**Masterarbeit**

Zur Erlangung des akademischen Grades Master of Science Global Change Geography

# Using the SIMulated Water Erosion (SIMWE) hydrological model to analyse potential flooding hotspots and the effects of Low Impact Developments (LIDs).

*A case study for the management of the Alna River catchment in Oslo, Norway.*

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# Table of Contents

## Table of Figures

## List of Tables

## List of Equations

## Abstract

This study investigates the impact of climate change-exacerbated storm events on the heavily urbanised catchment of the River Alna, located in the east of Norway's capital city, Oslo. Under predicted RCP 8.5 climate pathways stronger and more erratic storms are expected to hit Oslo. The current stormwater infrastructure in Oslo is outdated and is already struggling with recent flooding events occurring in 2014 and 2015, resulting in the formulation of the Oslo Stormwater Management Plan in 2016. In the Alna catchment, the urban infrastructure is of particular concern. This river was covered over as part of post-war development, and so is mainly fed by stormwater drains. The increased impermeable surface associated with increasing development over the past 75 years has resulted in a catchment where surface runoff is the dominant hydrological process. This results in flashy hydrographs, fast response times and a higher flood magnitude, which places further pressure on the current stormwater management network. To solve this, Low Impact Development solutions (LIDs) are under consideration. This study is one of the first to ever run the SIMWE hydrological model for the entire Alna catchment to predict flooding hotspots. The simulations were run under RCP 8.5 exacerbated 30-minute storms that have a return period of 20 years. Hotspot analysis allowed the identification of vulnerable regions, and the subcatchment of Grorud in the north-east of Oslo was chosen as the next area of analysis. Here, flooding hotspots were targeted for conversion to LID and the SIMWE model predicted the effects of these land use change measures. The end results show that LIDs would have a profound effect on reducing both depth and discharge of flooding hotspots in Grorud. Further study is required to investigate other regions of the Alna catchment, with the end goal to be the actual implementation of LIDs throughout.

# Introduction

## 1.1. Problem Statement

Two of the biggest problems facing humanity in the coming years are intertwined: increasing urbanisation and climate change. According to the United Nations, approximately 55% of the current global population lives in cities, and that this will most likely rise to around 68% by the year 2050 (United Nations, 2020). Areas vulnerable to climate change will also experience population emigration, and this will further place pressures on already large cities as their populations are likely to rise at even faster rates. Therefore, it is becoming increasingly important to improve the management of water in urban areas. In the case study region of Oslo there are further problems. Many streams and a large part of Oslo's longest river (the Alna) were built over after World War II, further increasing the area of impermeable surfaces in the city. For the Alna, much of it is closed off (though this is slowly changing) and its catchment is also consisting of impermeable urban surfaces. These types of catchments typically display lower levels of infiltration capacity, and flashier hydrographs which are characterised by short river response times, high magnitudes of floods and also shorter duration of floods (Paul and Meyer, 2005). Lower infiltration capacity results in less filtering of pollutants, meaning these are leaching into the river faster (Gold et al., 2001). Higher runoff volumes and discharges also cause the erosion of riverbeds and banks, as well as the displacement of flora and fauna and the increase of sediment and pollutant loading in watercourses (Julian and Torres, 2006). This means that there are many culverts in the city at risk of flooding damage, particularly at Kværnerbyen in the east of the city (VAV, 2016). This culvert is of particular importance, as this carries most of the lower reaches of the Alna river underground to its mouth in Oslofjord. There have already been problems here in 2014 and 2015 caused by flooding, prompting an overhaul in how urban water management will be undertaken in the future, through the 2016 Municipality of Oslo Action Plan for Stormwater Management.

This thesis is part of a wider project connected to this plan, known as the New Water Ways Project (NWWP), which researches and explores techniques to help cities in Norway move away from conventional water management methods, towards a more sustainable future with Low Impact Developments (LIDs) (NWWP, n.d.). These are an innovative approach to land management, which has the underlying principle of maintaining the hydrology as close as possible to natural state of the chosen site before it is developed (Ahiablame et al., 2012). The issues that were previously described can be examined on a multitude of scales, but for this thesis the focus will be on the local scale for the catchment of the Alna River, located in Oslo, the capital city of Norway. As of 2020, 82.3% of the country's 5.4 million inhabitants live in urban areas, with over 1 million living in Oslo (SSB, 2020). This represents an increase of

1.1% nationally (1.6% in Oslo) over the period of 2019-2020, which is indicative of a heavily urbanised population. With this comes a heightened vulnerability of a large percentage of the population being exposed to the increasingly erratic rain events predicted in cities in the future. In 2020, Oslo experienced an annual precipitation of 1022 mm (World Bank, 2021), but this is predicted to increase under increased warming of its climate. Over time, this has in fact been shown to be true based on historical data from 1901 up until 2020 (see Figure 1). During this period of the Anthropocene, annual precipitation for Oslo has risen gradually, and is expected to be further be exacerbated under future climate forcing. Further to this, precipitation projections under the Representative Concentration Pathway (RCP) 8.5 climate forcing conditions predict that annual values will increase significantly compared to the historical values. In Figure 1, a trendline is added to show how precipitation should increase under the climate conditions already experienced from 1901-2020. For the RCP 8.5 projected values to be so much higher than the current trending precipitation values is concerning, as this would put the existing strained stormwater management infrastructure under significantly more pressure.

