic stormwater management in a catchment, as one measure might reduce damages locally, but introduce additional damages downstream. In this case, the damage reduction provided by the floodways and culverts exceeded the cost of increased peak flow downstream, however there is no guarantee that this will be the case in another area.

Even though the damage reduction exceeded the costs of increased peak flow for Bundle 2 and 3, the net value of these effects were lower than the investment costs. The investment costs used in this analysis are quite high, as it was assumed that the floodways needed to be entirely rehabilitated. As cracks and holes in the road surface dramatically increases the erosion potential of water, this was considered a reasonable assumption. The high investment costs calls for utilizing possibilities that arise when existing roads are rehabilitated, and when new roads are constructed. By planning for implementing relevant roads as safe floodways when rehabilitation or construction is scheduled, the investment costs of introducing the road as a part of the stormwater management infrastructure can be greatly reduced.

The net CO_2 emissions proved to represent a small fraction of the overall costs. For Bundle 2, CO_2 emissions amounted to around 1% of the costs. According to the results of this analysis, CO_2 emissions would only differentiate investments that are otherwise very similar.

Overall, the large discrepancies in NPV display the importance of assessment and comparison of measures, as a failure to identify potentially large differences in NPV could lead to sub-optimal, and even unprofitable, investments.

The safe floodways have significant merit that the analysis fails to display. In the case of culvert blockages, the impact of safe floodways will be significantly larger than the effect displayed in this analysis. Floodways increase the resilience of the areas where they are implemented, and contribute to the transition towards safe-to-fail systems, where the system can function even after failure of some of the components (Kim et al., 2017). Therefore, in terms of resilience, Bundle 2 and 3 performs better than Bundle 1, however this is not evident from the analysis.

The inclusion of co-benefits in the analysis is not necessarily applicable for the Norwegian municipal water sector. Municipal water services are financed through a principle of "self-cost", where water fees finance the municipal water services, and the municipal water departments can only spend money directly influencing the quality of the service they provide. In this system, water fees can not be used to finance projects that would be unprofitable if it weren't for co-benefits not connected to the water services. This might act as a barrier to implementation of otherwise socioeconomically profitable investments. Creation of national guidelines on how these aspects can be taken into account was a common request among the people providing input for this study.

In the analysis, the damage costs and peak flow after implementation of the bundles were compared to the damage costs and peak flow in the current situation. However, to not implement measures in the area is not a realistic alternative. By only comparing bundles to the current situation, a bundle could be perceived as a good investment if other, more profitable bundles have not been assessed. For a more representative results, bundles should be compared with the effects of the bundle perceived to be the best investment.

4.7 MCDA Results

Both the CBA and the MCDA concluded with the same ranking of bundles. However, in the MCDA, the margins were very small, where as the CBA had a very clear distinction between bundles. Due to low weights for everything except costs and risk reduction, the MCDA was largely decided by these values.

Since the MCDA weights the impact of each measure within each bundle according to the measure's share of the total cost of the bundle, measures with low costs and high impacts, such as downspout disconnections, detention basins and culvert expansion, had little impact on the results of the MCDA. This is a significant weakness, as the score of the bundle is largely decided by the performance of the most costly measures, despite this not being the case in the CBA.

The category "Values" in the MCDA, consisted of "Damage Reduction", "Climate Change Adaption" and "Capacity". These values are to a large degree variations of the same concept, as climate change adaption mostly consists of facilitating for increased runoff quantities, and increased capacity leads to reduced damages. Combined with the category "Risk Reduction", they make up the assessment of the hydraulic effects of the measures. Within the category "Values", floodways and green roofs/rain gardens received similar scores. As these were the most expensive measures, the value of the "Value" category is very similar across the bundles. Within "Risk Reduction", the performance was more varied. However, the variation was far smaller than in the CBA. As the CBA showed, the impact on flood damage reduction was quite different for the bundles, especially for Bundle 3, as Detention Basin 1 proved to be very important for the overall damage reduction in the area. The MCDA failed to identify this. This exemplifies the difficulty of doing assessment of flood damages without modelling, and the weaknesses of weighting the impact of the measures according to the costs, as impacts of cheap but efficient measures become negligible in the MCDA.

The category "Environment" consists of "CO_2 Emissions" and "Ecosystem Services". For Bundle 1, this was dominated by the performance of the green roofs and rain gardens, due to the high costs. For this measure, CO_2 Emissions was given a score of -2, and ecosystem services a score of 4. Corresponding weights were 2 and 5, resulting in a weighted score of -0.57 for CO_2 Emissions, and 2.86 for ecosystem services. According to the implicit monetary valuation of the points in the MCDA, this corresponds to a value of - 107 000 and 535 000 after accounting for the weight of the category. The value of the net CO_2 emission was very accurate, while the value of the ecosystem services corresponded to about 28% of the value found in the CBA. For green roofs, ecosystem services should therefore ideally be scored around 12, when only accounting for improved air quality. However, the analysis only allows scoring as high as 5. This demonstrates another weakness of the MCDA, as it does not allow for significant differentiation of values of different magnitudes.

For all bundles, the implicit valuation of the category "Society" was around -800 000 NOK. The category consists of "Safety" and "Legal", representing safety issues with the measures, and potential legal problems. For the cheapest bundle, this corresponds to 10.6% of the investment costs. The implicit valuation of the category "Social" ranged from 1 067 000 to 1 405 000 NOK. The category consists of "Cooperation with other departments" and "Multi-use of area". For Bundle 3, this corresponds to 18.8% of the total investment costs. The implicit valuation of both "Society" and "Social" is quite high in comparison to the investment costs. As the values included in the categories were not evaluated in the CBA, no conclusion can be drawn as to the validity of this implicit valuation. However, the surprisingly high values underline the importance of assessing the implicit monetary valuation, so that the validity of the valuations can be assessed.

As several cost and benefits are not valued, and as the valuation of costs and benefits change as the society changes, the results of the CBA are neither complete nor static. Therefore, a MCDA should have some degree of freedom when it comes to determining how it weights different values. This enables the people performing the MCDA to adjust the analysis based on policy, as certain values might increase or decrease in importance. However, the implicit valuation should always be assessed, as to ensure that the resulting valuations are at a sensible scale compared to costs, and other values included in the analysis.

Since the MCDA weights scores within each category according to the cost of the measure, it was not possible to provide a general calibration of the MCDA using the results of the CBA. When the scores are weighted according to cost of the measure, a calibration of the scoring will not be valid for another case, where the distribution of costs might be different. Additionally, changing the weight of a category will disproportionately increase or decrease the impact of the most costly measure. Weighting scores according to costs assumes that the impact of each measure is proportional to its cost. This was far from the case in the CBA. The only possible calibration was that of non site-specific values for each single measure. The only measure with more than one non-site specific values was the green roofs. Here, a new scoring of CO_2 emissions and ecosystem services was suggested, as discussed above. As any further calibration of the scores and weights would not be transferable, a general calibration of the MCDA was not performed.

4.8 Limitations and Uncertainty

SWMM Model

Parameters for the rain gardens were set to the default parameters in the software. As no calibration data existed, and no calibrated parameters for similar setups were found, this was considered to be the best alternative. However, the results consequently have a higher degree of uncertainty than if the parameters had been calibrated. It is not possible to say to what degree, or in what way this impacted the results. However, as the rain events simulated were very large, and rain gardens typically are not performing well under these conditions, the impact of this uncertainty is not expected to have significant consequences for the analysis.

HEC-RAS Model

The effective roughness of surfaces is greatly dependant on the inundation depth. For small inundation depths, where the roughness elements, such as grass, are as tall or taller than the water level, effective roughness values are typically very high. For larger inundation depths, the effective roughness will be much lower. HEC-RAS does not account for this, and only one Manning's n value is entered for each land use. As a result of this, HEC-RAS will overestimate the flow velocity at small inundation depths. This might lead to more water being transported at the beginning of the rain event, consequently leading to a lower peak flow.

