Designing holistic analysis of stormwater control measures

Sigurd Semb Mikkelsen

NTNU, Department of Water and Environmental Engineering

December 20, 2020

Fig. 1: Pluvial flooding in Hvalstad, Asker. Photo: Asker Municipality

Abstract

In august 2016, Asker municipality experienced an extreme rainfall event, leading to significant damages due to pluvial flooding. As pluvial flooding events are expected to become more common in the future, the municipality has a large need for investments in stormwater control measures. In order to correctly prioritize between conflicting measures, there is a need for a holistic analysis tool, taking the many co-costs and co-benefits of stormwater control measures into account. In this project work, the framework for a cost-benefit analysis and a multi-criteria decision analysis of stormwater control measures has been established. For a case area in Asker municipality, stormwater control measures are suggested, based on consultations with professionals in the municipality. A literature review on potential costs and benefits of stormwater control measures is performed, and potential costs and benefits are identified. Several commonly assessed costs and benefits are excluded from the analysis, based on an assessment of their relevance and expected magnitude. The following criteria are identified as relevant:

- Flood risk reduction
- Runoff quantity reduction
- Investment cost
- Operation and maintenance cost
- Improved air quality
- Ecological benefits
- Net CO2 emissions
- Increased longevity
- Energy savings

Methods for monetary valuation, qualitative and quantitative scoring of the relevant criteria are determined based on findings from published literature. This includes monetary valuation of several costs and benefits which are not commonly valued, using non-market valuation methods. Lastly, sources of uncertainty and approaches to ensure comparable results from the multi-criteria decision analysis and the cost-benefit analysis are discussed.

Keywords: Co-benefits, Co-costs, Cost-benefit analysis, Flood risk reduction, Multi-criteria decision analysis

List of abbreviations

SCM - Stormwater Control Measures

MCDA - Multi-Criteria Decision Analysis

CBA - Cost-Benefit Analysis

NPV - Net Present Value

CSO - Combined Sewer Overflow

LID - Low Impact Development

PM - Particulate Matter

UHIE - Urban Heat Island Effect

SC-CO2 - Social Cost of Carbon Dioxide

Contents

1 Introduction . . . 4
2 Theory . . . 5
2.1 Stormwater . . . 5
2.2 Stormwater control measures . . . 5
2.3 Co-costs and co-benefits . . . 6
2.4 Multi-criteria decision analysis . . . 6
2.5 Cost-benefit analysis . . . 7
3 Method . . . 8
3.1 Selection of case area . . . 8
3.2 Description of case area . . . 8
3.3 Selection of SCMs . . . 10
3.4 Selection of success criteria . . . 11
3.5 Selection of assessment criteria . . . 11
3.6 Selection of modelling tool . . . 12
4 Results . . . 12
4.1 Description of SCMs . . . 12
4.2 Exclusion of assessment criteria: . . . 13
4.3 Impacts and assessment methods . . . 16
5 Discussion . . . 20
5.1 Sources of uncertainty . . . 20
5.2 Comparability . . . 20
6 Conclusion . . . 21

1 Introduction

Rainfall events leading to runoff exceeding the capacity of the stormwater drainage systems is causing significant damages in Norwegian municipalities. The Norwegian Official Report on stormwater in cities and densely populated areas estimates the total damages due to stormwater to be between 1.6 and 3.6 billion NOK, annually. (Skaaraas et al. 2015). These problems are expected to increase in the future, as urbanization leads to a higher degree of impervious area, and as the intensity of rainfall events are expected to increase due to climate change. In order to mitigate these impacts, there is a large need for investments to be made in stormwater control measures (SCM). SCMs take on many different forms, but they are typically divided into two main categories, grey and blue-green solutions, according to their approach to stormwater handling. Within each of these categories, a wide range of technical solutions exist, which alone or in combination can be utilized to provide the necessary degree of stormwater control. The investment costs of the measures differ significantly. Additionally, measures are associated with a wide range of co-costs and co-benefits, beyond their costs and performance for stormwater control. Hence, there is a need for a holistic assessment of SCMs, across the entire range of potential impacts, in order to identify the optimal measure or combination of measures in each case.

Multiple methods for holistic assessment of SCMs exists. One of the most widely used methods is the multi-criteria decision analysis (MCDA). It involves a combination of qualitative and quantitative scoring of performance within any number of criteria, and a weighting of criteria according to their relative importance to the overall investment decision. The method offers good possibilities for stakeholder and community inclusion, but can be prone to subjective biases, especially in the weighting of criteria. A potentially less subjective method is the cost-benefit analysis (CBA). In a CBA, measures are evaluated according to the net present value (NPV) of all costs and benefits. Several costs and benefits, such as CO2 emissions or increased biodiversity, are not typically valued monetarily. Since no market exist where the values are traded, they are known as non-market goods. A CBA thus requires a monetary valuation of several non-market goods. This is done using non-market valuation methods. The resulting values are often prone to large uncertainty, but can nonetheless provide valuable understanding of the potential impacts of SCMs.

Asker is a large municipality located outside of Oslo. With 94 578 inhabitants, it is the 8th most populous municipality in Norway (StatistiskSentralbyrå 2020). August 6th 2016, the municipality experienced an extreme rainfall event, estimated to have a return period of more than 200 years (AsplanViak 2017). The event lead to severe flooding in many areas, which caused disturbance of traffic and significant damages to infrastructure and private property. According to a report by Finans Norge, the total insurance compensations due to the rainfall event was 512 mill. NOK, in Oslo, Bærum and Asker municipality (Finans Norge 2020). This probably only represents a fraction of the total costs due to the rainfall. As the damage potential is expected to increase in the future, there is significant need for investments in SCMs in the municipality.

Asker municipality has contracted the consultation firm Norconsult to develop a MCDA tool for investments in SCMs. The tool offers a comprehensive evaluation of performance of SCM across a wide variety of assessment criteria. However, the municipality has not yet implemented the tool for assessment of projects, and cites the complexity of the tool as being a barrier for use. There is in other words a need to investigate potential ways to reduce complexity, without compromising the reliability of the tool. This serves as the main motivation for this project work. During the course of this project work and the following master thesis, I aim to provide a solid theoretical foundation for how the MCDA tool can be simplified, and for how the reliability of the tool can be ensured. In order to achieve this, a case area in Asker municipality will be selected. SCMs will be suggested, and both a MCDA and a CBA will be performed to assess the suggested measures. The analysis will be based on a combination of literature review and case-specific adjustments. Lastly, the results will be evaluated in order to identify ways to reduce the complexity and guide the use of the current MCDA tool. The results of the CBA will serve as a way to calibrate the MCDA, by providing information on appropriate weighting and scoring. Additionally, criteria them are shown to be insignificant in the CBA can be eliminated from the CBA. This will result in a simpler and more accurate MCDA tool, which will maintain a holistic approach to the SCM evaluation. This project work aims to lay the foundations for this work by answering the following questions:

- What are the potential costs and benefits of stormwater control measures in the case area?
- How can the costs and benefits be valued for use in a cost-benefit analysis?
- How can the costs and benefits be scored for use in a multi-criteria decision analysis?
- How can comparability between the results of the cost-benefit analysis and the multi-criteria analysis be ensured?

2 Theory

2.1 Stormwater

Stormwater is defined as runoff from roofs, roads and other impervious surfaces as a result of rainfall, storm surges or snow melt (Miljøverndepartementet 2013). Stormwater has traditionally been handled by a system of curbs and gutters, conveying the stormwater into underground drainage pipes. The drainage system can be either separate or combined. In a separate system, stormwater is conveyed in separate stormwater pipes, and discharged directly into recipients, such as streams or water bodies. In a combined system, stormwater is conveyed in the wastewater pipes and transported to the wastewater treatment plant, where the stormwater-wastewater mix is treated. As combined sewer pipes are not dimensioned to convey all the water from large precipitation events, these systems include combined sewer overflows (CSOs). Acting as a "safety valve" to avoid backflow, they discharge excess amounts of stormwater-wastewater mix directly to recipients when rainfall events leads to an exceedance of capacity. Combined systems have the disadvantage that they lead to increased amounts of water requiring pumping and treatment. According to a report by Norsk Vann, 25-40% of municipal wastewater costs are expected to be due to stormwater (NorskVann 2014). As separate systems have replaced combined systems as the standard, most Norwegian municipalities have a combination of both separate and combined systems.

When stormwater amounts exceed the capacity of the stormwater drainage system, it will lead to pluvial flooding. Pluvial flooding is associated with significant damages. The most common damages are damage to buildings, damage to infrastructure, damage to health and lives, and ecological damage (Rambøll 2019). Damage to buildings through basement flooding is typically responsible for the largest costs. In a report on expected costs due to pluvial flooding in Oslo, the authors estimated costs of 1076 NOK per square meter of catchment area, due to a single extreme precipitation event (Rambøll 2019). This speaks to a lack of capacity in the stormwater drainage system, which is increasingly the case for many municipalities as both urbanization and climate change leads to larger amounts of stormwater generated.

The amount of impervious surfaces is highly influential on the amount of stormwater generated, as impervious surfaces prevent stormwater to infiltrate into the ground, and reduced vegetation cover limits evapotranspiration. A fully urbanized downtown area can generate up to five times as much stormwater as undeveloped land. Urbanization is expected to lead to increased amounts of stormwater in the future. The effects of urbanization on stormwater generation are visualized in Figure 2.

Stormwater amounts are additionally expected to increase due to climate change. Climate change will lead to both more precipitation, and more intense precipitation events (Miljøverndepartementet 2013). The increased intensity of precipitation is of particular concern, as damages related to stormwater mostly occur when the capacity of the stormwater drainage system is exceeded. Increased intensity will both increase the number of times the capacity is breached, and increase the amount of excess water when exceedance occurs. To plan for the increased precipitation due to climate change, it is common to utilize a climate factor. The current design precipitation is scaled up by the climate factor, and a new design precipitation is obtained. In order to meet the new required capacity resulting from urbanization and climate change, significant investments are needed.