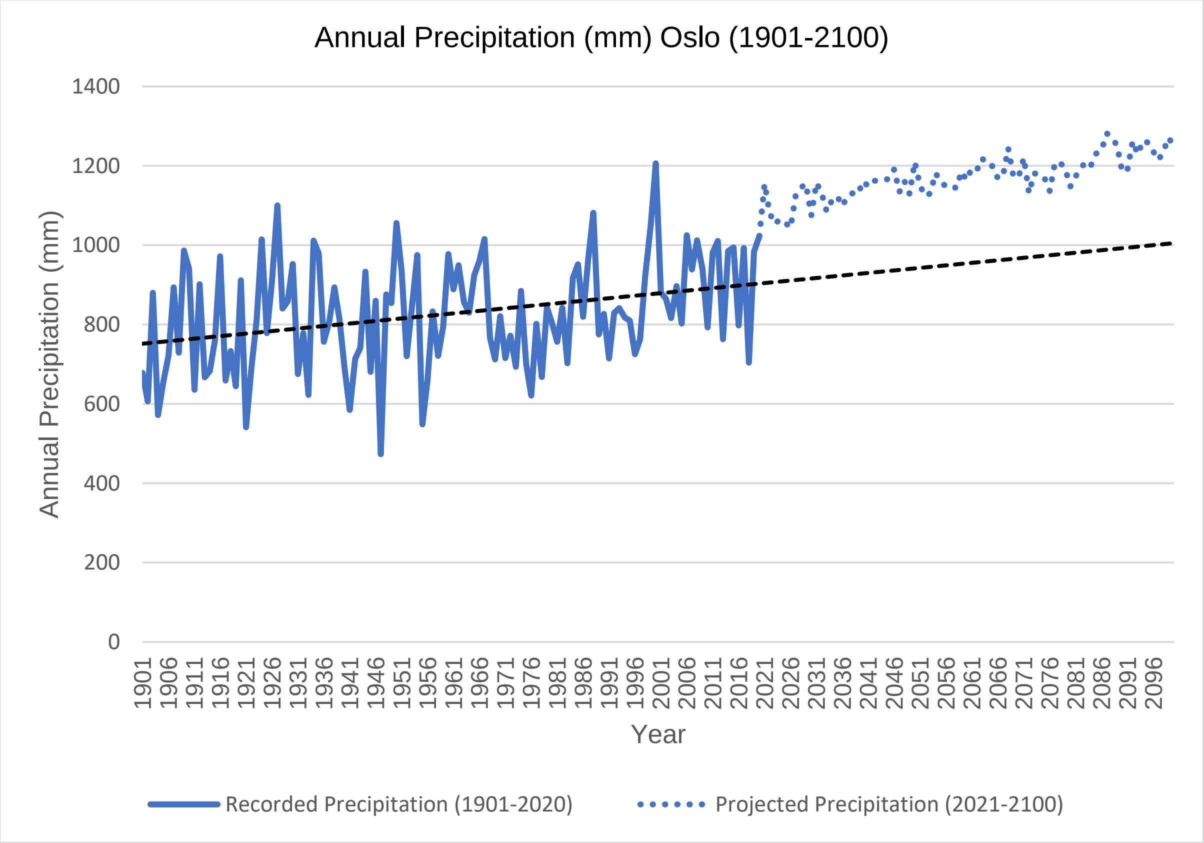


*Fig. 1: Annual precipitation recorded by the Oslo Blindern weather station for the time period of 1901-2020. Projected values under RCP 8.5 condition from 2021-2100 are also added. A trendline is added to highlight the increasing values based on recorded data. Data from World Bank (2021).*

This results in the risk of increased incidences of combined sewer overflows (CSOs), which negatively affects both the economic and social environments. Firstly, they contain higher concentrations of organic nutrients from sewage, leading to increased eutrophication in the water bodies that the water ends up in (Waajen et al., 2014). Secondly, decomposed organic matter reduces the dissolved oxygen levels, which can kill aquatic fauna (Mallin et al., 2007). The economic costs come from the damage caused to sewage systems, and the clean-up costs associated with dealing with the after-effects of CSOs. The Municipality of Oslo identified CSOs, and the associated impacts of flooding, as a major issue that the city wished to target with its 2016 action plan for stormwater management (Municipality of Oslo, 2016). This constitutes of a multi-stage approach intended to act as a guideline to follow as the city attempts to tackle CSOs. For each of the three stages, certain LID measures are suggested as options for helping to manage that particular stage. For example, stage 1 focuses on catching precipitation, as well as increasing infiltration rates to reduce surface runoff. For this stage, LID measures such as green roofs (used in this study) and planting more trees are suggested as possible methods. Stage 2 aims to delay and retain the precipitation so pooling can be avoided. Rain garden, open retention basins and trenches could be utilised to achieve this step. The final step, stage 3 encourages safe flooding areas, such as emergency waterways in the event of extreme weather, and the opening of rivers and streams (Municipality of Oslo, 2016). Recent research from the Norwegian Meteorological Institute (NMI) has indicated that the intense rainfall events of less than 1 hour duration, and a return interval between 5 to 200 years could increase between a factor of 1.42 and 1.55 by the year 2070 (Dyrrdal & Førland, 2019). This suggests an exacerbation of future storm events, and therefore also the risk of CSO events, and so the urgency to tackle this issue also increases. However, it is also important to take a sensible, pragmatic approach to dealing with CSOs. The appropriate measures must be taken to balance the trade-offs between doing too little, and risking rare, but severe, flooding damages, and doing too much which will result in a very expensive project.

Prioritisation of sites for LIDs is a cost-effective way of balancing these issues (Martin-Mikle, et al., 2015). Hotspot analysis is a useful tool for identifying “at risk” areas, and so this is utilised after running the SIMWE model for both the Alna and Grorud subcatchments. Therefore, this research will attempt to identify risk areas for urban flooding under 20-year storm events in the Alna River catchment (described in Chapter 3), before focusing on the Grorud subcatchment level. Here, mitigation of flooding hotspots with LIDs on a targeted basis will be investigated to show the differences that could be made with these minor measures.