Several of the hydrological processes are approximated by simplistic approaches in the HEC-RAS model. Infiltration is simulated by removing an amount of water from the input precipitation for each time step, according to the infiltration capacity and percent impervious cover for the land use where the precipitation falls. Consequently, water that enters an area as runoff, and not as precipitation, will not infiltrate in the model. This will lead to increased runoff volumes in the model compared to in real life, as water that accumulates on highly permeable surfaces will not infiltrate. HEC-RAS does not account for evapotranspiration or interception by vegetation. This will further increase surface runoff, especially from vegetated areas.

The effects of culvert expansion was implemented in the model by increasing the dimensions for the entire culvert. However, for two of the culverts, only the first two meters were expanded. This is a common measure to increase culvert capacity, as the inlet size often is the limiting factor for capacity. However, the resulting capacity in the model could potentially be overestimated. If this was the case, the valuation of culvert expansions would drop, and the valuation of safe floodways would be expected to increase.

EAD and Peak Flow

The hyetographs were constructed using a climate factor of 1.5, and do not represent the current condition. Damages will consequently be overestimated for events occurring early in the life-span of the measures. This could lead to an underestimation of damage reduction potential. For a more accurate assessment, the model could have been run two times: once for the current condition, and once with a climate factor, and the damages could have been derived based on interpolation between these events. However, due to the time-consuming calibration, and high run times for the model, this was not feasible for this study.

Costs and Benefits

Several costs and benefits included in the analysis are prone to high degrees of uncertainty. The investment costs of the detention basins were estimated based on the costs of culvert expansion. According to the municipality, the measure would not be expensive, however, the exact costs are unclear. Higher costs would lead to worse performance of all bundles, especially Bundle 1, 2 and 1a. However, as the investment costs are still expected to be small compared to those of other measures, this is not expected to have a significant impact on the results. Operation and maintenance costs are estimated based on assumptions about the minimum required maintenance of rain gardens. The resulting value is therefore also quite uncertain, however, as the required maintenance is nevertheless considered to be small, this is not expected to impact the results of the CBA in a major way. The detention basins were assumed to be installed without additional measures to ensure stability of the surrounding soils. If this assumption does not hold true, it might significantly impact the costs of the detention basins, leading to worse performance for all bundles, especially Bundle 1, 2 and 1a.

Investment costs, operation and maintenance costs and CO_2 emissions for the safe floodways are also prone to significant uncertainty. The investment and operation and maintenance costs varied substantially in the underlying data used for valuation in this study. As the costs of the safe floodways were significant, this could have impacted the results of the analysis. Bundle 3 would have been especially impacted by this. Additionally, as it is necessary to maintain a durable cover that can withstand the runoff without erosion damages, operation and maintenance costs of safe floodways would most likely be higher than for normal roads.

Operation and maintenance costs for rain gardens are quite uncertain. Despite their widespread implementation, no requirements for maintenance and operation of rain gardens exists, and none of the municipalities asked could provide information on their maintenance costs, or even maintenance practice. As hydraulic performance of rain gardens is significantly dependant on proper maintenance, this is concerning. Commonly, the maintenance responsibility is placed with the entity owning the property where the rain garden is placed. Consequently, maintenance, if done at all, is mostly done by personnel without stormwater-specific knowledge, increasing the risk of improper maintenance.

Generally, the investment costs of stormwater control measures are highly site specific. The measures analysed in this study were assessed based on more general costs, and are therefore not expected to be directly representative of the actual costs of implementation in the case area.

The effects of green roofs on improved air quality have been little researched. In the literature review performed for this study, only one case of actual measurements of pollutant capture in green roof substrate was found, however this was done on green roofs samples placed on existing roofs for a limited period of time, and not on full-scale green roofs in operation. To the knowledge of the author, no studies on the effects on air quality of full-scale green roofs has been conducted.

Several potential co-costs and co-benefits were not included in the CBA, due to lack of valuation studies. Exclusions include reduced urban heat island effect, improved water quality, and aesthetic values. One notable exclusion was increased biodiversity. Green roofs and rain gardens can have a significant positive impact on local biodiversity, by providing habitat for a wide variety of species. Some valuation studies on the improved biodiversity resulting from green roofs have been done, however all have been based on avoided cost methods, where the avoided cost have been the result of local policy. Since no equivalent policies exist in Norway, no valuation of increased biodiversity was done in this study. The monetary value of biodiversity is generally considered to be difficult to quantify, and hard to assign on a local scale (Gallet, 2012). However, as the value of biodiversity might very well be significant, analysis of green roofs and rain gardens that do not take this into account risk underestimating their worth. The methodology concerning how to value biodiversity have long been a contested topic, however in March 2021, the UN adopted a common framework for ecosystem accounting. This introduces the potential for more universally applicable valuation studies on increased biodiversity in green roofs and rain gardens over the coming years. Generally, the exclusion of several recognized co-benefits of green roofs from the CBA results in a poorer performance by the green roofs than they would otherwise achieve.

Reduced energy consumption is a much recognized co-benefit of green roofs, which can be quite significant, especially in warm climates (Teemusk and Mander, 2009). Due to evaporative cooling in the roof substrate, cooling demands in warm periods are reduced. The potential for energy savings due to increased insulation from the green roof substrate has been well documented, however the yearly energy saving of well insulated buildings in cold climates remains uncertain (Andenæs et al., 2018). As the same evaporative cooling increases the energy demands for heating in the spring and fall, the net effect on energy demands is not clear, and might in fact be positive. Due to the limited research on impact on energy demands in cooler climate, the value was not assessed in this study.

4.9 Further Work

In order to enable more accurate CBAs, more data should be collected on investment and operation and maintenance costs for stormwater control measures. Especially the operation/maintenance costs of detention basins, rain gardens and safe floodways remain highly uncertain. More accurate data on these costs will lead to more accurate CBAs, resulting in more optimal investment decisions for Norwegian municipalities.

To increase the accuracy of flood modelling, data on extreme rain events should be gathered systematically. This would also contribute towards identifying vulnerable areas.

Several important co-benefits of stormwater control measures have not been the subject of transferable valuation studies. This is especially the case for green infrastructure, which introduces a wide variety of co-benefits which have not been valued. The effects on energy demand by green roofs in cold climates should also be further evaluated, for a more accurate assessment on the cost-effectiveness of green roofs.

The methodology used in this study should be expanded upon, by introducing additional thresholds, or replacing the threshold value system with depth-damage curves for each asset. Modelling of more events, for both the current condition and with climate factor would lead to a more accurate assessment of damages.

The potential of using CBAs to calibrate MCDA should be investigated further, by developing a MCDA tool that more closely resembles the setup of CBAs, and analysing several case areas with both it and a CBA.

5 Conclusion

In this thesis, several stormwater control measures in a case area in Asker municipality were analysed using both a cost-benefit analysis (CBA) and a multi-criteria decision analysis (MCDA). The CBA was performed by a assessing the monetary value of several costs and benefits through modelling, literature review, and conversations with industry professionals. Three different combinations, or bundles, of measures were assessed. A hydrodynamic flood model of the case area was created in HEC-RAS, to assess flood damage reduction and peak flow reduction for each measure. Additional modelling in SWMM was done for green infrastructure measures, and the SWMM model was manually coupled with the HEC-RAS model. The MCDA was performed in cooperation with representatives from the municipality, using an existing tool currently in use by the municipality. This provided results of two different analysis methods on a set of stormwater control measures. The results were analysed and compared with the goal of answering the following research questions:

- How does the valuations and optimal solution in the CBA and the MCDA differ?
- How can a CBA be used to calibrate a MCDA?
- What data does Asker municipality need to perform more accurate CBAs?