2.2 Stormwater control measures

The traditional system for stormwater handling as described above is commonly referred to as grey infrastructure. As the amount of stormwater generated is increasing, it is increasingly evident that the existing grey infrastructure is not sufficient for adequate stormwater handling. A mere up-scaling of the current system in order to reach the needed capacity is very costly, inflexible and often inadequate for solving the problem posed by the increased loads (Eckart, McPhee, and Bolisetti 2017). As an alternative, a different approach to stormwater management is emerging, where stormwater is instead detained, slowed down, and managed locally. By utilizing nature-based solutions such as green roofs, swales and rain gardens, it seeks to mimic the characteristics of undeveloped land. With the help of infiltration, evapotranspiration and storage, the total amount of stormwater is reduced, while the time it takes to reach critical points in the system is increased. This provides the sewer system with less water over more time and thereby reduces the probability of flooding. The terminology surrounding this approach is diverse; and varies from country to country (Fletcher et al. 2015). In this paper, the approach as a whole will be referred to as low impact development (LID), while the specific measures will be referred to as green infrastructure.

This approach is also implemented in Norway, where a three step method for stormwater handling has been introduced. Small rain events are to be detained and infiltrated locally. Larger rain events should be delayed, while a safe flood way should be provided for the largest events, in order to avoid damages (NorskVann 2008).

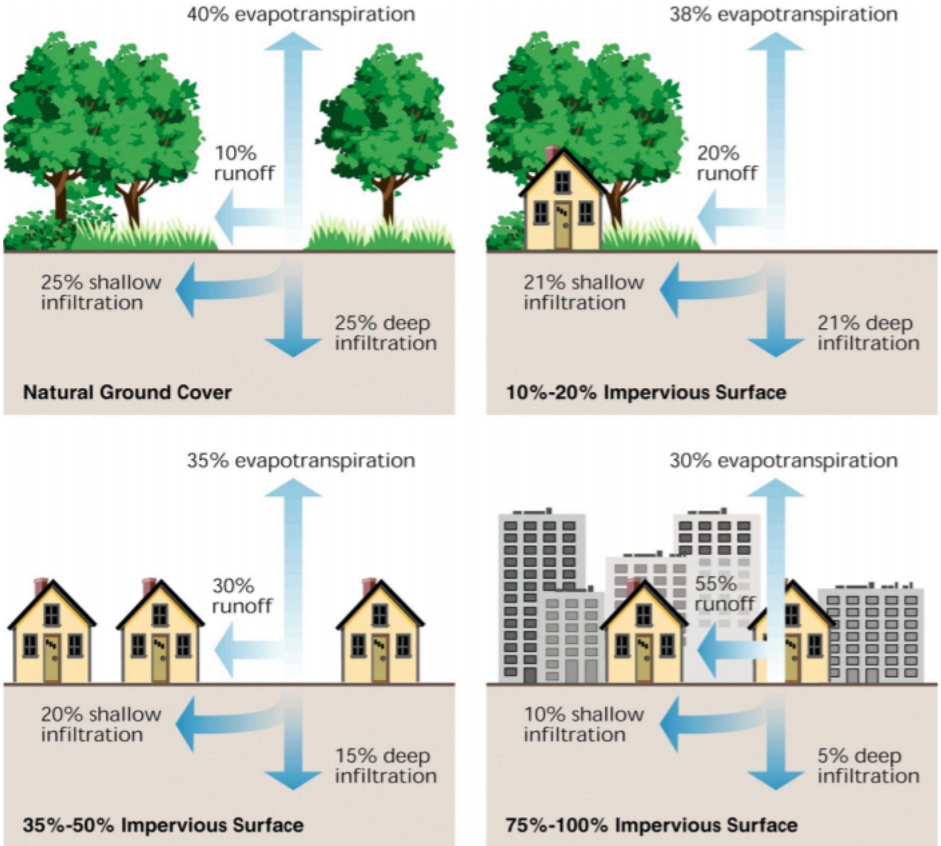

Fig. 2: Urbanization - Runoff relation.
(FISRWG 1998).

While LID shows great promise, and a number of successful implementations can be listed, it is in itself not enough to deal with the expected amounts of stormwater. This is especially the case for the largest rainfall events. LID should be used as a tool in combination with the traditional grey infrastructure, hence continued investments into existing grey infrastructure systems is needed to provide sufficient stormwater control (Eckart, McPhee, and Bolisetti 2017).

2.3 Co-costs and co-benefits

The costs and benefits associated with SCMs are both diverse and numerous. While some costs, such as investment and operation/maintenance costs, and some benefits, such as reduced flood risk, are universally considered and widely recognized, SCM can have several other costs and benefits associated with them. Costs and benefits beyond the main budgetary costs and the main performance goals are commonly referred to as co-costs and co-benefits. These are dependant on both the type of measure and the local conditions where they are implemented. Co-costs of SCMs include emissions of CO2, dust and harmful gasses during construction, and alternative uses of the required area. Co-benefits include stormwater volume reduction, CSO reduction, runoff quality improvement, increased property values, CO2 sequestration, energy savings, recreational values, aesthetic values, reduced urban heat island effect, improved air quality, groundwater recharge, ecological benefits, and in the case of green roofs and facades: increased longevity (Alves, Gersonius, Kapelan, et al. 2019).

This list of co-costs and co-benefits, while not exhaustive, highlights the need for decision making processes that assess SCM on more criteria than those typically included. These have traditionally not been a factor in investment decisions, however as understanding of the broader impacts of SCMs is deepening, they are increasingly considered in the decision making process, for instance through use of MCDA or CBA.

2.4 Multi-criteria decision analysis

The multi-criteria decision analysis is a common tool for assessing SCMs. The analysis method is recognized as being a suitable method for analysing measures when conflicting criteria exists, and trade-offs must be made. A MCDA is performed by determining a set of criteria to be evaluated, scoring each measure by their performance within each criterion, and applying a weight to each criterion according to their relative importance to the stakeholders. Based on this approach, a total grade of each measure can be obtained, and measures can be ranked accordingly. The measure with the highest grade will then be the measure who's performance is most in line with the preferences of the stakeholders. A successful MCDA consequently relies on three main criteria: The successful identification of all relevant assessment criteria, accurate scoring of each criterion, and criteria weighting in accordance with the preferences of the stakeholders (Alves, Gersonius, Sanchez, et al. 2018).

Since relevant criteria to a large degree depend on local factors, the identification of relevant criteria to include in MCDAs depends on involvement of experts with a broad understanding of the case area. However, some criteria could be considered universally applicable, and the failure to include these would indicate an incomplete MCDA.

The relevant criteria are usually very diverse, and will therefore have to be scored using a wide range of techniques. Depending on the criteria, both quantitative and qualitative methods might be applicable. Cost is for instance easily measured in the relevant currency, while e.g. contribution towards biodiversity usually is measured qualitatively, e.g. "poor", "moderate" or "good". Many criteria are commonly scored by referring to relevant literature on standard performance, but can also be assessed by more detailed analysis, for instance modelling. Since the performance in all criteria should contribute towards a combined grade, all scores have to be standardized and expressed in a common format. The most common approach is to convert the scores in each criteria to a numeric scale, e.g. from 1-5 according to the measures performance within each criteria. This can be done in several ways, e.g. by assessing the performances according to a predetermined benchmark value, or by giving the top score to the most effective measure, and scoring the other measures relatively to the most effective one(Morales-Torres et al. 2016).

After a thorough scoring of the identified criteria, the criteria have to be weighted according to their relative importance. Criteria are often organised in hierarchies, with a few main criteria made up of several subcriteria. These criteria can either be assessed using hierarchical weighting or non-hierarchical weighting. Hierarchical weighting is done by first determining what weights to apply to the main criteria, and then determining how the main criteria are made up by applying weight factors to the respective subcriteria. This approach is also known as the top-down approach. Non-hierarchical weighting, also known as the bottom-up approach, is performed by determining how much each subcriterion should contribute to the overall valuation. The weight of the main criteria are then the sum of the weights of their respective subcriteria.

In most cases, the importance of criteria will differ significantly from each other. Often, one objective, e.g. flood risk reduction, has triggered the initiation of the project, and is subject to absolute performance requirements. In those cases, one should compare different measures that all meet the given requirements, and differentiate between them using the remaining criteria. This also introduces a degree of initial screening, where insufficient measures are disregarded, and only plausible alternatives are assessed. In addition, initial screening of measures is commonly done on basis of their applicability in the case being examined, given e.g. physical or legal constraints (Marttunen, Belton, and Lienert 2018).

Weighting allows stakeholders to value measures according to how important different aspects of the given measure are to them. As stakeholders often will emphasise different aspects according to their needs and professional background, weighting should ideally be done in stakeholder meetings, with all relevant stakeholders represented. This is also a key to achieve acceptability for the project. The weighting of criteria will often be a deciding factor in the resulting ranking of measures. As such, weights should be carefully considered, to avoid under- or over-valuation. There is reason to suspect a certain degree of subjectiveness in the weighting process, and steps should be taken to mitigate this. (Marttunen, Belton, and Lienert 2018)

Weight assessment is generally understood to be an expression of the values of the stakeholders involved. However, there are important caveats to this understanding. As monetary costs are always involved, the valuation of other criteria always carry an implicit monetary value. If this is not carefully considered, the implicit valuation of non-monetary costs and benefits could be highly unrealistic.