## 1.2. Aims and Objectives

Based on the issues noted in Chapter 1.1, it is clear that the uncertainty of future weather conditions should be modelled to provide a theoretical identification of where flooding hotspots in the study area may occur with the representative concentration pathway (RCP) 8.5. The SIMulated Water Erosion (SIMWE) hydrological model will be used in this research and will be described later in Chapters 2 and 3. This model will be run for storms with a 20-year return period under RCP 8.5 conditions. This was chosen based on the City of Oslo's preparations for "realistic worst-case scenarios" when undertaking stormwater management plans. RCP 8.5 data that predict by how big of a factor that precipitation will increase by was the strongest available data. Though there was the possibility of running models for storms of a 50-year return period, the likelihood of these events occurring was deemed too low to be used when considering the building of infrastructure. Therefore, storms of a 20-year return period were determined to be the most realistic worst-case scenario. Running models under this scenario then allows a basic implementation of LIDs in these areas to also be modelled, which can then be analysed to see if there are statistically significant changes in surface depth and discharge. The following research question will steer the study throughout, and by answering this question the final conclusions can be determined:

**What is the impact of implementing LIDs on reducing urban flooding in the Alna catchment?**

Furthermore, these sub-questions will also be answered:

- SRQ1: What are the spatial variabilities in flooding hotspots in the Alna catchment?
- SRQ2: How does the implementation of LIDs change water depth and discharge?

To help answer these questions, the following objectives will guide the study towards this goal:

1. **Run the SIMWE model under 20-year flood events for the Alna catchment to identify predicted flooding hotspots.**
2. **Implement a form of LID in these hotspots, and then run the model again to predict the impact these measures will have on those hotspots.**

## 1.3. Thesis Outline

Chapter 2 shows a review of the relevant literature surrounding the topics covered in this study. These include the modelling of urban flooding, the usage of LIDs in stormwater management and using the SIMWE model to identify flood hotspots in urban areas. These topics place the work behind this thesis in the context of research already undertaken in the field of urban stormwater modelling and the implementation of LIDs. Gaps in this research area are then identified to give credence to this thesis. In Chapter 3, the methodology behind which the research was carried out will be described, and the rationale for these methods. Chapter 4 presents the results, with comparisons made between pre- and post-LID implementation and how these impact the predicted depth and discharge of future large storm events in the study area. Chapter 5 then delves into the deeper discussions behind the results, and how they answer the research questions set out in Chapter 1.2. It will also conclude this thesis with an explanation of the wider implications of this study and finally where future research can carry this project further.

# 2. Background

This is a review that will discuss the literature in the wider field of urban flood modelling and relates to the problem statement discussed in Chapter 1. It will draw together different academic pieces to provide the background to the multiple facets of this research, namely: modelling urban flooding, what representative concentration pathways are (and what was chosen for this study), and how LIDs are used in urban planning. The chapter will end with an overview of the previous research of these topics in the study area, and the usage of the SIMWE model as a whole to justify the need for the research conducted in this thesis.

## 2.1. Modelling Urban Flooding

Current stormwater management systems in urban areas are generally poor in coping with intense precipitation events. They are outdated and degrading infrastructure, with their specifications are based upon historic climate data. They also do not account for land-use change impacting on average discharges and peaks (Pour et al., 2020). Furthermore, as most urban areas are impermeable, paved surfaces, direct runoff is much higher than in rural areas. Due to the built-up nature of cities, storing and discharging runoff water is very difficult as there is less space to do so (Chocat et al., 2007; Zhou, 2014). The impact of this can range from minor to severe. Surface water on streets may disrupt the flow of traffic, or even cause damage to the actual road surface. Additionally, as water tends to flow off roads and pavements into the municipal sewer systems, there is a risk of overflowing under extreme precipitation conditions. If this occurs in combined sewers, resulting in a CSO, this may result in serious environmental issues. These include the increased loading of household pollutants in rivers, increased levels of oestrogen and androgen (affecting aquatic fauna), and even the spreading of viruses through attracting greater numbers of mosquitos due to the higher amount of human waste present in the watercourse (Kim et al., 2007; Vazquez-Prokopec et al., 2010; Phillips et al, 2012). Further to this, CSOs flush waste, toxic materials, and pollutants into watercourses, causing damage to both flora and fauna. Approximately 40% of Oslo is served by combined sewer systems, and in total 67 CSO weirs are classified as problematic by the municipality

(Hernes et al., 2020). In Fredrikstad, another Norwegian city located approximately 100 km south of Oslo, studies there have shown that a 20% increase in precipitation would lead to a total increase of CSO events by 36% compared to figures from 2004 (Nie et al., 2009). This study also demonstrated that an increase in precipitation between 30 and 50% would result in an exponential growth in the volume of CSOs (Nie et al., 2009). Since Fredrikstad is very close to Oslo, with very similar climatic conditions, these results should come as a warning to the government in the capital. Warming on a global scale is likely to result in greater evapotranspiration, increasing atmospheric moisture content and therefore increasing variability in rainfall patterns (Wang et al., 2016). In urban areas, this is amplified due to the urban heat island (UHI) effect, which affects the microclimates present in a city and produces increasingly severe rainfall events in these areas (Şimşek & Ödül, 2019).

It has already been noted that there is a link between increased rainfall intensities and higher return periods in large cities, and these effects have been attributed to ongoing urbanisation (Pour et al., 2020). Therefore, mitigation against urban flooding is vital for the maintenance of comfortable living conditions in our ever-growing cities. For Oslo, a study by Nilsen et al. (2011) simulates end-of-century flood impacts on a sewer system in the city. This predicted that there would be a 33 to 83% increase in CSO volume compared to the events from 1980 (the year with the maximum overflow measurement) and 1988 (the wettest year in the study period), respectively (Hernes et al., 2020). In the past, and indeed now, two other hydrological models are used to simulate the impact of storm events on catchments. These are also the most widely used modelling techniques: the MIKE series and the Storm Water Management Model (SWMM). Whilst these are used to estimate water balance components in urban areas and to route flow in pipeline networks, neither model can produce flood depth maps or estimate water depth over a large area. They also both require a lot of manual work to set them up (Li et al., 2020). This is where the SIMWE model has an advantage over both models as previous work has shown that this model is able to show gradual changes in water depth across entire catchments, which prove how robust and flexible SIMWE is (Hofierka & Knutová, 2015). However, it has rarely been used in urban flood modelling.