The optimal solutions were the same for both analysis methods. However, the margin which separated the different bundles was much larger for the CBA than for the MCDA. Consequently, the MCDA failed to identify significant differences between the bundles. For valuation of specific measures, the results of the analysis also differed significantly. In the CBA, the bundles performed very differently in terms of reduced flood damages, but this far less apparent in the MCDA. The MCDA was performed without any flood modelling, and this demonstrates the difficulty of assessing damage reduction potential without the aid of flood models. Due to low weights for everything except costs and risk reduction, the MCDA was largely decided by these values. The CBA however showed significant values for both flood damage reduction and improved air quality. This highlights the need for appropriate weighting in the MCDA, to avoid misrepresenting the magnitude of values. As the contribution of each measure towards overall score of the bundle was weighted according to costs in the MCDA, cheap measures with good performance was severely underrepresented in the MCDA. As a result, weighting contribution according to costs in MCDAs should be avoided. Overall, the MCDA failed at both appropriately weighting different values, and at identifying the impact of each individual measure. The ranking of measures was the same in both analysis, but this was largely incidental, and did not originate in similar assessment of neither magnitude of values nor performance of measures.

By assessing the implicit monetary valuation of the points in the MCDA resulting from the difference in scoring of costs, an implicit valuation for each value included in the MCDA can be obtained. This can be used to compare the implicit valuation in the MCDA, to the valuation performed in the CBA. As the CBA is a much more detailed and accurate assessment, the results of the CBA can be used to calibrate the use of weights in the MCDA. However, as the MCDA used in this thesis weighted impact of each measure according to cost, the potential of using the CBA to calibrate the MCDA were limited, as neither weighting of values nor scoring of performance across different measures would be applicable to cases where the distribution of costs are different. Minor calibrations were suggested for the scores within one specific measure. For a MCDA with a setup more similar to that of CBAs, further calibration should be possible.

In order to perform more accurate CBAs, Asker municipality would need to systematically gather data on investment costs, operation and maintenance costs and CO_2 emissions. This includes measures not traditionally used in stormwater management, such as roads. Systematic collection on data, such as pictures, of extreme rain events would both increase accuracy of flood models and contribute towards identification of vulnerable areas. In addition, as more valuation studies are completed for co-costs and co-benefits of stormwater control measures, these values should be included in future CBAs for a more complete assessment. Further development of the threshold value system for damage assessment, or damage assessment using depth-damage curves would contribute towards more accurately representing the damages done during the largest rain events.

References

[Alv+19] Alida Alves, Berry Gersonius, Zoran Kapelan, et al. "Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management". In: *Journal of Environmental Management* 239.February (2019), pp. 244–254. ISSN: 0301-4797. DOI: 10.1016/j.jenvman.2019.03.036. URL: https://doi.org/10.1016/j.jenvman.2019.03.036.

[Alv+18] Alida Alves, Berry Gersonius, Arlex Sanchez, et al. "Multi-criteria Approach for Selection of Green and Grey Infrastructure to Reduce Flood Risk and Increase CO-benefits". In: *Water Resources Management* 32.7 (2018), pp. 2505–2522. ISSN: 15731650. DOI: 10.1007/s11269-018-1943-3.

[And+18] Erlend Andenæs et al. "Performance of blue-green roofs in cold climates: A scoping review". In: *Buildings* 8.4 (2018). ISSN: 20755309. DOI: 10.3390/buildings8040055.

[Ask20] Asker Kommune. *Temaplan vann og vannmiljø*. Tech. rep. 2020.

[Bar97] Brian Barry. "Sustainability and Intergenerational Justice". In: *Intergenerational Justice* 89 (1997), pp. 183–208. DOI: 10.4324/9781315252100-10.

[BMB16] Mareike A Becker, Tone M Muthanna, and Bent C. Braskerud. "Trinn 1 : Reduser overvannet i avløpsnettet ved å frakoble taknedløp". In: Desember (2016), pp. 359–369.

[Bjö04] Folke Björk. "Green roofs effect on durability of roof membranes". In: 006 (2004), pp. 1–24. URL: http://greenroofmalmo.files.wordpress.com/2012/02/006-green-roofs-effect-on-durability-of-roof-membranes1.pdf.

[BP20] Bent C Braskerud and Kim H Paus. "FNs bærekraftsmål og bruk av lokal overvannsdisponering". In: *Vann* (2020), pp. 75–86.

[BPE13] Bent C Braskerud, Kim H Paus, and Arvid Ekle. *Anlegging av regnbed*. Tech. rep. 2013. URL: http://publikasjoner.nve.no/rapport/2013/rapport2013_03.pdf.

[BS13] Bent C Braskerud and Ole Petter Skallebakke. "Frakobling av takrenner til overflate . Flomdemping i små nedbørfelt". In: (2013), pp. 569–572.

[Bre20] Thomas Breen. *Kronikk: Behov for store investeringer i vann og avløp*. 2020. URL: https://www.norskvann.no/index.php/meninger/investeringsbehov/2422-kronikk-behov-for-store-investeringer-i-vann-og-avl%C3%B8p/.

[Bru88] Gro Harlem Brundtland. "The Brundtland Report: 'Our Common Future'". In: *Medicine and War* 4.1 (1988), pp. 17–25. ISSN: 07488009. DOI: 10.1080/07488008808408783.

[Cur05] Beth Anne Currie. "Estimate of air pollution mitigation with green roofs using the UFORE model". In: (2005).

[EMB17] Kyle Eckart, Zach McPhee, and Tirupati Bolisetti. "Performance and implementation of low impact development – A review". In: *Science of the Total Environment* 607-608 (2017), pp. 413–432. ISSN: 18791026. DOI: 10.1016/j.scitotenv.2017.06.254. URL: http://dx.doi.org/10.1016/j.scitotenv.2017.06.254.

[Fin05] Finansdepartementet. *Veileder i samfunns- økonomiske analyser*. Tech. rep. 2005.

[Fle+15] Tim D. Fletcher et al. "SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage". In: *Urban Water Journal* 12.7 (2015), pp. 525–542. ISSN: 17449006. DOI: 10.1080/1573062X.2014.916314. URL: http://dx.doi.org/10.1080/1573062X.2014.916314.

[Fra+12] C. F. Fratini et al. "Three Points Approach (3PA) for urban flood risk management: A tool to support climate change adaptation through transdisciplinarity and multifunctionality". In: *Urban Water Journal* 9.5 (2012), pp. 317–331. ISSN: 1573062X. DOI: 10.1080/1573062X.2012.668913.

[Gal12] Danielle Gallet. "The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits". In: *Proceedings of the Water Environment Federation* 2011.17 (2012), pp. 924–928. ISSN: 19386478. DOI: 10.2175/193864711802639741.

[Hag11] Kåre P Hagen. *Verdsetting av fremtiden. Tidshorisont og diskonteringsrenter*. Tech. rep. 27. 2011.

[HM19] Vladimír Hamouz and Tone Merete Muthanna. "Hydrological modelling of green and grey roofs in cold climate with the SWMM model". In: *Journal of Environmental Management* 249.January (2019), p. 109350. ISSN: 10958630. DOI: 10.1016/j.jenvman.2019.109350. URL: https://doi.org/10.1016/j.jenvman.2019.109350.

[Her18] Ragni Rønneberg Hernes. *Kostnader ved lokale overvannstiltak*. Tech. rep. 2018.

[Kav+18] Emad Kavehei et al. "Carbon sequestration potential for mitigating the carbon footprint of green stormwater infrastructure". In: *Renewable and Sustainable Energy Reviews* 94.November 2017 (2018), pp. 1179–1191. ISSN: 18790690. DOI: 10.1016/j.rser.2018.07.002. URL: https://doi.org/10.1016/j.rser.2018.07.002.