2.5 Cost-benefit analysis

Another analysis framework for assessing multiple costs and benefits is the cost-benefit analysis (CBA). In a CBA, the monetary value of all costs and benefits is determined, across the entire lifespan of the measure. Since some costs and benefits are realized immediately, while others are occurring during the entire lifespan, all costs and benefits are converted to the net present value (NPV). NPV is calculated by taking into account the fact that there is an expected return on monetary investments, which means that the value of an amount of money available today, is higher than the same amount of money being available in the future. Consequently, the net present value of benefits realized in the future is smaller that the value of the same benefit if realized today. The downscaling factor of future value is known as the discount rate. By combining the NPV of all costs and benefits, a NPV of the entire measure can be obtained. All measures with a positive NPV are considered socioeconomically profitable, and the measure with the highest positive NPV will be the best measure to invest in.

Many costs and benefits associated with SCM are not associated with an immediately apparent monetary value, as there is no market where the value is traded. These are referred to as non-market goods, and their values are assessed by using non-market valuation methods.

Common non-market valuation methods include revealed preference methods, stated preference methods and avoided costs analysis. Revealed preference methods uses existing markets as proxies for the non-market goods they try to value. Stated preference methods determine the value of a non-market good by asking people how much they would be willing to pay, or how much compensation they would be willing to accept, for a given good or harm. Avoided costs analysis evaluates how much it would cost to provide a given good in another way (Wise et al. 2010).

There has been done extensive research in non-market valuation of several benefits of SCMs. The results are however often not unison. Additionally, many costs and benefits can only be said to have been partly valued, as some aspects of their values have been investigated, while others have not. The values resulting from non-market valuation methods should not be understood as absolute values, but rather as an indication of the magnitude of a given value. The estimates resulting from non-market valuation methods can sometimes be very conservative, as they paint an incomplete picture of the total value of a benefit. At other times they might be excessive, if for instance an unrealistic benefit transfer is performed.

3 Method

3.1 Selection of case area

In order to determine the impacts of the SCMs, to test the analysis frameworks in practice, and to provide data for adjustments to the MCDA, the methods have to be implemented in a case study. For this purpose, a case area had to be chosen. There was extensive work done on selecting the case area. Based on a risk- and vulnerability assessment conducted by Norconsult, several potential areas were identified, where Asker municipality had known problems with inadequate stormwater handling. One area was chosen, for its relative simple layout and limited size. However, after an inspection, the area was decided to be unfit for the purpose, as there was significant uncertainty in the layout of the stormwater infrastructure in the area, and as there was a lack of data to be used for model calibration.

Parallel to this work, Asker municipality had been developing an updated knowledge base for strategic planning for the water sector of the municipality. This work was done in late November, and provided an updated list of prioritized areas. From this list, some areas were deemed too complex or too large. Others were of less interest to this work, as detailed models had already been made and measures were already planned. Further exclusion were made, as it was thought that some areas were especially suited to one specific type of measure, and would provide little basis for comparison between different measures.

After all the exclusions were made, one area stood out as particularly suited. The area of Hvalstad was chosen. The decision was based on its relatively small size, and a reasonable complexity, known issues with stormwater handling in the area. In addition, it was assumed that several measures could potentially be feasible, providing an interesting case for comparison of measures.

3.2 Description of case area

Although the description of the area is not a question of methodology, it provides an important backdrop for the selection of the SCMs, and was therefore included here.

The area of Hvalstad was selected as the case area for this study. Both the main highway west of Oslo, E18, and the only westward railway from Oslo goes through the area, which means that a significant portion of Oslo's more than 150.000 commuters pass through the area daily (OsloKommune n.d.). This highlights the critical importance of the area. The entire area is served by a separate sewer system. The area is approximately 0.15 square kilometers large, and about 1700 meters long. The case area is thus long and thin, characterized by a small urban stream that runs through the area. It runs partly in the open, and partly in closed pipes. In the uppermost part of the area there is a small dam, Bikkjedammen. The dam collects runoff from the surrounding forested and agricultural area. From Bikkjedammen, the stream runs under the busy road of Kirkeveien, into the upper part of the case area. This part of the area is characterized by single housing with large gardens, large open spaces and small suburban roads. The stream runs closed under several of the roads, and through a small pond. About halfway through the case area from the west, there is a small field, along the railway tracks, which run on a large embankment. The stream runs in a culvert under the embankment. On the eastern side of the railroad, there is another small area of single/combined housing and gardens, and another larger field, surrounded by Kirkeveien and single housing areas. The stream runs through the housing area, mostly open, but closed under three driveways. The stream runs open through the field. The eastern part of the area is dominated by industrial buildings and large amount of impervious area. In the industrial area, the stream runs partly closed and partly open, including an open stretch in a deep and wide hollow. Figure 3 and 4 shows the location and layout of the case area.

Downstream of the case area, the stream is piped under a sporting facility. There, it meets another piped stream, and they are conveyed together. The municipality has had problems with lack of capacity at this critical point during intense precipitation events. During the food in 2016, the area was severely flooded, disturbing the traffic from and to the highway. Figure 5 shows a picture of the flood event. Reduction of runoff in the stream during precipitation events is therefore desirable.

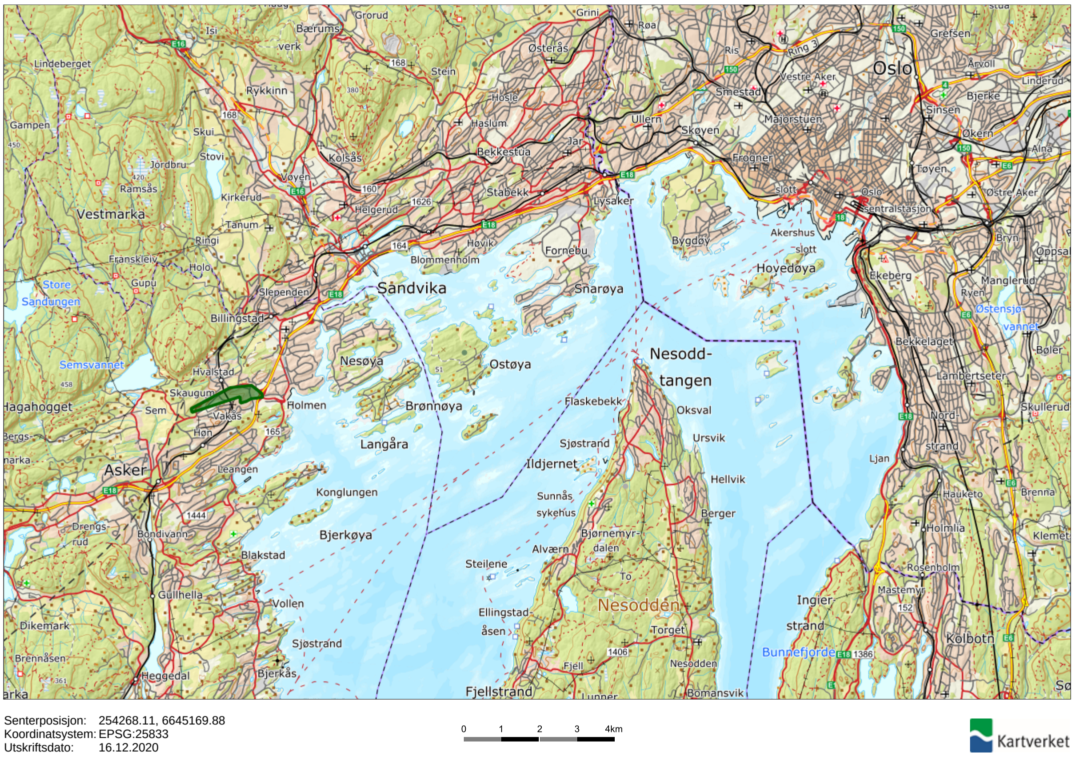

Fig. 3: Case area location
(Kartverket n.d.).

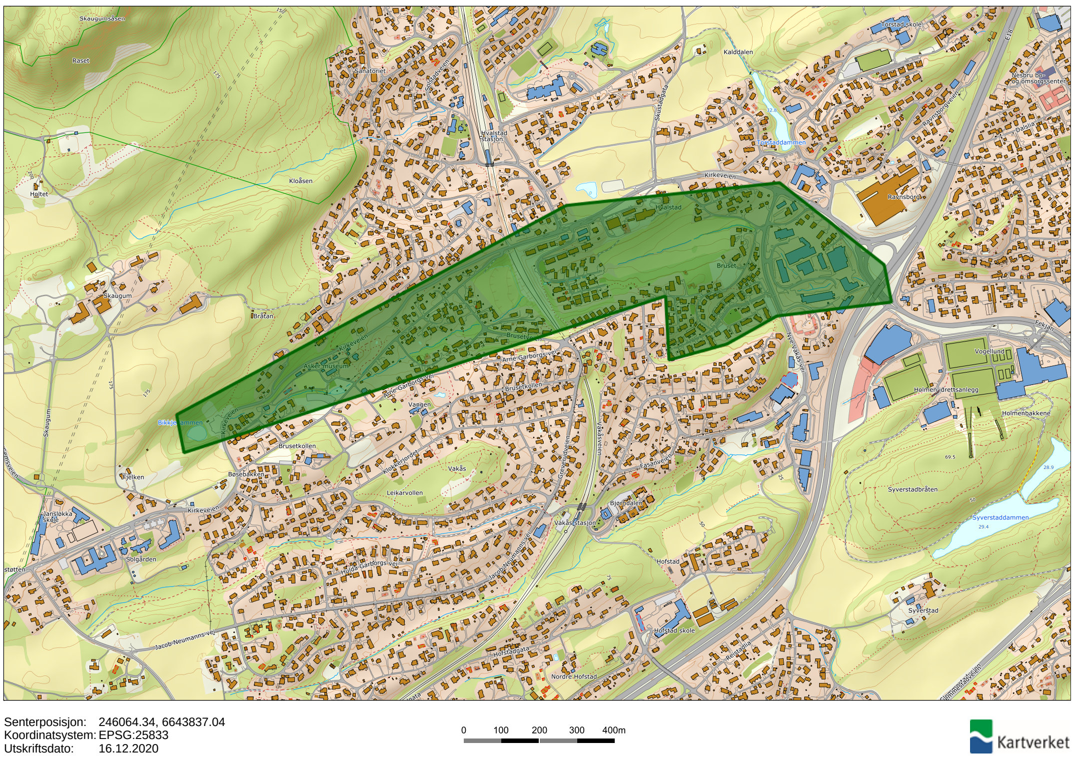

Fig. 4: Case area layout
(Kartverket n.d.).