### 2.2. Using SIMWE for Urban Flooding

The SIMWE model is an open-source and physically based spatially distributed overland flow model. This model is integrated into the open-source GRASS GIS and is an easy model to use as it allows the easy update of input data and model parameters (Li et al., 2020). SIMWE is its own function in GRASS GIS, under the name r.sim.water (GRASS Development Team, 2017) and requires simple inputs of rainfall intensity, infiltration rate, surface roughness and a digital elevation model (DEM), whilst the outputs are water depth and discharge maps at either a coarse or fine spatial resolution. This allows the identification of estimated flood risk areas on both a small and large scale (Li et al., 2020). There has been very little research using the SIMWE model for urban flood risk management. The previously cited work of Li et al., 2020 evaluated the effectiveness of this model on both a city-wide scale (the whole of Oslo) and also on a sub-catchment basis (in the Grefsen area of Oslo). There, they found that the SIMWE model produces more overland flow and a higher flood risk estimation with low rainfall inputs, but larger areas of risk with higher rainfall inputs than in comparison to other hydrological models (Li et al., 2020). There have not been any other recorded uses of the SIMWE model for urban flood risk management. It has, however, been used to study the impact of land use and topography changes on overland flow and sediment transport at the campus of North Carolina State University. Here it predicted that standard construction buffers against sediment transportation provided little protection and was deemed to be robust in simulating changes on small-scale landscapes (Mitasova et al., 2004). SIMWE has also been used to simulate the spatial aspects of a flash flood in the Malá Svinka Basin in Slovakia. Here it was used to replicate a 100 mm/hr flood event that occurred in 1998 and helped to identify source areas contributing to flooding in urban areas (Hofierka & Knutová, 2015). The most common usage of this model is to predict erosion of gullies under different land use practices, with studies of vineyards in both northern Italy and the Douro Valley in Portugal. In both cases, the SIMWE model was praised for its effectiveness in recognising soil erosion process occurring during intense rainfall conditions (Fernandes et al., 2017; Pijl et al., 2020). SIMWE has also been used for simulating time-limited erosion and deposition rates for Tinto Vallis on planet Mars with some success and will be further developed to adapt to the Martian environment in future studies (Steinmann & Kereszturi, 2020).

### 2.3. Representative Concentration Pathways

To run the SIMWE model for future storm events, predicted future rainfalls based on historical data are required to fulfil the need for a climate scenario as a parameter of this model. Climate change scenarios are a product of work from the Intergovernmental Panel on Climate Change (IPCC), which first introduced emission scenarios, before replacing this with representative concentration pathways. These describe the potential consequences of increased additional radiative forcing in W/m² due to greenhouse gas (GHG) concentrations in the atmosphere based on economic growth, energy production and population growth. Therefore, they can be used to calculate certain climatic variables like precipitation and temperature (Wayne, 2013). RCPs were created as a more up-to-date, and more holistic way of considering future climatic conditions compared to the previously used emission scenarios. This is reflected in its name. “Representative” refers to each of the scenarios utilises a wider range of literature to formulate them and should be compatible with the full range of emissions scenarios present in current scientific literature, even when considering those studies with or without climate policy. On the other hand, “concentration pathways” emphasises the fact that RCPs are not the final, fully integrated scenarios, but instead are consistent projections of the components of radiative forcing (van Vuuren et al., 2011). In total, there are four RCPs produced that will result in projected radiative forcing levels of 2.6, 4.5, 6 and 8.5 W/m² by the year 2100. Each RCP covers the time period of 1850-2100, and there are also extensions which have been developed up until the year 2300 (van Vuuren et al., 2011). Whilst it is important to use multiple scenarios for effective urban planning, in this study only one is used due to Municipality of Oslo preferring to use the worst-case scenario to prepare for future flooding events. Therefore, for this study RCP 8.5 will be used. This trajectory is based on the highest predicted concentrations of emissions of atmospheric $CO_2$ (>1370 parts per million (p.p.m.)) and a radiative forcing of 8.5 W/m² by 2100 (van Vuuren et al., 2011).

### 2.4. LIDs in Urban Planning

Mitigation requires long-term sustainable planning solutions, which must include a degree of flexibility to account for unexpected climatic and socio-economic variabilities that can hinder strong political decision-making. A popular current mitigation method is to increase infiltration into the subsurface using LIDs. These are wide-ranging strategies used in land use planning, which intend to mitigate the impact of impervious urban features on the environment, primarily on a subcatchment level (Martin-Mikle et al., 2015). LIDs use natural structures used to attenuate peak discharges and runoffs by encouraging infiltration and storage of surface water, therefore mitigating flood impacts (Pour et al., 2020). The increase in infiltration results in the filtering of pollutants (and sediment) from stormwater runoff before it reaches the main network of a watercourse. (Craig et al., 2008). Due to their pleasing aesthetics, and proven effectiveness in reducing surface water runoff and peaks (Son et al., 2017), LIDs have emerged as an environmentally friendly supplement to assist the traditional stormwater management strategies. As discussed earlier, these are subject to greater pressures on their construction due to climate change. Traditional stormwater management techniques tend to involve hard infrastructure, like gutters and pipes. The U.S. Environmental Protection Agency (EPA) undertook a cost-benefit analysis for implementing LID measures as opposed to conventional measures across seventeen different projects. In almost all of these projects, cost savings ranged from 15 to 80%. Significant savings coming from reduced costs for site grading and preparation, stormwater infrastructure, site paving and landscaping (EPA, 2007). Further to this, more benefits were discovered. It was found that in the majority of these case studies, the interviewed residents appreciated the improved aesthetics. It was also discovered that the property values tended to increase (due to the desirability of the plots with LIDs). There were also environmental benefits that were found, including reduced runoff volumes and less CSO incidents (EPA, 2007). Many other studies have reported the effectiveness of LIDs for urban flood mitigation. In the Templeton Gap catchment in Colorado, it was found that using small-scale LID features such as porous pavements, rain gardens and infiltration trenches would be beneficial (Tredway & Havlick, 2016). In Bergen, swales (a form of LID) are implemented in the area around the Bryggen World Heritage Site. These are grassy areas of 20 m in length and are used to increase the groundwater level and humidity in the topsoil in what is a predominantly impermeable urban area. These swales have been shown to effectively capture stormwater runoff from upstream roads and roofs. This reduces the incidence of pooling near the terminus points of surface runoff streams (Boogaard et al., 2017).