[KC83] Emmett B. Keeler and Shan Cretin. “Discounting of Life-Saving and Other Nonmonetary Effects”. In: *Management Science* 29.3 (1983), pp. 300–306. ISSN: 0025-1909. DOI: 10.1287/mnsc.29.3.300.

[Ker59] W. Kerby. “Time of concentration for overland flow”. In: *Civil Engineering* 29 (1959), p. 60.

[Kim+17] Yeowon Kim et al. “Fail-safe and safe-to-fail adaptation: decision-making for urban flooding under climate change”. In: *Climatic Change* 145.3-4 (2017), pp. 397–412. ISSN: 15731480. DOI: 10.1007/s10584-017-2090-1.

[LPF20] Goffredo La Loggia, Valeria Puleo, and Gabriele Freni. “Floodability: A New Paradigm for Designing Urban Drainage and Achieving Sustainable Urban Growth”. In: *Water Resources Management* 34.10 (2020), pp. 3411–3424. ISSN: 15731650. DOI: 10.1007/s11269-020-02620-6.

[Law15] S Lawrence Dingman. *Physical Hydrology*. 2015.

[Lin+08] Oddvar Lindholm et al. *Veiledning i klimatilpasset overvannshåndtering*. Tech. rep. 2008, p. 79.

[MBL18] Mika Marttunen, Valerie Belton, and Judit Lienert. “Are objectives hierarchy related biases observed in practice? A meta-analysis of environmental and energy applications of Multi-Criteria Decision Analysis”. In: *European Journal of Operational Research* 265.1 (2018), pp. 178–194. ISSN: 03772217. DOI: 10.1016/j.ejor.2017.02.038.

[Mil13] Miljøverndepartementet. *Klimatilpasning i Norge*. Tech. rep. 2013. URL: http://www.regjeringen.no/nb/dep/md/dok/regpubl/stmeld/2012-2013/meld-st-33-20122013.html?id=725930.

[Mil10] Miljøverndepartementet. *Tilpassing til eit klima i endring*. Tech. rep. 2010, p. 240. URL: https://www.regjeringen.no/contentassets/01c4638b3f3e4573929f3b375f4731e0/nn-no/pdfs/nou201020100010000dddpd pdf.

[Nor17a] Norconsult. *ROS-analyse overvann*. Tech. rep. 2017.

[Nor20] Norges geologiske undersøkelse. *Løsmasser WMS*. 2020. URL: https://kartkatalog.geonorge.no/metadata/loesmasser-wms/aa780848-5de8-4562-8f35-3d5c80ea8b48.

[Nor17b] Norsk Klimaservicesenter. *Klima i Norge 2100 - A knowledge base for climate adaptation*. Tech. rep. 1. 2017, p. 204. URL: www.miljodirektoratet.no/20804.

[Nor06] Norsk Kommunalteknisk Forening. *Kartlegging av kommunenes ressursbruk på kommunale veger Forprosjektutredning for Kommunal- og regionaldepartementet*. Tech. rep. November. 2006.

[Nor21] Norsk Vann. *Kommunalt investeringsbehov*. Tech. rep. 2021.

[NVE98] NVE. *Vassdragshåndboka - Håndbok i forebyggingsteknikk og vassdragsmiljø*. 1998.

[Ols+15] Anders Skovgård Olsen et al. “Comparing methods of calculating expected annual damage in urban pluvial flood risk assessments”. In: *Water (Switzerland)* 7.1 (2015), pp. 255–270. ISSN: 20734441. DOI: 10.3390/w7010255.

[Pal19] Elisa Palazzo. “From water sensitive to floodable: defining adaptive urban design for water resilient cities”. In: *Journal of Urban Design* 24.1 (2019), pp. 137–157. ISSN: 14699664. DOI: 10.1080/13574809.2018.1511972. URL: https://doi.org/10.1080/13574809.2018.1511972.

[PSL19] Av Phan, Åge Samyo, and Oddvar Georg Lindholm. “Metode for valg av kostnadseffektive overvannstiltak i et endret klima ”. In: *Vann* 4 (2019), pp. 279–292.

[Råd19] Rådgivende Ingeniørers Forening. *State of the nation*. Tech. rep. 2019, pp. 30–.

[Ram19] Rambøll. *Ekstremnedbør Oslo - Skadeomfang Og Kostnader*. Tech. rep. 2019. URL: https://no.ramboll.com.

[Ras16] Jan Rasmussen. *The economics of managing heavy rains and stormwater in Copenhagen – The Cloudburst Management Plan*. 2016. URL: https://climate-adapt.eea.europa.eu/metadata/case-studies/the-economics-of-managing-heavy-rains-and-stormwater-in-copenhagen-2013-the-cloudburst-management-plan.

[Ska+15] Helge Skaaraas et al. *NOU 2015: 16 Overvann i byer og tettsteder*. Tech. rep. 2015, p. 276. URL: www.fagbokforlaget.no/offpub.

[Spe+12] A. F. Speak et al. “Urban particulate pollution reduction by four species of green roof vegetation in a UK city”. In: *Atmospheric Environment* 61 (2012), pp. 283–293. ISSN: 13522310. DOI: 10.1016/j.atmosenv.2012.07.043. URL: http://dx.doi.org/10.1016/j.atmosenv.2012.07.043.

[SSB20] SSB. *Befolkningsframskrivinger for kommunene , 2020-2050*. Tech. rep. 2020, p. 87. URL: https://www.ssb.no/en/befolkning/artikler-og-publikasjoner/_attachment/429172?_ts=173fc97ddf0.

[Sta] Statens Vegvesen. *Veinormalene*. Tech. rep. URL: https://www.vegvesen.no/en/professional/publikasjoner/handboker/om-handbokene/vegnormalene/n100/.

[Sta18] StatensVegvesen. *Prissetting av helse- belastning av svevestøv*. Tech. rep. 2018.

[Swe17] Sweco. *Oversvømmingskartering vid ekstreme regn – asker kommune*. Tech. rep. 2017.

[TM09] Alar Teemusk and Ülo Mander. “Greenroof potential to reduce temperature fluctuations of a roof membrane: A case study from Estonia”. In: *Building and Environment* 44.3 (2009), pp. 643–650. ISSN: 03601323. DOI: `10.1016/j.buildenv.2008.05.011`.

[Tra14] Transportøkonomisk Institutt. *Marginale eksterne kostnader ved vegtrafikk*. Tech. rep. 2014, p. 126. URL: `https://www.toi.no/getfile.php?mmfileid=38978`.

[Tra99] Transportøkonomisk Institutt. *Marginale kostnader ved transportvirksomhet*. Tech. rep. 1999.

[Van20] Vann- og avløpsetaten. *Teknisk mulighetsstudie – Bakåsbekken Furuset*. Tech. rep. 2020.

[Wis+10] S. Wise et al. “Integrating valuation methods to recognize green infrastructure’s multiple benefits”. In: *Low Impact Development 2010: Redefining Water in the City - Proceedings of the 2010 International Low Impact Development Conference* (2010), pp. 1123–1143. DOI: `10.1061/41099(367)98`.