Fig. 5: Flooding under E18, 2016. Photography: Asker Municipality

.

The area is quite steep, with an elevation difference of 106.5 meters from Bikkjedammen to the easternmost point near the highway. This means that stormwater will drain quickly, and the response time from rain events to possible flooding will be short. There is a total of 14 stretches where the stream is closed. Many of these are privately owned. The municipality has previously stated a need for information campaigns directed at owners of stream-closures, highlighting the importance of proper maintenance (Norconsult 2017). In addition, they state that there is a need for rehabilitation of some of the inlets and outlets.

The area has been associated with significant problems in the past, especially due to basement flooding. There has been reports of basement flooding both as a result of stream flooding and as a result of pluvial flooding. In addition, there is reason to believe that a large scale event could cause damage and disruption to the railway (Norconsult 2017). Stream flooding has been particularly prevalent when intakes have been blocked. An up-scaling of stream intakes should therefore be considered.

3.3 Selection of SCMs

In order to reduce the risk of flooding in the area, SCMs should be implemented. Before assessing different measures, potential SCMs had to be identified. Over the course of several video conferences and a physical inspection, possible SCMs were discussed. Due to previously occurring problems with intake blockages, an up-scaling of several of the stream intakes should be assessed. Several of the properties in the area have drainage pipes leading directly to the stream, causing increased discharge. This practice is also partly in violation of the regulations for constructions, TEK §15-8 (Ministry of Local Government and Modernisation 2017). Disconnections of private drainage pipes should be assessed. The stream runs through two distinct areas where there is large amount of unused space. This opens the possibility of utilizing these areas as retention areas for the water. The first possible area is just before the railway line, in a agricultural field. The second is in the industrial area, where the stream runs in a deep hollow. Construction of these two retention areas should be assessed. The stream runs along several roads in areas where there is known issues with flooding. The possibility of using these roads as safe flood-ways should be assessed. In the eastern part of the case area there is an industrial area with a high degree of continuous impervious cover. The effect of implementing a system of green roofs and rain gardens should be assessed.

In summary, the following SCM should be assessed:

- Increase capacity of stream intakes
- Construction of retention area in agricultural field
- Construction of retention area in hollow
- Disconnection of private drainage pipes
- Construction of green roofs and rain gardens
- Construction of safe flood-ways

3.4 Selection of success criteria

The measures implemented in the area will be subject to certain absolute requirements, henceforth referred to as success criteria. These are requirements set by the relevant strategies in the municipality, and any measure that does not meet these requirements is not considered viable. However, in order to meet the success criteria, several potential measures will be combined into potential solutions. A measure is a single implementation of a single SCM, while a solution is a combination of SCMs that make out one possible way to meet the success criteria.

The following success criteria are defined:

- Events with a recurrence interval of 50 years or less, including a climate factor of 1.5, should not lead to significant flood damages or uncontrolled runoff.
- A safe flood way should be designed for events with a recurrence interval of 200 years.

3.5 Selection of assessment criteria

There has been done extensive work in analysis of SCM considering co-costs and co-benefits, and there is a lot of published literature on the subject. To identify relevant assessment criteria, a literature review was performed. Six papers which employed CBA to assess SCM were reviewed, as well as four papers which assessed SCM using MCDA. These papers included seven case studies where SCM had been assessed based on a wide variety of co-costs and co-benefits were found. Based on review of these seven case studies, a list of commonly considered criteria was synthesized. Table 1 summarizes the criteria included in the assessment of the case studies. The MCDA tool that was developed for Asker municipality was also included in the table, in the second column, under "Asker". Otherwise, each column refers to a specific case study, in the following order: (Alves, Gersonius, Sanchez, et al. 2018), (Morales-Torres et al. 2016), (Radinja et al. 2019), (Jia et al. 2013), (Vincent and Radhakrishnan 2017), (Bianchini and Hewage 2012), (Johnson and Geisendorf 2019).

Assessment Criteria	Asker	Alves	Morales	Radinja	Jia	Vincent	Bianchini	Johnson
Flood risk reduction	x	x	x	-	-	x	x	-
Runoff quantity reduction	x	x	x	x	x	x	x	x
Runoff quality improvement	x	x	x	-	x	-	-	x
Investment cost	x	x	x	x	x	x	x	x
Operation and maintenance cost	x	x	x	x	x	x	x	x
Energy savings	-	x	x	-	-	x	x	x
Multi-functional / Recreational use	x	x	-	x	-	-	x	-
Climate resilience / Reduced UHIE	x	x	-	x	x	-	x	-
Improved air quality	x	x	-	x	-	x	x	x
Groundwater recharge	x	x	x	-	-	-	-	x
Feasibility regarding ownership	x	x	-	x	-	-	-	-
Educational opportunities	x	x	x	-	-	-	-	-
Rainwater capture and reuse	x	x	x	-	x	x	-	-
Ecological benefits / Habitat creation	x	x	-	x	x	-	x	x
Aesthetic benefits	x	x	-	x	x	x	x	x
Increased longevity	x	-	-	-	-	x	x	x
Net CO2 emissions	x	-	x	-	-	x	x	x
Increased property values	-	-	-	-	-	x	x	x

Tab. 1: Included assessment criteria in case studies and Asker MCDA tool

Assessment criteria that were only included in one of the studies were excluded. Additionally, some criteria were combined, as it was decided that it made more sense to address them as one. These criteria are separated by a slash. As criteria are locally dependant, the list provided here should not be understood as a complete list of criteria. However, as Table 1 clearly shows, there are certain criteria that are very commonly assessed. This list could therefore serve as a starting point for identification of assessment criteria. Exclusions should be made, as our case study differs significantly from many of the ones included here. Additionally, it might be necessary to add assessment criteria in order to account for abnormalities in our case area. However, this list serves as a point of reference, and both additions and exclusions should be justified.

3.6 Selection of modelling tool

In order to assess flood damage reduction, a modelling of pluvial flooding in the area was needed. Since both inundation depth and flow velocity is of interest, the modelling tool had to be able to provide information on distribution, depth and velocity of water. The flood modelling tool MIKE 21 FM was selected. It is a flexible and versatile tool, often advertised for use in modelling offshore and coastal structures and coastal flooding. However, it can also be used for modelling inland flooding (DHI n.d.). Asker municipality has previously used MIKE 21 for flood modelling in cooperation with master students, and the tool has proven to be successful (Gamman and Urrang 2019).

There is little data available for calibration of the model. However, there are several photos taken during the extreme event in 2016, which to a degree show both inundation depths and extension of the flood. This pictures will be used for calibration of the model, to the degree possible.

4 Results

4.1 Description of SCMs

The following SCMs are to be assessed for potential implementation in the area:

Increase capacity of stream intakes

The capacity of stream intakes has proven to be insufficient in two areas. In the residential area immediately downstream of the railway, and further downstream, just after the largest field. The areas are displayed in figure 6 and 7, respectively.

In these areas there have been rain induced floods in the past, affecting many of the houses in the area. In both areas, a safe flood-way which can convey the water without damage should be designed. The water should travel along the safe flood-way before reentering the stream further downstream.

Construction of retention area in field: In the field just upstream of the railway line, there is a lot of unused space which could be utilized as a retention area for the water. A retention area should be designed. Figure 8 displays the area.

Construction of retention area in hollow: Near the end of the industrial area, there is a large hollow where the stream runs open for about twenty meters. This area is both deep and wide, with a lot of unused, but vegetated space. This area could serve as a retention area. A retention area should be designed in the hollow. Figure 9 displays the area.

Disconnection of private pipes: A lot of private drainage pipes in the area drain directly into the stream. This practice is currently in violation of TEK, however, this does not apply to houses that implemented these solutions before the law was implemented. In many of the cases, both foundation drainage and rooftop drainage goes directly to the stream. Where the solutions predate the current law, the municipality will have to come to an agreement with the owners of the property about possible disconnections. However, the municipality have good experiences with this approach, and the measure is therefore considered feasible.

Construction of green roofs and rain gardens: In the industrial area in the eastern part of the case area, there are a lot of large continuous roof areas. In order to reduce runoff from these roods, green roofs could be implemented. By conveying the excess water from the green roofs to rain gardens, the effectiveness can increase, and the risk of failure will be distributed on several assets. Therefore, rain gardens should be planned as well. There is currently some unused green spaces in the area, and rain gardens will be planned here.

Fig. 6: Inadequate stream intakes 1
Photography: Author

Fig. 7: Inadequate stream intake 2
Photography: Author

Fig. 8: Retention area - Field
Photography: Author

Fig. 9: Retention area - Hollow
Photography: Author

4.2 Exclusion of assessment criteria:

For our case area, there are indeed exclusions that should be made from the list in Table 1. As the Hvalstad case area is quite different from the areas included in the case studies summarized in Table 1, there are several criteria that are of little interest for this case study. In the following, exclusions of assessment criteria will be presented and explained.

Recreational value: The measures are not expected to contribute towards recreational value. SCMs can provide recreational value, by facilitating different recreational activities, like walking or doing sports. The impact is highly dependant on the type of measure. Recreational use is not considered relevant for the measures suggested here, as none of them provide additional space for multi-functional use.

Aesthetic value: The suggested measures are not expected to provide aesthetic benefits. The measures that potentially could provide aesthetic benefits are the constructed retention areas, the green roofs and the rain gardens. The first potential retention area is in an existing field. The field should be preserved, which means that significant visual alterations are not expected. The second potential retention area is in a deep hollow, that already is covered with brush and trees. Aesthetic improvement is therefore not expected. The rain gardens will replace existing green area, and are therefore not expected to contribute additionally to aesthetic values. Finally, the green roofs will be out of sight for all residents, as the roofs are not accessible. Thus, aesthetic benefits are excluded from the analysis.