The installation of green roofs is also an LID measure that has increased in popularity in recent years. From an urban water management perspective, these can play an important role in slowing down and reducing overall runoff volume. Studies have shown that high evapotranspiration from a green roof may reduce the annual runoff to less than half the precipitation, dependent on the substrate mixture and the climatic conditions (Bengtsson et al., 2005; Vijayaraghavan et al., 2012). Another study in Oklahoma investigated the effects of implementing LIDs on a broad-scale mixed-use urban catchment area. This was a rare study, as most broad-scale LID implementations occur in agricultural catchments, as the land use complexity is less than in urban areas (Martin-Mikle et al., 2015). This case study identified LID-suitable locations throughout the Lake Thunderbird watershed, based on a spatially explicit approach that also considered topography and land use in each location. They converted approximately 6% of the entire catchment (in this study 5% of Grorud is converted, but this is also a smaller subcatchment of the Alna). The results showed that for a subcatchment of the Lake Thunderbird watershed, LIDs placed in 11 priority areas may lead to reductions in nutrient and sediment loadings to receiving waterbodies up to 16% and 17%, respectively (Martin-Mikle et al., 2015). These encouraging results suggest that it is worth investigating further the effects of LIDs on urban areas, and on broader scales. Furthermore, it was determined that this approach could be ecologically beneficial. This is based on the fact that targeting sites instead of a general approach result in problematic areas for nutrient and sediment loading being dealt with, and the knock-on effects of these results in better ecological security further downstream in watercourses (Martin-Mikle et al., 2015). Therefore, this thesis will investigate the potential impacts of LIDs in the chosen study area. As many of the aforementioned LIDs have similar physical properties (infiltration capacity and Manning's roughness coefficient, respectively), from a modelling perspective the only specified LID measure implemented will be green roofs. For other areas, generalised LID areas are theoretically "installed", and these will cover various identified flooding hotspots which will act as priority locations for LID measures.

## 2.5. Previous Research and Rationale for this Thesis

As mentioned in Chapter 2.2., there has been very little research done using the SIMWE model in the context of urban flooding. Despite urban flooding being a hot research topic in recent years, most current stormwater management models are too complex to apply on a large scale. Li et al., 2020 showed that the simple SIMWE model can be used effectively on both a district and city-wide scale, therefore this thesis will attempt to build upon that research by using this model for a separate, larger area of Oslo (the catchment of the Alna River). The work of Li et al., 2020 is believed to be the first usage of the SIMWE model for urban flood simulation, and also the first time that an urban flood simulation for the whole of Municipality of Oslo has been undertaken. Therefore, this research has the potential to identify new flood risk areas in Oslo. Furthermore, this is certainly the first ever recorded usage of the SIMWE model as a method of identifying and theoretically implementing LIDs. Thus, this research certainly has the potential to provide the Municipality of Oslo a possible new method of identifying risk areas to focus their future research on. It also gives an idea as to how effective possible LID measures can be in mitigating flood risk in Oslo. On a wider scale, the results of this research may encourage the usage of SIMWE as the model of choice for governments in their respective urban water management plans. The simplicity of this model makes it a more attractive, faster way of generating predictions compared to more established, albeit complex, models such as the MIKE series and SWMM.

This research also builds upon other studies of testing the effectiveness of LIDs on urban areas, such as that of Martin-Mikle et al., 2015. Studies which investigate the usage of LID measures on a broad scale are rare, particularly when the catchment in question is a complex, mixed-use urban area. This is in contrast to the more homogenous agricultural catchments where LIDs are more frequently implemented (Martin-Mikle et al., 2015). Previous research of using LIDs in urban catchments has shown that installing these measures could be useful in at least partially restoring the natural hydrological cycle and maximising the infiltration capacity at a site that is prone to flooding (Bae and Lee, 2020). In that particular study it was found that LID techniques could reduce the runoff volume, peak flow and inundation volume compared to conventional grey stormwater infrastructure (Bae and Lee, 2020). Specific LID infrastructures have also been tested against each other in urban catchments. Green roofs that cover the entirety of a catchment are as effective at managing stormwater runoff as a bioretention cell that covers 3%-5% of the same catchment (Yang and Chui, 2018). Though it is not possible to cover the entirety of this study area in green roofs, the literature does give credence to using green roofs as an LID measure in this study. All of these studies suggests that it would be interesting and important to test the effectiveness of LIDs in the urban Grorud subcatchment, as this could solve some of the flood risks currently present there.