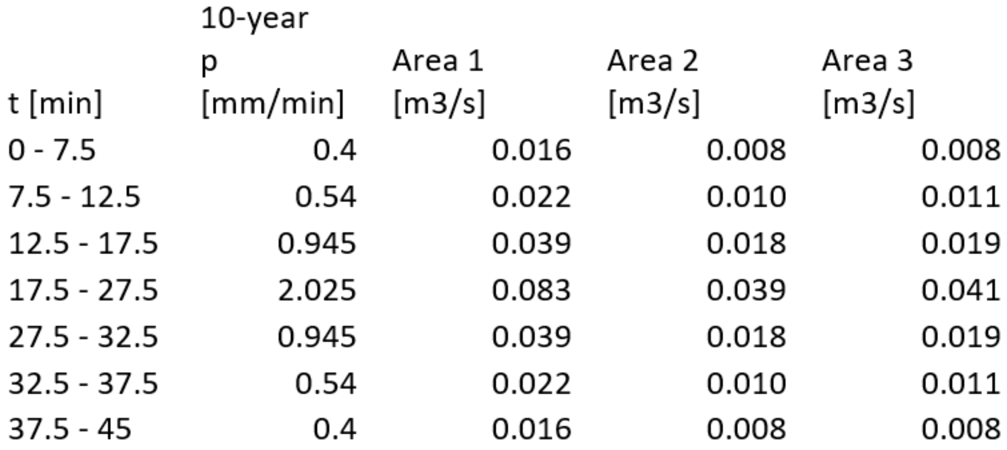
[YYG08] Jun Yang, Qian Yu, and Peng Gong. “Quantifying air pollution removal by green roofs in Chicago”. In: *Atmospheric Environment* 42.31 (2008), pp. 7266–7273. ISSN: 13522310. DOI: `10.1016/j.atmosenv.2008.07.003`.

[Zer18] Zero. *Å kutte utslipp fra bygging av en vei*. 2018. URL: `https://zero.no/a-kutte-utslipp-fra-bygging-av-en-vei/`.

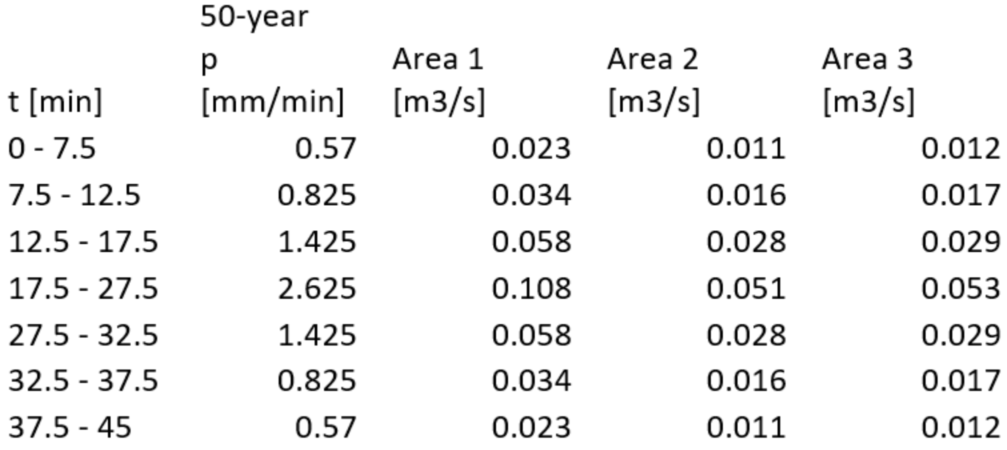
Appendix A - Downspout Disconnections

The connected downspouts discharges into the stream at three different locations. For each location, the contributing buildings were determined based on inspections. The number of contributing buildings was divided by two, assuming that 50% of downspouts leading into the ground was connected to the drainage system. Based on the precipitation events and the resulting areas, input hydrographs were synthesized, and added as boundary conditions in the model. The hydrographs were calculated using the rational formula, with C = 0.85.

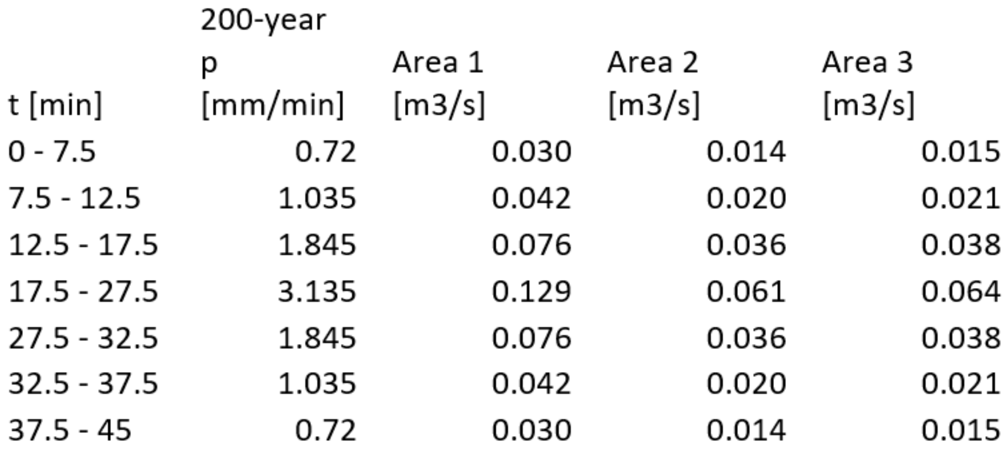
The following is the resulting hydrographs for the three areas.



t [min]	10-year p [mm/min]	Area 1 [m3/s]	Area 2 [m3/s]	Area 3 [m3/s]
0 - 7.5	0.4	0.016	0.008	0.008
7.5 - 12.5	0.54	0.022	0.010	0.011
12.5 - 17.5	0.945	0.039	0.018	0.019
17.5 - 27.5	2.025	0.083	0.039	0.041
27.5 - 32.5	0.945	0.039	0.018	0.019
32.5 - 37.5	0.54	0.022	0.010	0.011
37.5 - 45	0.4	0.016	0.008	0.008



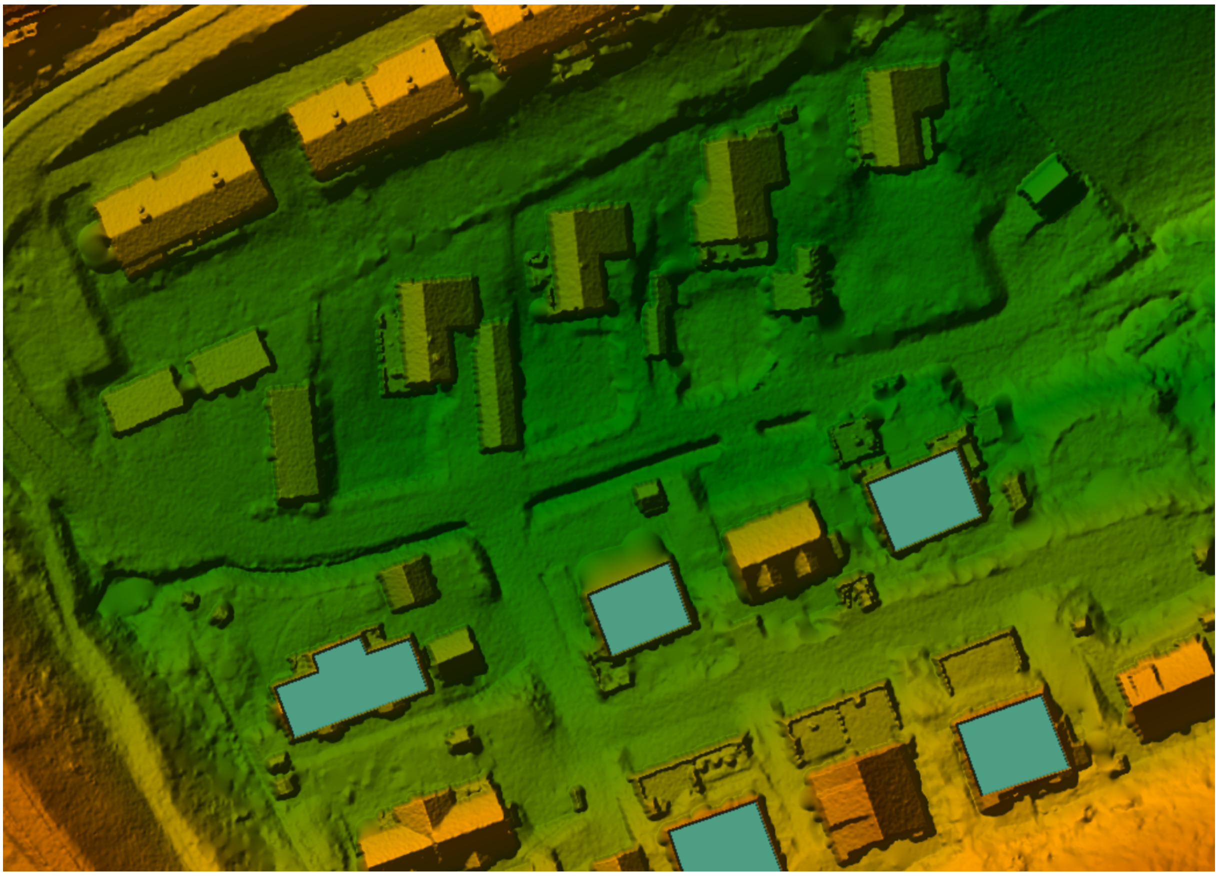
t [min]	50-year p [mm/min]	Area 1 [m3/s]	Area 2 [m3/s]	Area 3 [m3/s]
0 - 7.5	0.57	0.023	0.011	0.012
7.5 - 12.5	0.825	0.034	0.016	0.017
12.5 - 17.5	1.425	0.058	0.028	0.029
17.5 - 27.5	2.625	0.108	0.051	0.053
27.5 - 32.5	1.425	0.058	0.028	0.029
32.5 - 37.5	0.825	0.034	0.016	0.017
37.5 - 45	0.57	0.023	0.011	0.012