Increased property values: The introduction of green infrastructure to urban areas can have a significant impact on property values (Johnson and Geisendorf 2019). Multiple factors such as distance, size and type of greenery and initial property value has been shown to influence the valuation increase. The effect on property values is often ascribed to a combination of increased aesthetic and recreational values. This highlights a difficult but important topic within non-market valuation methods. By pricing increased property values, and increased recreational and aesthetic values independently, one runs the risk of pricing the same value multiple times.

Assessing the influence that green infrastructure has on property prices is often done with a revealed preference method called hedonic pricing, where the value of a property is decomposed into several isolated factors, which are subsequently valued individually. Examples of isolated factors used for assessing the impact of green infrastructure are proximity to parks, community gardens or number of trees on the area (Johnson and Geisendorf 2019). As the green spaces introduced by the suggested SCMs are either inaccessible or replaces existing greenery, and as the area already is very green, with multiple parks, and private gardens for almost every household, the suggested SCMs are not expected to influence property prices. I have already argued the exclusion of recreational and aesthetic values, as I don't expect the suggested measures to contribute to either aesthetic or recreational values. Potential increases in property prices due to reduced flood risk are assumed to be covered by the valuation of reduced flood risk.

Runoff quality improvement: Several SCMs will have positive effect on runoff water quality. As the runoffs ability to carry pollutants is in large part determined by the velocity, which in turn is impacted by the volume, a mere volume reduction will have positive effect on the quality of water discharged to the recipient. In addition, several SCM provide a degree of treatment, through for instance sedimentation or adsorption. Increased runoff quality is of particular concern in separate systems, since the stormwater is not treated before being discharged to recipients. However, as wastewater treatment plants have limited effect on several pollutants commonly found in stormwater, increased runoff quality will have a positive effect, regardless of the system in question. For combined systems, the increased quality will also contribute to less pollutant load in the case of CSO activation, albeit perhaps insignificantly compared to the pollutant load from the wastewater.

As the case area is served by a separate system, and as most of the measures will not impact water quality, the impact on water quality in the area is expected to be limited. However, it is still of interest to see the order of magnitude on the resulting value, for future reference. The original plan was to include water quality in the main analysis, by estimating the reduction in effective imperviousness. The current effective imperviousness and effective imperviousness after measures would have been determined. It is defined as the product of total imperviousness and direct connections to the recipient (Walsh, Fletcher, and Ladson 2005). By referring to literature on the connection between effective imperviousness and stream water quality, the impact could have been estimated. Then, valuation could have been done using previous studies on the public's willingness to pay for improved water quality. However, it became apparent that the resulting values were expected to be completely insignificant. To illustrate this point, an initial assessment was made to estimate the magnitude of the value. A study on co-benefits of SCM in Berlin found a willingness to pay of 9.5€ per person per year for an improvement in water quality from poor to moderate according to the Water Framework Directive in the local river Spree (Johnson and Geisendorf 2019). This value was not related to recreational activities such as bathing or fishing, but is considered to capture the willingness to pay for increased water quality for no external purpose. Another possible valuation comes from "Benefits and costs by achieving environmental goals for urban streams", a report by Vista analyse for Oslo municipality (VistaAnalyse 2014). They found a willingness to pay among the public, of 140 NOK per household and year, for a good water quality for bathing. However, as the stream in our case area is too small to be used for bathing, the value from the German study will be used. This value is of course not representative of the local stream in our catchment area. It is therefore downscaled according to discharge. The average discharge in Spree is $36\text{m}^3/\text{s}$. The average discharge in the stream is estimated to be 20l/s. The resulting value is roughly 0.05 kr/person per year. A rough estimate gives a total number of 500 households in the area. Asker has an average of 2.36 persons per household (StatistiskSentralbyrå 2020). This gives a total value of 59 kr per year in willingness to pay for improved water quality, of a magnitude similar to one grade in the Water Framework Directive. The expected impact on water quality is significantly lower than this. The resulting total value of improved water quality is therefore considered so insignificant that it will not be assessed in detail. This also suggests that water quality does not need to be included in MCDA for similar projects.

Reduced urban heat island effect: Reduction in urban heat island effect is often included as a benefit of green infrastructure. Due to lower amount of green spaces leading to less evapotranspiration, and lower albedo values, urban areas often experience higher temperatures than the surrounding areas (Bianchini and Hewage 2012). Green infrastructure can mitigate this by introducing both areas with higher albedo and provide evaporative cooling. According to Wise et al (Wise et al. 2010), quantifying the impact on the urban heat island effect is "notoriously difficult". However, as referenced in the same study, some studies have been conducted on the effect of large scale use of green infrastructure on the urban heat island effect in some major cities.

The most commonly cited cost of urban heat island effect is the potential loss of human life. (Gallet 2012) cites a study in Philadelphia that concluded that 196 premature fatalities could have been avoided if green infrastructure had been implemented to mitigate the cities issues with frequent activation of combined sewer overflows. By applying "the value of a statistical life" of 7.4 million USD, the study concludes that the city could have saved 1.45 billion dollars in the time period.

As the value of reduced urban heat island effect is mainly evaluated through the reduction in loss of human life, it is only relevant to assess if there is reason to expect heat-induced fatalities in the case area. In the summer of 2018, Norway experienced a severe heat wave, resulting in 21 county temperature records (Nettavisen n.d.). However, despite the high temperatures, no evidence of increased fatalities due to the extreme temperatures was found (Hygen, Ruscio, and Rao 2018). Therefore, reduced urban heat island effect will be excluded from the analysis.

Groundwater recharge: Groundwater recharge is often considered as a major benefit of LID. Since urbanization often leads to reduced infiltration, groundwater levels tend to drop as areas get urbanized. This can lead to structural damages due to setting, eradication of low-flows in urban streams and problems for groundwater-based drinking water systems. As the groundwater level reportedly is already high in the area, groundwater recharge will be excluded from the list of assessment criteria.

Feasibility regarding ownership: Feasibility regarding ownership is often included in MCDA to assess measures with varying degrees of ownership-related challenges. An alternative to this approach is to only assess measures that indeed are feasible with regards to ownership. This approach will be taken in this study, and the criteria will therefore be excluded.

Educational opportunities: Educational opportunities is often cited as a potential benefit of stormwater infrastructure that is visible to the public. This could include both gray and green infrastructure. As water infrastructure mostly is hidden underground, the public awareness of the function and service of water infrastructure is limited. By using stormwater infrastructure that is visible to the public, the public's understanding of both the service provided and its importance is expected to increase. This benefit is often included in MCDA. I have not been able to find a single case where it has been valued monetarily, nor have I been able to find monetisation studies on similar effects. The effect will therefore be excluded, unless relevant studies are found during the thesis work.

Rainwater capture and reuse: Rainwater capture and reuse is a potential benefit of several SCM. It mostly involves collecting rainwater for non-potable use, such as watering a garden. The value of collection and reuse is closely related to the cost of potable water, which in Norway is so low that rainwater reuse is extraordinarily rare. None of the suggested measures involve rainwater capture or reuse, and the criteria will therefore be excluded.

The exclusions explained here results in the following list of assessment criteria:

- Flood risk reduction
- Runoff quantity reduction
- Investment cost
- Operation and maintenance cost
- Improved air quality
- Ecological benefits
- Net CO2 emissions
- Increased longevity
- Energy savings

The diversity of the assessment criteria raise an interesting question, regarding how SCMs are financed. Stormwater measures in Norwegian municipalities is financed in several ways, depending on ownership of the area producing the runoff. According to the regulations for constructions, TEK §15-8, stormwater from private property should be infiltrated or in another way be handled locally, to the largest possible degree. Furthermore, conveyance of stormwater from private property should not lead to flooding or other detriments (Ministry of Local Government and Modernisation 2017). Stormwater from roads should be handled by the relevant road authorities, be it municipal, county or state. Municipal water authorities should in theory only handle stormwater from other sources than roads and private properties. In practice however, few private properties are in complete compliance with the stormwater regulations in TEK.

Municipal water authorities are entirely financed through water fees. In return, they are only allowed to spend money that will directly influence the water services in the municipality. This is known as the principle of self-cost. Therefore, the municipality might not be able to justify investments made on the basis of other values than those directly related to water. For the purposes of this project work, this will be ignored, and all values will be considered. However, as they will be priced individually, it will be simple for the municipality to only choose the values relevant to them, and ignore the rest. Therefore the results will be flexible, and solutions can be evaluated socioeconomically, or just according to the effects on the budget of the municipal water authority. It will be interesting to see whether this will impact what solution is considered the optimal. If the different approaches yield different results, the current method of financing stormwater solutions might be seen as a barrier for implementation of the solutions that would be best for society as a whole.

4.3 Impacts and assessment methods

In the following, each of the assessment criteria will be explained in terms of why and how they are impacted by the SCM. In addition, the planned approach for evaluation in both CBA and MCDA will be presented.

Flood risk reduction:

Risk is commonly understood as being a product of the probability and the consequence of an unwanted event. By implementing SCMs, we can reduce either the probability, the consequence, or both. In this study, the evaluation of flood risk reduction will be done on the basis of changes in expected damages. Whether the changes in expected damages comes from reduced probability or reduced consequence will not be discussed.

Flood damages from stormwater occur when the capacity of the stormwater drainage system is exceeded, or when stormwater conveyed to local streams cause the stream to flood. This will lead to overland flooding, and can cause severe damage to buildings, vehicles, infrastructure and ecosystems. Damage to buildings is mainly occurring through flooding of basements, but given sufficient inundation depth, buildings without basements can be damaged as well. The damages consists of damages to property stored inside the buildings, as well structural damages related to wetting and erosion. Vehicles can be damaged due to intrusion of water, or due to crashing from being moved with the current. Damages to infrastructure such as roads and electrical installations occur due to wetting and erosion. Ecosystems can be damaged from wastewater contamination, erosion and wetting.