# 3. Research Design and Methodology

## 3.1. Study Area

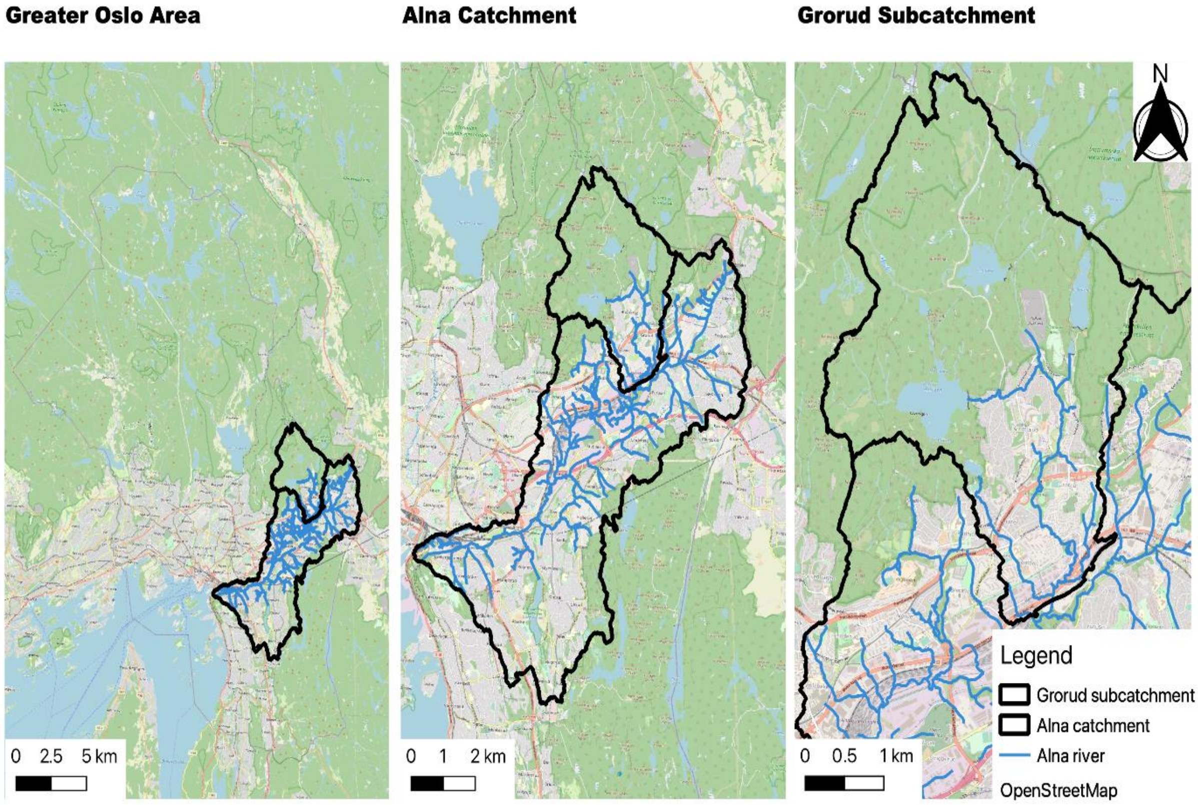


*Fig. 2: Open Street Map depicting the study region of Oslo (left), catchment of the Alna river (centre) and the Grorud subcatchment (right).*

### 3.1.1. Alna Catchment

The Alna River is the longest in Oslo, with a length of 15 km and a catchment area of 69 km² (NIVA, 2018). Approximately two thirds of this area is located in the eastern urban region of Oslo (NIVA, 2020). As shown in Figure 2, the river begins at the Alnsjøen lake in the north and travels through the east of Oslo before ejecting into Oslofjord in the Bjørvika neighbourhood in the Sentrum district. The Alna has been heavily developed and re-developed throughout the years. In 1922, the lower section was forced underground through a series of pipes by the aforementioned Kværnerbyen culvert (NIVA, 2020). Since World War II, much of the river was covered up and forced through culverts as a way of allowing greater urbanisation to take place, as well as being used for sewage disposal for the large housing developments that have been built since then. Further to this, 80% of the Alna's tributaries are closed, which further exacerbates the poor hydrological and ecological situations in the Alna (NIVA, 2020). As a result, the Alna is one of the most polluted rivers in Norway (NIVA, 2018), with very high levels of phosphorus and nitrates due to the highly urbanised catchment area. Most of these pollutant sources come from urban surface runoff (mainly roads) as well as point and diffuse discharges from wastewater, small-scale industry, landfill, and contaminated ground caused by older industries (NIVA, 2020). The scale of urbanisation is demonstrated by the land cover map in Figure 5. This plays a big role in impacting the water quality, as two of Norway's busiest roads (Trondheimsveien and Østre Akervei) cross the Alna, and also through the centre and south of Grorud, respectively. Major roads, coupled with industrial areas along some sections of the river, means that pollution from surface runoff is a key factor that must be addressed (NIVA, 2020). Most of the tributaries are closed either partially or completely, and this results in fast response times and fast discharge into the main river, as well as high flood peaks during extreme storm events. This means that much of the areas close to the Alna are at risk of flooding under current conditions (NIVA, 2020). Further to this, the closed tributaries have been shown to suffer from faulty pipe connections which allows wastewater and water from contaminated ground to enter these tributaries (and later, the Alna) without being detected quickly enough (NIVA, 2020). This is the case even before the threat of CSOs. On top of this, average temperatures in the Alna catchment have risen by 1.9°C since 1980, and yearly average precipitation has risen by 128 mm in the same timeframe (NIVA, 2018). It is therefore very important to mitigate CSOs occurring as much as possible, as the changing climatic conditions suggest that if nothing is done, then extreme flood events (and hence CSOs) are expected to increase in frequency.

In recent years, the Municipality of Oslo has encouraged better care of the Alna river. It has done this by creating linked walking trails and developed more green space areas along the length of the river. Furthermore, the municipality is trying to re-open many covered sections of the Alna (Li et al., 2020), as an attempt to create more pleasant green and blue areas of Oslo. This creates a more natural system where self-purification can take place, as sunlight will once again be able to reach aquatic flora in the Alna, generating better dissolved oxygen concentrations (NIVA, 2020). Opening the Alna and its tributaries also allows more natural flooding to take place, so that less pressure is placed on the already vulnerable culverts. This is in response to the 2014 and 2015 floods. In these incidents, major damage to the Kværnerbyen culvert was caused by an extreme flood event of 93 $m^3/s$ and a return period of 850 years (Grange et al., 2015).