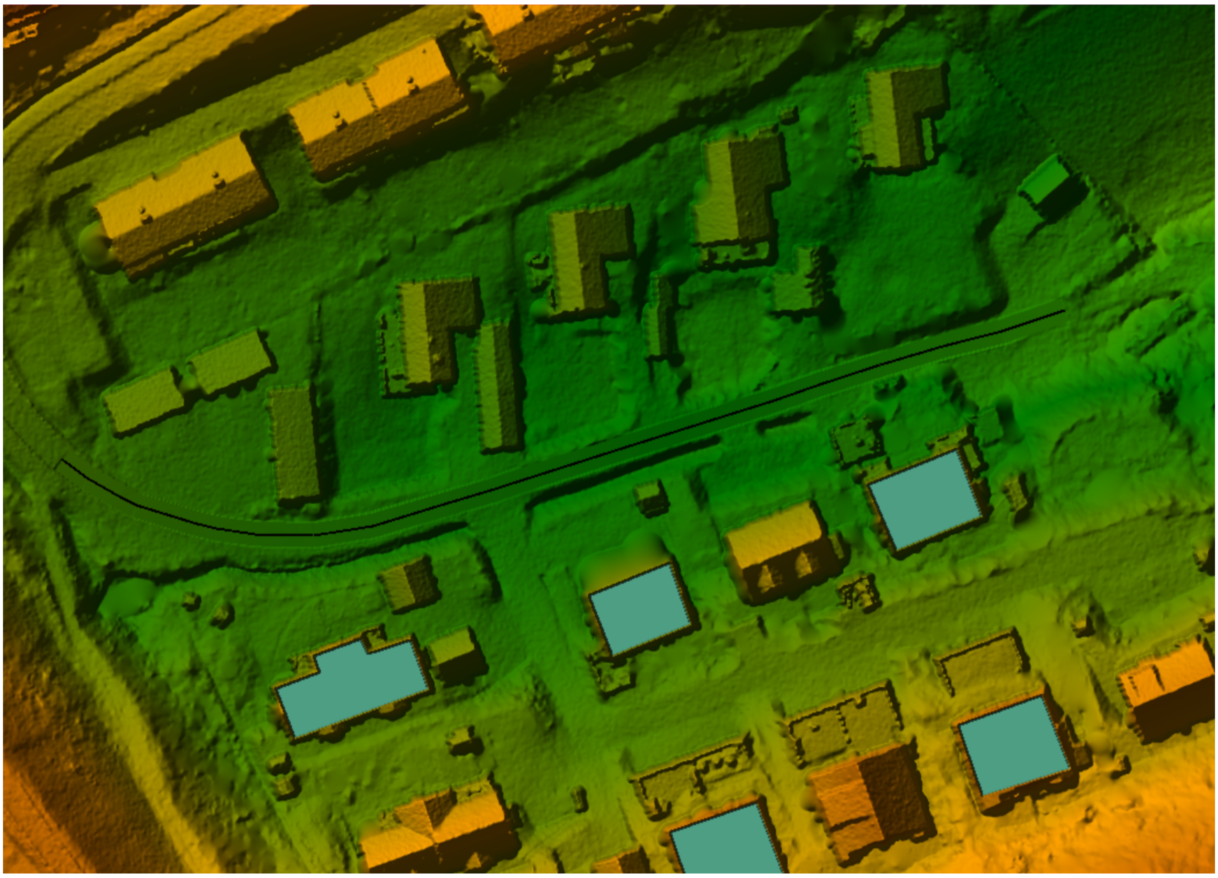


t [min]	200-year p [mm/min]	Area 1 [m3/s]	Area 2 [m3/s]	Area 3 [m3/s]
0 - 7.5	0.72	0.030	0.014	0.015
7.5 - 12.5	1.035	0.042	0.020	0.021
12.5 - 17.5	1.845	0.076	0.036	0.038
17.5 - 27.5	3.135	0.129	0.061	0.064
27.5 - 32.5	1.845	0.076	0.036	0.038
32.5 - 37.5	1.035	0.042	0.020	0.021
37.5 - 45	0.72	0.030	0.014	0.015

Appendix B - Safe Floodway 1

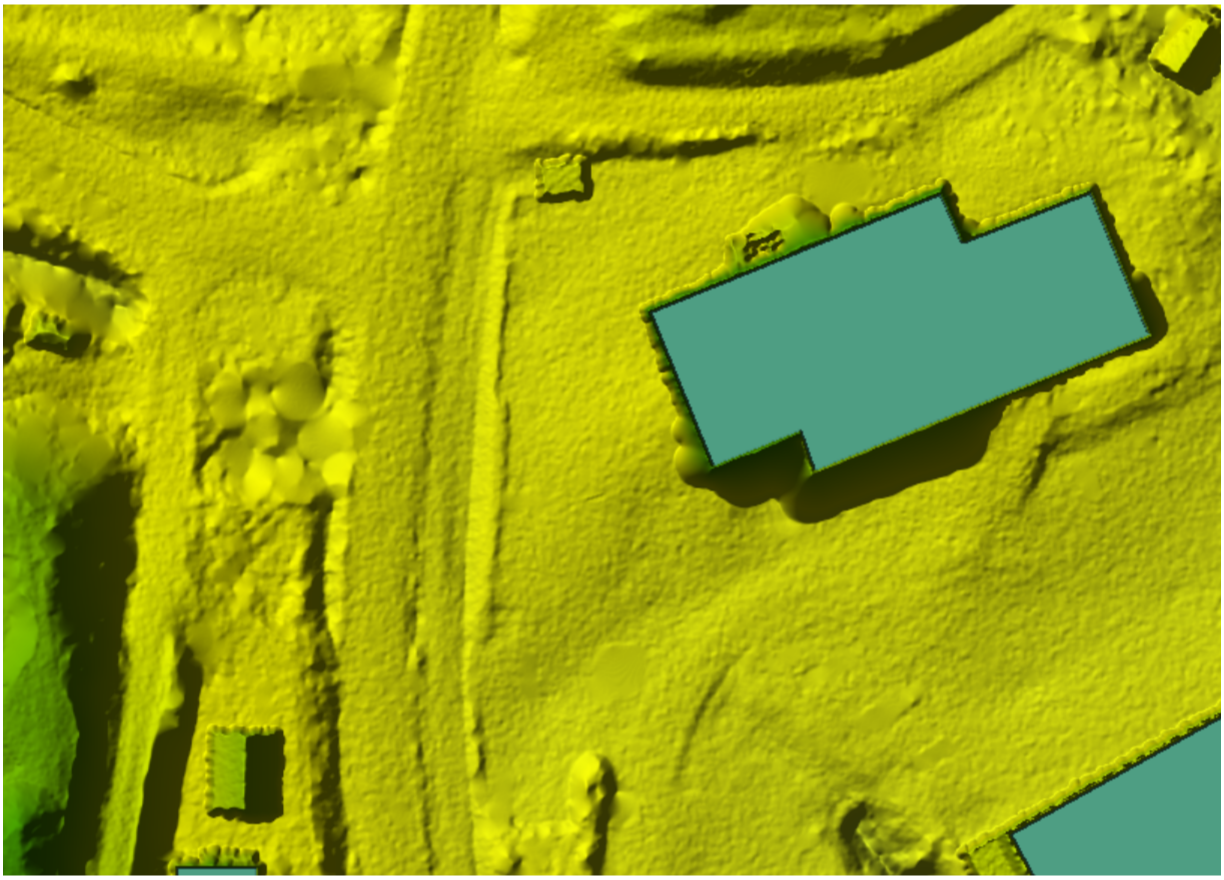
Safe Floodway 1 was implemented in the model by lowering the road and applying a sideways fall of 3%.