In addition, flooding can cause damages to human health, or in the worst case, lead to loss of human lives. Damages to health can occur due to exposure to sewage from in-house back-flows when the capacity of the combined sewage system is exceeded. This can lead to infections due to the high pathogen load in sewage. Given sufficient flood depth and velocity, flooding can also cause loss of life due to drowning. Children and old/disabled people are especially at risk.

The costs occur due to repair/reconstruction work, destruction of property, production loss due to disruption of businesses, production loss due to disruption of infrastructure, hospitalization and deaths. By assessing the total costs of flooding before and after a solution is implemented, the value of the reduced flood damages can be obtained.

The reduction in flood damages in the area will be assessed through modelling. The modelling will result in data on distribution, water depth and water velocity. Flood damages are influenced by both depth and velocity. Commonly, they are assessed using either stage-damage curves or using threshold values. Stage-damage curves represent a empirical relation between inundation depth and damages. They are dependant on both the type of buildings and the uses of buildings, and are thus depending on both regional and very local factors. Another common approach is to use threshold values. The method assumes that damages will occur given a sufficient inundation depth or sufficient water velocity. The threshold values can be different for different types of buildings/structures, and one can include threshold values for damages to individuals and ecosystems as well.

Threshold values for assessing flood damages have been used in several studies on flood damages. A report by Rambøll on potential stormwater damages in Oslo used threshold values to assert the costs of the event. The threshold values were partially chosen based on literature review, partially on inspection, and partially based on he experience of the authors (Rambøll 2019). Another report, done as a part of the PREPARED project, funded by the European Commission, used threshold values for investigating effectiveness of flood risk reduction measures (Strehl et al. 2013).

Using the values from these projects as a starting point, threshold values will be decided in cooperation with stormwater professionals from the municipality, given their knowledge of previous events which have lead to damages.

When thresholds are exceeded, damages occur. The magnitude of these damages depend on the structure in question. In the report on expected damages and costs for extreme precipitation in Oslo, Rambøll synthesised a comprehensive list of threshold values with related damage costs a wide variety of structural, infrastructural, ecological and personal damages. The list of based on 29 sources of cost data due to flooding events, mainly from Norwegian and Danish sources. This list will be used as a basis for the flood damage assessment in this study. However, values will be adjusted for inflation, and regional differences between Oslo and Asker, as suggested by the authors of the report (Rambøll 2019). These differences include differences in average income and property prices, which influences the cost of lost time and structural damages.

The value of reduced flood risk is not limited to the reduction in flood damages. A 2011 master thesis from the Norwegian University of Life Sciences found a 92 NOK higher willingness to pay for better flood protection, compared to average willingness to pay for a flood insurance that would cover any damages (Grann n.d.). The difference was ascribed to the value of the feeling of safety that would come from knowing that there was little risk for experiencing flood. Consequently, reducing the flood risk carries additional value: in addition to the material value, individuals increased feeling of safety should also be considered.

The change in expected damages will be assessed by modelling, using threshold values for damage occurrence, and corresponding adjusted values of damage costs, in addition to the value of the feeling of safety. For the cost benefit analysis, the NPV of the reduced flood damages will be assessed.

For evaluation in the MCDA, the flood risk reduction can be assessed by determining the number for houses impacted by flooding before and after each measure. By giving measures with no impact a grade of 0, and measures which achieve a complete elimination of houses being affected a grade of 5, each measure can be graded according to their impact on flood risk reduction. Since the flood damages are expected to mainly occur due to damages to buildings, this approach is considered sufficiently accurate for use in the MCDA.

Runoff quantity reduction

The value of a reduction in stormwater volume is of particular interest in combined systems. There, a volume reduction will decrease the amount of water to be pumped and treated, resulting in cost savings. Since the case area is entirely served by a separate sewer system, this effect will not be present here. However, as there is a known capacity issue downstream of the case area. All stormwater in the case area will eventually drain there, contributing to the breach of capacity. If the stormwater from the case area can be reduced enough to avoid having to increase the capacity downstream, it will carry a significant value. In order to assess the value of reduced stormwater volume, the amount of water contributed to the conveyance system will be assessed by modelling, before and after implementation of SCMs. The cost of having to reconstruct the downstream drainage system will be assessed through use of data on similar previously constructed projects in the municipality. If the measures are enough to avoid further investments, the avoided costs will be considered a benefit of the SCMs. For the CBA, the NPV of the runoff quantity reduction will be calculated based on expected cost and time of construction of downstream capacity increase.

In the MCDA, each measure that achieve sufficient runoff reduction to avoid downstream up-scaling will receive a score of 5. Each measure that fail to do this will receive a grade of 0.

Investment cost

The investment cost is typically represent the largest cost, and is highly influential on the total assessment. One challenge in determining the cost of SCM is the fact that SCM are often implemented as a part of larger projects. This often leads to lack of detailed data on the SCM themselves. In addition, costs vary quite a lot according to local differences. One project might be significantly more expensive than another similar project, e.g. because of differing ground conditions. To gather a reasonable base of data on the costs of the measures, several sources of data will be used. Firstly, previously constructed projects in Asker municipality will be assessed. Secondly, data on completed projects in other municipalities will be assessed. Thirdly, price estimates from relevant entrepreneurs will be collected. This should provide a good basis from investment cost estimation.

For the green roofs and the rain gardens, the investment cost will be based on the work of Ragni Rønneberg Hernes, who collected data on investment costs of green infrastructure from entrepreneurs. (Hernes 2018).

The total cost of the investment is the amount of money payed, plus the alternative cost of using the municipal land for the SCM. In many cases, utilization for stormwater control will limit the use of the land for other purposes. This is often cited as an argument for gray, underground measures. In order to assess the alternative cost of using municipal land for SCM, the average land value in the case area will be used. For the cost benefit analysis, the NPV of the investment cost will be equal to the investment cost, as it occurs at the beginning of the lifetime of the SCM.

In the MCDA, the cheapest measure will receive a score of 5, and the most expensive measure will receive a score of 0. The rest of the measures will be scored based on a linear relation between investment costs and scores.

Operation and maintenance cost

Operation and maintenance costs are costs related to maintaining the performance of SCM over time. This includes landscaping, collection of trash, clearing of inlets, and other regular maintenance activity. The cost of operation and maintenance should be covered by the owner of the measure. This could be private, municipal, county or state. Within a municipality, the owner could be either road authorities or water authorities. For the purposes of this project work, the distribution of costs will not be considered. The total operation and maintenance costs will be assessed by reviewing data from the operational section of the water authority in the municipality. Those data will be taken as representative, regardless of ownership of the measure. The annual values for operation and maintenance cost will be converted to NPV for use in the CBA.

For use in the MCDA, operation and maintenance costs will be scored in the same way as investment costs.

Improved air quality

During construction of SCM, several pollutants will be released into the air. The main pollutants of concern are SO2, NO2 and particulate matter (PM) which will be suspended in the air. These can cause respiratory illnesses, and consequently have costs associated with hospitalization and possible fatalities. The Norwegian Institute for public health has estimated that between 115 and 185 premature deaths can be attributed to air pollution from PM in Oslo every year (FHI n.d.). Green infrastructure has the ability to improve air quality, by both absorbing potentially harmful gases, and trapping particulate matter (Wise et al. 2010). By considering removal rates for SO2, NO2, PM, as well as O3, and comparing it with the amounts emitted during construction, the net impact on air quality can be assessed. Then, this effect can be valued by considering the adverse health effects of different pollutants, and the accompanying costs related to hospital admissions and mortality (Johnson and Geisendorf 2019).

I have not been able to find any credible sources on amounts of air pollutants released from construction of SCM, nor have I been able to find emissions from the construction sector in Norway as a whole. I will therefore proceed to only evaluate the positive impact on air pollution, but recognize that this is a source of uncertainty. Depending on the magnitude of the resulting values, this topic will be revisited if it is considered important for the total outcome of the analysis.

Several studies on green infrastructure's positive effect on air quality have been conducted. Currie 2005 used the UFORE model (Urban Forest Effects Model) to estimate the impact of "grass roofs" on air quality. Rowe 2011 references a study by Yang et al, which used a similar model to estimate the same thing. The results are summarized in table 2. The values had to be slightly worked, in order to present them in the same units.

	CO	NO2	O3	PM10	SO2
Currie 2005	*3.2*	*14.6*	*28.7*	*19.8*	*5.6*
Yang et al 2008	-	*22.95*	*44.2*	*11.9*	*5.95*

Tab. 2: Kg of pollutant captured per hectare of green roof per year

Considering the amount of uncertainty in these models, these results are remarkably similar. The green roofs in this study will be assessed with an average of the performance of roofs in the two studies.

The valuation of reduced air pollution is dependant on the pollutant type. A report by the Norwegian state road authorities (Statens Vegvesen) estimated a socioeconomic cost of 15 090 NOK (2016) per kg of PM10 (StatensVegvesen 2018). This value was for use in "red zones" where the air quality is particularly low. As the part of the case area where green roof could be implemented is within a couple hundred meters from the main highway E18, it is assumed that the air quality is poor, and the value for the red zone can be used.

A report from the Institute of Transport Economics (Transportøkonomisk institutt) estimated a total cost of NOx from road traffic of 316 NOK (2012) per kg of emissions (TransportØkonomiskInstitutt 2014). The value was based on a Norwegian study from 2010, but up-scaled according to a higher value of the statistical life. This value will be used as the value of reduced NO2 concentrations.

Another report by the Institute of Transport Economics estimated the costs associated with SO2 emissions from road traffic to be 70 NOK (1997) per kg emitted (TransportØkonomiskInstitutt 1999). This value will be used for valuation of SO2 capture in this study.