### 3.1.2. Grorud

In the north-east of Oslo is the borough of Grorud, which lies in the northern upper course of the Alna River. Grorud is home to the source of the Alna river, which starts at the Alnsjøen lake. The lake was dammed off in the 1970s to facilitate the capabilities for providing drinking water to Oslo, and this heavily altered the hydrological regime of the Alna, as even at its source it is partially piped through to the next section of its course in the Ammerud part of Grorud (see Figure 3) (NIVA, 2020).

*Fig. 3: Source of the Alna at Alnsjøen lake in the north-east of Oslo. Red dashed lines indicate piped sections of the river*, blue signals open sections and dots denote point-source pollution. At the top of the map shows the Aurevannsbekken tributary passing under Huken quarry (Source: NIVA, 2020).

The result of this is some contamination by wastewater and overflows, which are caused by incorrect or damaged piping links (NIVA, 2020). Grorud also contains part of the large Oslomarka forest, which dominates the hills of the city. This subcatchment of the Alna river measures 13.7 km$^2$ and so is approximately 1/5th of the size of the total Alna catchment. Grorud is the smallest of Oslo’s districts, with 27,455 inhabitants (SBB, 2021) and is known for its history in granite mining and textile industries. These economic sectors historically used the Alna and its waterfalls as a power supply, which contributed to the inevitable pollution of the river. In recent years, the Alna in this district has been subject to multiple developments as an attempt to reverse the post-WWII urbanisation and ‘greying’ of this part of the catchment. One of these projects is the closing of the Huken granite mine, and the planned reconversion to recreational forest area. There will be multiple facilities developed here, with a focus on nature and sports (Municipality of Oslo, 2019). Another important facet of this project includes the reopening of the Aurevannsbekken, a small tributary of the Alna which flows through some pipes past and below the Huken quarry site (see Figure 3). This has also suffered contamination due to drainage from the quarry, which in turn affected the Alna (NIVA, 2020). The reopening will be implemented in the model by converting the previously impervious area to grass. This will help to predict the impact of this project. An example of a completed project in Grorud is the Hølaløkka park in the south of the borough (see Figure 4). Here, 15% of the Alna's flow passes through a series of artificial lakes built into the park, with the rest flowing in a culvert directly underneath (NIVA, 2020). Hølaløkka is the first area in which the Alna was reopened (albeit partially) as part of the wider programme to reopen rivers and streams in Oslo. Much of the sewage system in Grorud is combined sewers, so this is therefore an interesting region to model flood risk and to implement LID measures to combat the threat of CSOs. Furthermore, the subregion around the train station of Grorud is also important in this study, as it contains 2 outlet points from the Grorud subcatchment, as well as the confluence with the Tokkerudbekken (shown in Figure 4). The Østre Akevrvei road is also present here, and is one of the busiest roads in Norway, alongside Trondheimveien, which runs through the centre of the Grorud district. North of the train station, many LIDs were placed, with the hope of reducing runoff into the combined sewers and hence the Alna itself.