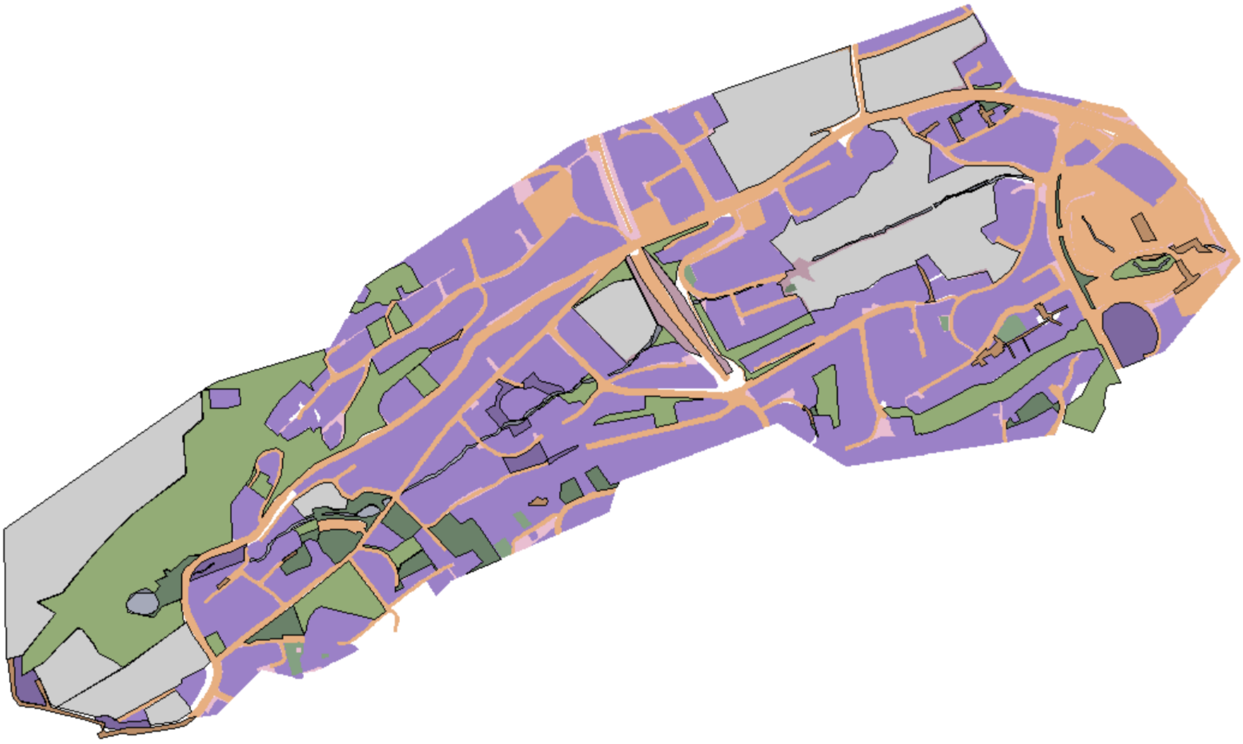


Appendix C - Safe Floodway 2

Safe Floodway 2 was implemented in the model using a system of rounded curbs, a speedbump, an elevated section of a sidewalk and a lowered part of a parking lot.



Appendix D - Land Use Polygons

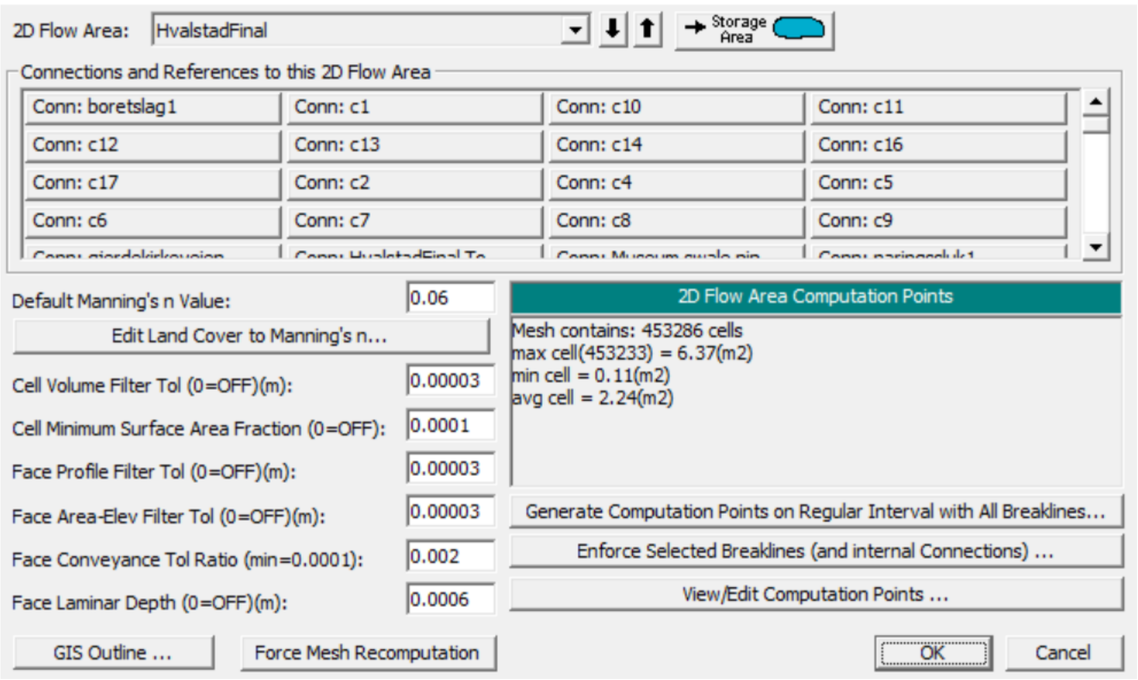


Land Use	Percent Impervious
Developed - High Intensity	Orange
Developed - Low Intensity	Purple
Green Area	Deep Green
Fields	Light Grey
Forested Area	Light Green
Stream	Dark Grey

Appendix E - HEC-RAS Settings

The following setting were used for the HEC-RAS simulations.