I have not been able to find credible sources on the socioeconomic cost of ozone and carbon monoxide emissions, and these will therefore be excluded from the assessment. This is partially justified by the fact that the CO reduction is low in one study, and undetermined in the other. Additionally, according to a report from Statistics Norway (Statistisk Sentralbyrå), the ozone concentration in Norwegian cities are significantly lower than in the rest of Europe, and the concentrations are mainly due to foreign emissions (SSB 2000). Based on this, I assume that the socioeconomic benefit of further reduction in the ozone concentration will be limited.

In the MCDA, each measure that is expected to have an impact on the air quality will be given a score of 5. Measures with no expected effect on air quality will be given a score of 0.

Ecological benefits:

The literature on the value of biodiversity in green infrastructure in quite varied. Often, the ecosystem services provided by green infrastructure are valued as a whole. Ecosystem services is commonly understood as the benefits that humans reap from nature. In the case of green infrastructure, this definition would also cover their impact as SCMs, as well as all other impacts listed here. By the value of ecological benefits, I mean the value of increased biodiversity. By providing habitat, one can facilitate for the survival of more biological individuals, especially insects. As death of insects is a large and growing concern, this benefit of green infrastructure has been getting more attention in recent years.

However, the economic effect of increased biodiversity is both extremely hard to quantify, and also very hard to attribute on a small scale (Gallet 2012). Bianchini and Hewage 2012 approaches this problem by making a series of assumptions. Portland made large investments into buying land and restoring it to pre-developed conditions. The study assumes that extensive green roofs will provide 15 percent of the benefit of biodiversity of pre-developed land. Johnson and Geisendorf 2019 makes the same assumptions, and justifies the valuation by assuming the value of any additional habitat to be at least as large as the cost of creating it. Thus, the 275.000 USD per acre invested by

Portland is applied a factor of 0.15 and then stated as the value of the biodiversity of green roofs. The resulting value is about 100 NOK per square meter of green roof, as a one time value.

A study on the economic value of green roofs in Lisbon, Portugal, valued the biodiversity in green roofs by comparing it with the cities annual expenditures towards preservation of biodiversity (Teotónio, Silva, and Cruz 2018). By dividing this value on the amount of built-up area in Lisbon, they determine a potential avoided cost per square meter. They adjust for the relative limited biodiversity in extensive green roofs by reducing the value by 80%. The resulting value of biodiversity in green roofs is about 5 NOK per square meter, as a one time value.

The resulting valuation of biodiversity in these three studies vary by a factor of 20. The studies use avoided cost of local policy to determine the value, and the variations is essential only resulting from variations in local policy. Therefore, thee values are not necessarily representative of the potential values in Norway. However, to avoid overestimation, the lowest value will be used for valuation in this study.

In the MCDA, all measure with an expected effect on biodiversity will be given a score of 5, and all measures with no expected effect will be given a score of 0.

Net CO2 emissions

During construction, all SCM will emit CO2 to the atmosphere. The amount depends on the size and type of measures. However, green infrastructure can also contribute to a reduction in atmospheric CO2, through sequestration. By comparing the CO2 emitted during the construction with the CO2 captured during over the lifetime of the measure, the net CO2 emission can be estimated. The net CO2 emission can consequently be both a cost and a benefit.

The municipality has some data on their annual carbon emissions, gathered through use of an early iteration of a tool currently being developed for Norsk Vann by Asplan Viak. This tool is expected to become more sophisticated than the current implementation (Asker n.d.), and the development will therefore be monitored through the thesis period.

Carbon sequestration in green roofs has been the subject of several studies. But in order to find representative values for common Norwegian green roofs, a provider of green roofs, Bergknapp, was contacted. However, they could not provide information on carbon sequestration in their product. Research data on carbon sequestration in green roofs will be used for the analysis in this study. A study on carbon sequestration in green roofs in Michigan, US, found an average net sequestration of $378 g/m^2$ in extensive green roofs, over the course of two years (Rowe 2011). As green roofs reach carbon equilibrium, where decomposition equals sequestration, significant additional sequestration was not expected after this. It is worth noting that the amount sequestered in fact was smaller than the expected carbon emissions related to the construction of the green roofs.

Similar studies have been done on the carbon sequestration in rain gardens. An Australian study on life cycle carbon emissions of green infrastructure found that rain gardens were the most efficient measures at recapturing the carbon associated with their construction (Kavehei et al. 2018). Achieving as much as 70% recapture of the carbon they emitted. The same study found that green roofs achieved 45% recapture, reasserting the results from Rowe (Rowe 2011).

Valuation of the CO2 emissions will be done according to the social cost of carbon (SC-CO2) (EPA n.d.). The SC-CO2 is a price put on a ton of CO2, which should represent the total long-term damage caused by the emission. The concept was developed by the US Environmental Protection Agency. Since the scope of this study is to assess the socioeconomic cost and benefits of SCM, this value is chosen instead of the price of CO2 emissions in the EU quota system, as the SC-CO2 is expected to be a more realistic estimate of the actual costs related to emissions.

By assessing emissions and sequestration, net carbon emissions can be determined for each SCM. By using the SC-CO2, the NPV of the carbon emissions can be determined for use in the CBA.

In the MCDA, the measures will be scored according to their impact on CO2 emissions. As all measures are expected to be net contributors to CO2 emissions, they will be given scores from 0 to -5. The measure expected to contribute the most will be given a score of -5, and the rest of the measures will be scored according to a linear relationship between negative score and net emissions, where 0 net emissions give a score of 0, and equal emissions to those of the worst measure give a score of -5.

Increased roof longevity

One specific benefit associated with green roofs is the significantly increased lifetime compared to conventional roofs. Since the roofs are protected from UV radiation and major temperature swings are reduced, the expected lifetime of a green roof is greatly extended, from about 20 years for conventional roofs to 40 to 55 years for green roofs (Bianchini and Hewage 2012). According to a Norwegian provider of green roofs, green roofs can lead to a doubling of the expected life time of the building (*Blomstertak.no* n.d.). By assessing expected increase in life time, and average costs for roof rehabilitation, the value of increased lifetime can be determined.

In the MCDA, measures that have a positive impact on roof longevity will be given a score of 5, while measures that do not will be given a score of 0.

Energy savings:

Another benefits exclusive to green roofs is energy savings. Due to the insulating effect of the substrate, the building temperature will be more stable, leading to less energy for heating in winter, and less energy for cooling in summer. Energy savings from SCM are also attributed to reduction of stormwater volume in combined systems, as it will lead to energy savings from a reduction in water to be pumped and treated. This effect is not relevant in the case area, as it is served by a separate system.

The energy savings from green roofs can be quantified by calculating the annual specific heat savings in kWh/m2 using the thermal resistance values of green and conventional roofs as well as temperature data for the region (Johnson and Geisendorf 2019). Then the energy savings can be multiplied with the average price for electrical power or gas, and a monetary value of the reduced energy use can be obtained.

In the MCDA, measures that are expected to have a positive impact on energy savings will be given a score of 5, while the rest will be given a score of 0.

5 Discussion

5.1 Sources of uncertainty

The analysis methods presented here have a lot of uncertainty associated with them. Several of the benefit and cost valuation methods are based on estimations, modelled data or averages. In some cases, such as with the value of increased biodiversity, there is significant variation in valuation in published literature. Additionally, the valuation methods might not be able to cover the entire extent of a cost or benefit. In the case of air quality, the value of CO and O3 will not be assessed, which can cause an underestimation of the impact. In addition, cost of air pollution during construction will not be assessed. There is also a problem of so called "unknown unknowns". The entire scope of impacts caused by SCMs might not yet be fully understood. If there are significant unknown impacts, this can cause both a under- and overestimation of the value.

The flood modelling will introduce additional uncertainty. An iconic quote in the modelling community is: "All models are wrong, but some are useful". The quote is commonly attributed to the statistician George Box, and is an excellent frame for questions about model uncertainty. The model will not be a perfect representation of what will actually happen during an actual flood event. The lack of data for calibration and validation is significantly contributing to the model uncertainty, but even with great data, one could not expect such a complex system to be perfectly represented by a model. It will hopefully provide sufficiently trustworthy and accurate results as to be useful, but the resulting valuations of reduced flood damages will only be estimates, and the values have to be handled with a degree of scepticism.

In order to quantify the impact of potential changes in the input data to the analysis, a sensitivity analysis should be performed. By assessing which values have the most impact on the outcome, additional effort can be put into making sure that these values are well defined and realistic.

5.2 Comparability

The CBA presented here will be a methodical, meticulous and laborious approach to analysing and comparing the effects of different SCMs. The work load is well beyond the scope of what can realistically be done in normal municipal small scale investment decisions. In practice, MCDA is a much more commonly used tool for impact assessments. As the methodology in MCDA is much less thorough, it raises the question: How can we ensure that the MCDA will give us comparable results to the CBA?

This question essentially assumes the CBA to be correct. In truth, a CBA will never give a perfect representation of the actual total socioeconomic value of a SCM. The impacts are far too many, too complicated and too unsure for us to assume that our assessment of them is complete and correct. However, a thorough and well thought out CBA is the closest we can currently come to describing the actual value of SCMs. Lacking perfect knowledge, they are the next best thing, and could therefore be considered our best approximation of the true value. If we assume this to be true, and we assume that MCDA will continue to be the dominant analysis method for SCMs, it is critical that we conduct MCDAs in such a way that they as closely as possible replicate the results of CBAs.

MCDA is inherently much more subjective than the CBA. Measures are partly scored qualitatively, based on the understanding of the person performing the analysis. Additionally, the scores are weighted according to the relative importance of each assessment criteria to the overall investment decision. This is also largely done based on the understanding of the person performing the analysis. However professional the person is, there is reason to believe that this process will be subject to several biases (Marttunen, Belton, and Lienert 2018).