2D Flow Areas



2D Flow Area: HvalstadFinal

Connections and References to this 2D Flow Area

Conn: boretslag1	Conn: c1	Conn: c10	Conn: c11
Conn: c12	Conn: c13	Conn: c14	Conn: c16
Conn: c17	Conn: c2	Conn: c4	Conn: c5
Conn: c6	Conn: c7	Conn: c8	Conn: c9

Default Manning's n Value: 0.06

Cell Volume Filter Tol (0=OFF)(m): 0.00003

Cell Minimum Surface Area Fraction (0=OFF): 0.0001

Face Profile Filter Tol (0=OFF)(m): 0.00003

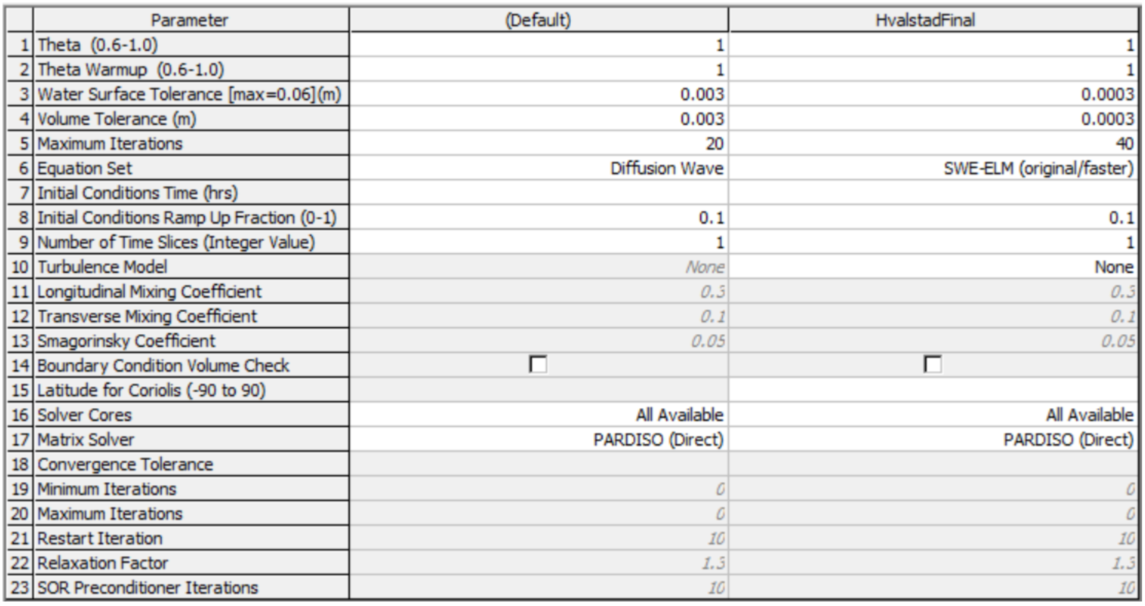
Face Area-Elev Filter Tol (0=OFF)(m): 0.00003

Face Conveyance Tol Ratio (min=0.0001): 0.002

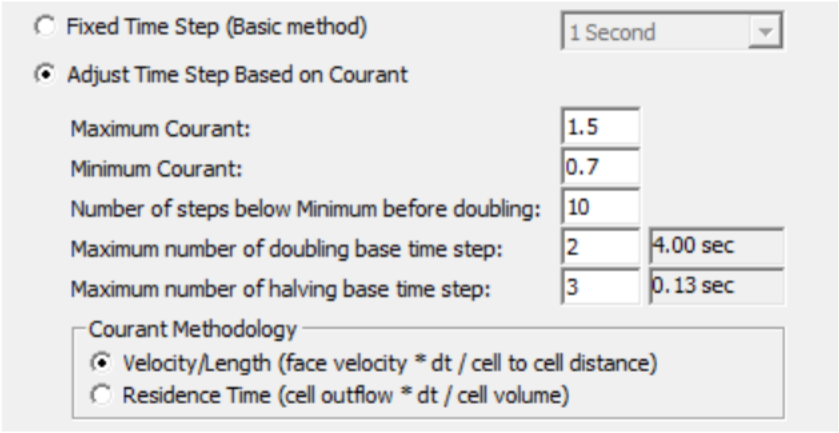
Face Laminar Depth (0=OFF)(m): 0.0006

2D Flow Area Computation Points

Mesh contains: 453286 cells
max cell(453233) = 6.37(m2)
min cell = 0.11(m2)
avg cell = 2.24(m2)



	Parameter	(Default)	HvalstadFinal
1	Theta (0.6-1.0)	1	1
2	Theta Warmup (0.6-1.0)	1	1
3	Water Surface Tolerance [max=0.06](m)	0.003	0.0003
4	Volume Tolerance (m)	0.003	0.0003
5	Maximum Iterations	20	40
6	Equation Set	Diffusion Wave	SWE-ELM (original/faster)
7	Initial Conditions Time (hrs)		
8	Initial Conditions Ramp Up Fraction (0-1)	0.1	0.1
9	Number of Time Slices (Integer Value)	1	1
10	Turbulence Model	None	None
11	Longitudinal Mixing Coefficient	0.3	0.3
12	Transverse Mixing Coefficient	0.1	0.1
13	Smagorinsky Coefficient	0.05	0.05
14	Boundary Condition Volume Check	☐	☐
15	Latitude for Coriolis (-90 to 90)		
16	Solver Cores	All Available	All Available
17	Matrix Solver	PARDISO (Direct)	PARDISO (Direct)
18	Convergence Tolerance		
19	Minimum Iterations	0	0
20	Maximum Iterations	0	0
21	Restart Iteration	10	10
22	Relaxation Factor	1.3	1.3
23	SOR Preconditioner Iterations	10	10



○ Fixed Time Step (Basic method) 1 Second

● Adjust Time Step Based on Courant

Maximum Courant: 1.5

Minimum Courant: 0.7

Number of steps below Minimum before doubling: 10

Maximum number of doubling base time step: 2 4.00 sec

Maximum number of halving base time step: 3 0.13 sec

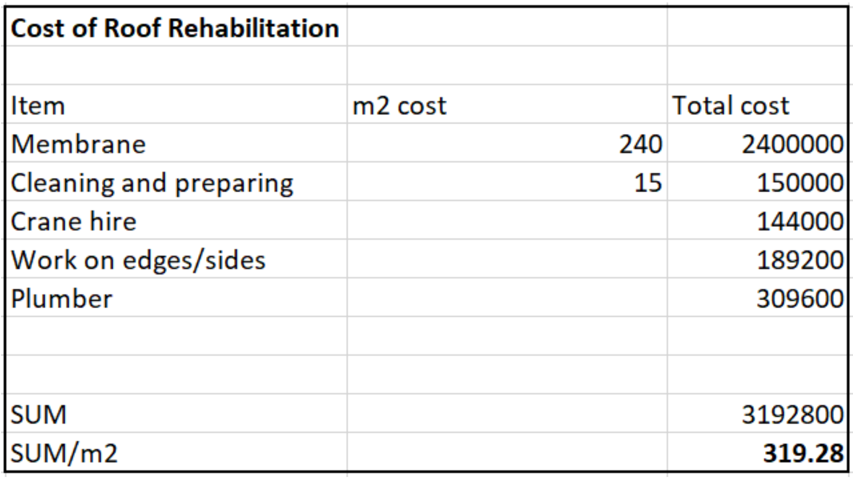
Courant Methodology

● Velocity/Length (face velocity * dt / cell to cell distance)

○ Residence Time (cell outflow * dt / cell volume)

Appendix F - Roof Rehabilitation

Roof rehabilitation cost was determined based on a conversation with a representative from the roofing supplier Nortekk AS. He supplied costs for the different aspects of the roof rehabilitation, and they were added, and a average cost per square meter was obtained.



Cost of Roof Rehabilitation		
Item	m2 cost	Total cost
Membrane	240	2400000
Cleaning and preparing	15	150000
Crane hire		144000
Work on edges/sides		189200
Plumber		309600
SUM		3192800
SUM/m2		**319.28**

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