To achieve comparable results from the MCDA and the CBA, the results from the CBA should provide guidance on the weight assessment in the MCDA. As MCDA also considers costs, every other assessment criteria is implicitly given a monetary value, according to how it is scored and weighted relative to the cost criteria. The implicit valuation in the MCDA should be approximately equal to the absolute valuation in the CBA. This should primarily be achieved by choosing appropriate weighting. However, scoring can also be assessed in the same way, by evaluating the difference in implicit value within a certain criteria for different measures. When weights and scores have been reviewed in such a way that the MCDA and the CBA give comparable results, the scores and weights in the MCDA should be noted for future reference. In future MCDA, they can serve as a frame of reference, default values, or as a starting point. This way, the weights and scores in the MCDA will be "calibrated" against the results of the CBA. This should result in a more reliable process for MCDA.

As the construction of criteria hierarchies are an important source of subjectivity, the assessment criteria should be weighted using non-hierarchical weighting. Non-hierarchical weighting can suffer from unmanageable complexity when too many criteria are to be valued at the same time (Marttunen, Belton, and Lienert 2018). Since the exclusion of criteria has provided a quite manageable number of criteria, this should not be problematic.

6 Conclusion

In this project work, the framework for a master thesis has been established. The thesis will address analysis methods for holistic evaluation of stormwater control measures. It will consist of a cost-benefit analysis and a multi-criteria decision analysis of several stormwater control measures. To facilitate the analysis, a case area in Asker municipality was chosen. Several stormwater control measures were suggested. Based on the stormwater strategy in the municipality, success criteria for SCMs in the area were defined. Then, extensive literature review of previous analysis on stormwater control measures was performed, and several costs and benefits were identified. Multiple costs and benefits were then excluded from the analysis based on their relevance in the case area or for the suggested measures. Additionally, some benefits were excluded after initial estimations indicated that their values would be insignificant. The following assessment criteria were determined to be relevant:

- Flood risk reduction
- Runoff quantity reduction
- Investment cost
- Operation and maintenance cost
- Improved air quality
- Ecological benefits
- Net CO2 emissions
- Increased longevity
- Energy savings

Following their identification, the costs and benefits were described, to highlight how and why they are relevant. Several potential valuation methods for the costs and benefits were presented, and the planned valuation methods to be used in the CBA were determined. Additionally, the planned scoring method for use in the MCDA was presented. The limitations of the analysis methods were discussed, and potential sources of uncertainty were presented. The valuation methods for the cost benefit analysis are based on a wide variety of approaches, and there are several cases of severe discrepancy in published literature. This is indicative of large uncertainties in the valuation methods. In order to avoid overvaluation of measures, the lowest values are used when discrepancies arise.

The problem of ensuring comparability between the analysis methods was discussed. In order to ensure comparability, both the scoring and the weighting procedure in the MCDA should be carefully adjusted so as to match the results of the CBA. Even though there will be a lot of uncertainty in the results of the CBA, the results stem from a much more scientific approach than the results of the MCDA, and are therefore expected to paint a more realistic picture of the actual values than the MCDA. The results of the CBA will therefore be used for calibration of the MCDA.

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.

[Ask] Asker. *Klimagassregnskap Vann og vannmiljø*. Tech. rep.

[Asp17] AsplanViak. "Evaluering av nedbørhendelse 6.august 2016 Asker kommune". In: august 2016 (2017), pp. 2–32.

[BH12] Fabricio Bianchini and Kasun Hewage. "Probabilistic social cost-bene fi t analysis for green roofs : A lifecycle approach". In: *Building and Environment* 58 (2012), pp. 152–162. ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2012.07.005. URL: http://dx.doi.org/10.1016/j.buildenv.2012.07.005.

[] *Blomstertak.no*. URL: http://www.blomstertak.no/gronne-tak-fordeler/http://www.blomstertak.no/gronne-tak-fordeler/.

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

[DHI] DHI. *Mikepoweredbydhi.com*. URL: https://www.mikepoweredbydhi.com/products/mike-21.

[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.

[EPA] EPA. *The Social Cost of Carbon*. URL: https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html.

[FHI] FHI. *Luftforureining i Norge*. URL: https://www.fhi.no/nettpub/hin/miljo/luftforureining--i-noreg/.

[Fin20] Finans Norge. *Klimarapport Finans Norge 2020*. Tech. rep. 2020, pp. 1–28. URL: https://www.finansnorge.no/siteassets/statistikk/artikkel/2020/lansering-klimarapport/finans-norges-klimarapport-2020.pdf.

[FIS98] FISRWG. *Stream Restoration: Principles, Processes and Practices*. 1998.

[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.

[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.

[GU19] Kaisa Gamman and Katrine Urrang. "En sammenligning av SCALGO Live og MIKE 21 FM for modellering av overvann". PhD thesis. 2019.

[Gra] Siv Linette Grann. "Utrygghet for flom -En betinget verdsettingsstudie Anxiety for floods Siv Linette Grann". PhD thesis. NMBU.

[Her18] Ragni Rønneberg Hernes. "Kostnader ved lokale overvannstiltak". PhD thesis. 2018.

[HRR18] Hans Olav Hygen, Francesco D I Ruscio, and Shilpa Rao. "Varm sommer 2018 – økt dødelighet blant eldre ?" In: (2018).

[Jia+13] Haifeng Jia et al. "Development of a multi-criteria index ranking system for urban runoff best management practices (BMPs) selection". In: *Environmental Monitoring and Assessment* 185.9 (2013), pp. 7915–7933. ISSN: 01676369. DOI: 10.1007/s10661-013-3144-0.

[JG19] Daniel Johnson and Sylvie Geisendorf. "Are Neighborhood-level SUDS Worth it ? An Assessment of the Economic Value of Sustainable Urban Drainage System Scenarios Using Cost-Benefit Analyses". In: *Ecological Economics* 158.July 2018 (2019), pp. 194–205. ISSN: 0921-8009. DOI: 10.1016/j.ecolecon.2018.12.024. URL: https://doi.org/10.1016/j.ecolecon.2018.12.024.

[Kar] Kartverket. *Norgeskart.no*. URL: https://norgeskart.no/#!?project=norgeskart&layers=1002&zoom=9&lat=6641623.68&lon=249021.53&markerLat=6630914.442751274&markerLon=252189.0351386508&panel=searchOptionsPanel&sok=Lillerudveien.

[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.

[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.

[Min17] Ministry of Local Government and Modernisation. *TEK17*. 2017. URL: https://lovdata.no/dokument/SF/forskrift/2017-06-19-840/KAPITTEL_15#KAPITTEL_15.

[Mor+16] Adrián Morales-Torres et al. "Decision Support Tool for energy-efficient, sustainable and integrated urban stormwater management". In: *Environmental Modelling and Software* 84 (2016), pp. 518–528. ISSN: 13648152. DOI: 10.1016/j.envsoft.2016.07.019.

[Net] Nettavisen. *Sommeren 2018 var en forsmak på framtidens somre*. URL: https://www.nettavisen.no/nyheter/sommeren-2018-var-en-forsmak-pa-framtidens-somre/s/12-95-3423528981.

[Nor17] Norconsult. *ROS-analyse overvann*. Tech. rep. 2017.

[Nor08] NorskVann. *Rapport 162 2008*. Tech. rep. 2008, p. 79.

[Nor14] NorskVann. *Rapport 200 2014*. Tech. rep. 2014.

[Osl] OsloKommune. *Næringsliv, sysselsetting og pendling*. URL: https://www.oslo.kommune.no/statistikk/boliger-byggevirksomhet-arbeids-og-naringsliv/naringsliv-sysselsetting-og-pendling/.

[Rad+19] Matej Radinja et al. "Assessing stormwater control measures using modelling and a multi-criteria approach". In: *Journal of Environmental Management* 243.May (2019), pp. 257–268. ISSN: 10958630. DOI: 10.1016/j.jenvman.2019.04.102. URL: https://doi.org/10.1016/j.jenvman.2019.04.102.

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

[Row11] D. Bradley Rowe. "Green roofs as a means of pollution abatement". In: *Environmental Pollution* 159.8-9 (2011), pp. 2100–2110. ISSN: 18736424. DOI: 10.1016/j.envpol.2010.10.029. URL: http://dx.doi.org/10.1016/j.envpol.2010.10.029.

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

[SSB00] SSB. *Helseeffekter og samfunnsøkonomiske kostnader av luftforurensning*. Tech. rep. 2000.

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

[Sta20] StatistiskSentralbyrå. *Kommunefakta, Asker*. 2020. URL: https://www.ssb.no/kommunefakta/asker.

[Str+13] Clemens Strehl et al. *Quantification of risk reduction measures Methods and examples for quantification using the RRDB*. Tech. rep. 2013.

[TSC18] Inês Teotónio, Cristina Matos Silva, and Carlos Oliveira Cruz. "Eco-solutions for urban environments regeneration: The economic value of green roofs". In: *Journal of Cleaner Production* 199 (2018), pp. 121–135. ISSN: 09596526. DOI: 10.1016/j.jclepro.2018.07.084.

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

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

[VR17] Santiago Urrestarazu Vincent and Mohanasundar Radhakrishnan. "Enhancing the Economic Value of Large Investments in Sustainable Drainage Systems (SuDS) through Inclusion of Ecosystems Services Benefits". In: *Water* (2017). DOI: 10.3390/w9110841.

[Vis14] VistaAnalyse. *Nytte og kostnader ved å oppnå miljømål for byvassdrag*. Tech. rep. 2014.

[WFL05] Christopher J. Walsh, Tim D. Fletcher, and Anthony R. Ladson. "Stream restoration in urban catchments through redesigning stormwater systems: Looking to the catchment to save the stream". In: *Journal of the North American Benthological Society* 24.3 (2005), pp. 690–705. ISSN: 08873593. DOI: 10.1899/04-020.1.

[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.