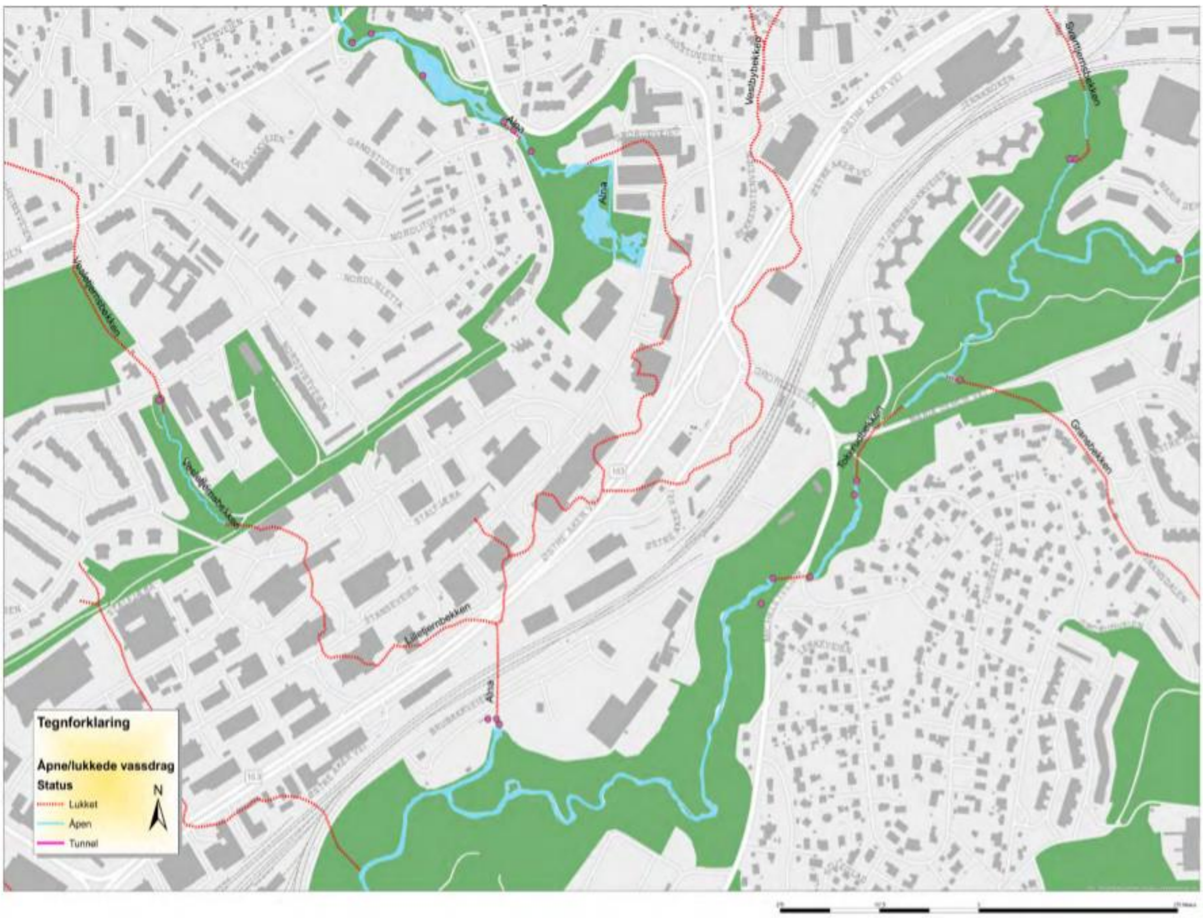


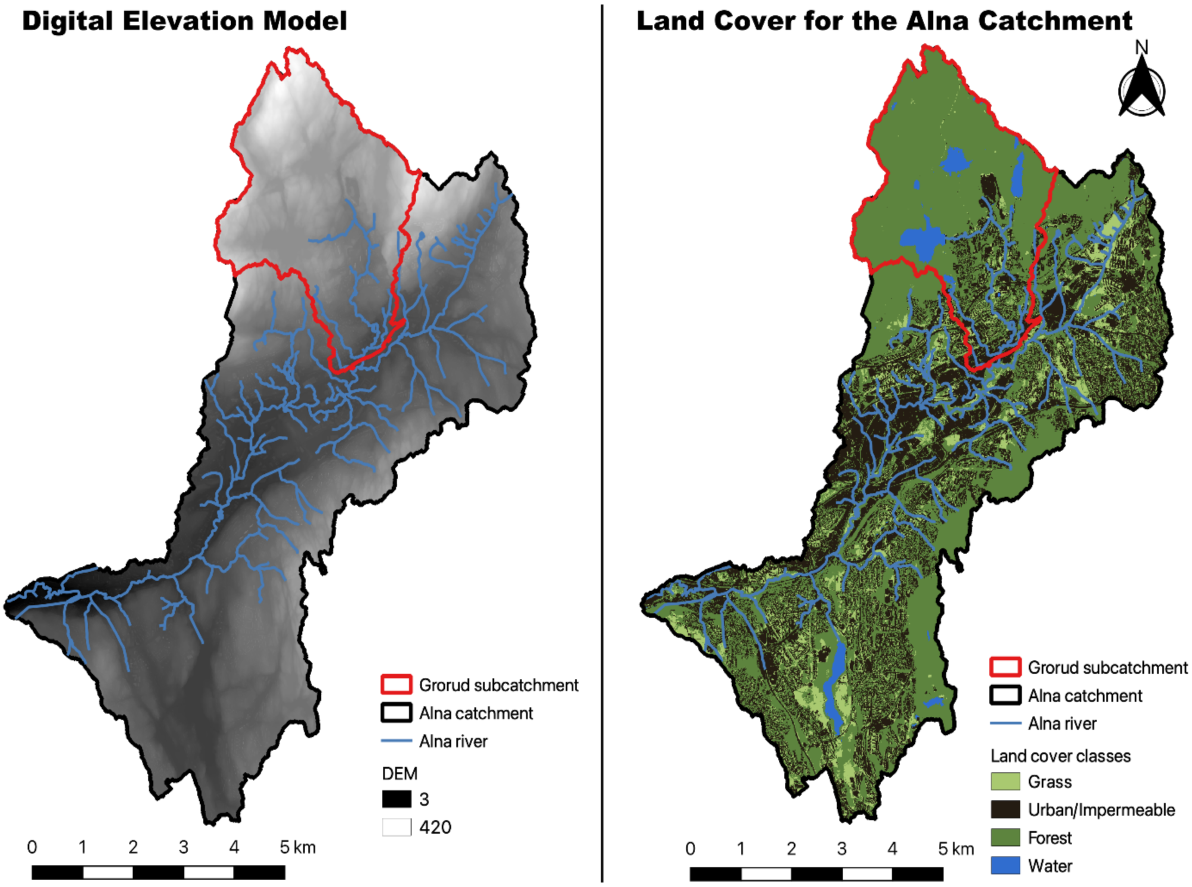
*Fig. 4: Map of the subregion around the Grorud train station. Dots indicate point-source pollution, red dashed lines show closed sections of watercourses, with blue showing open watercourses. Hølaløkka park is present in the upper-middle of this map (Source: NIVA, 2020).*

## 3.2. Data Collection

### 3.2.1. Catchment Data

The Alna catchment boundary was downloaded from the Nedbørfelt-Vannføring-INdeks-Analyse website (NEVIA, n.d.). The data is split into two sections, and these were merged to form the overall Alna catchment (see Figure 5). This data is important as it allows the focus area of the study to be the catchment for the Alna river. All raster inputs and the region in GRASS GIS were set to the extent of this boundary, and therefore the outputs are also generated in this area. A digital elevation model (DEM) is also required for the SIMWE model to operate. Two DEMs were provided, one with just the ground data and the other including the roofs of buildings. This is necessary for the elevation of the buildings to be considered by the SIMWE model so that directions of overland flow can be accurately predicted. These were then merged to form a DEM of 2 m spatial resolution. As the SIMWE model requires both dx and dy derivatives of the slope of the terrain, these were created in GRASS GIS by using the r.slope.aspect function to extract them from the DEM. After being isolated as an area of interest, the Grorud subcatchment was derived using the r.watershed function. This was done by using the shapefile of the Alna river as a reference, which was downloaded from the Oslo river forum (Oslo Elveforum, n.d.). Points were plotted along the course of the Alna at certain key tributaries and saved as a point vector. The DEM for the Alna river was used in the r.watershed function alongside this shapefile to derive subcatchments for the whole river, and this produced the Grorud subcatchment. Subsequent model runs used this boundary as the new working region, and all inputs required for the SIMWE model were clipped to this boundary.

### 3.2.2. SIMWE Input Data



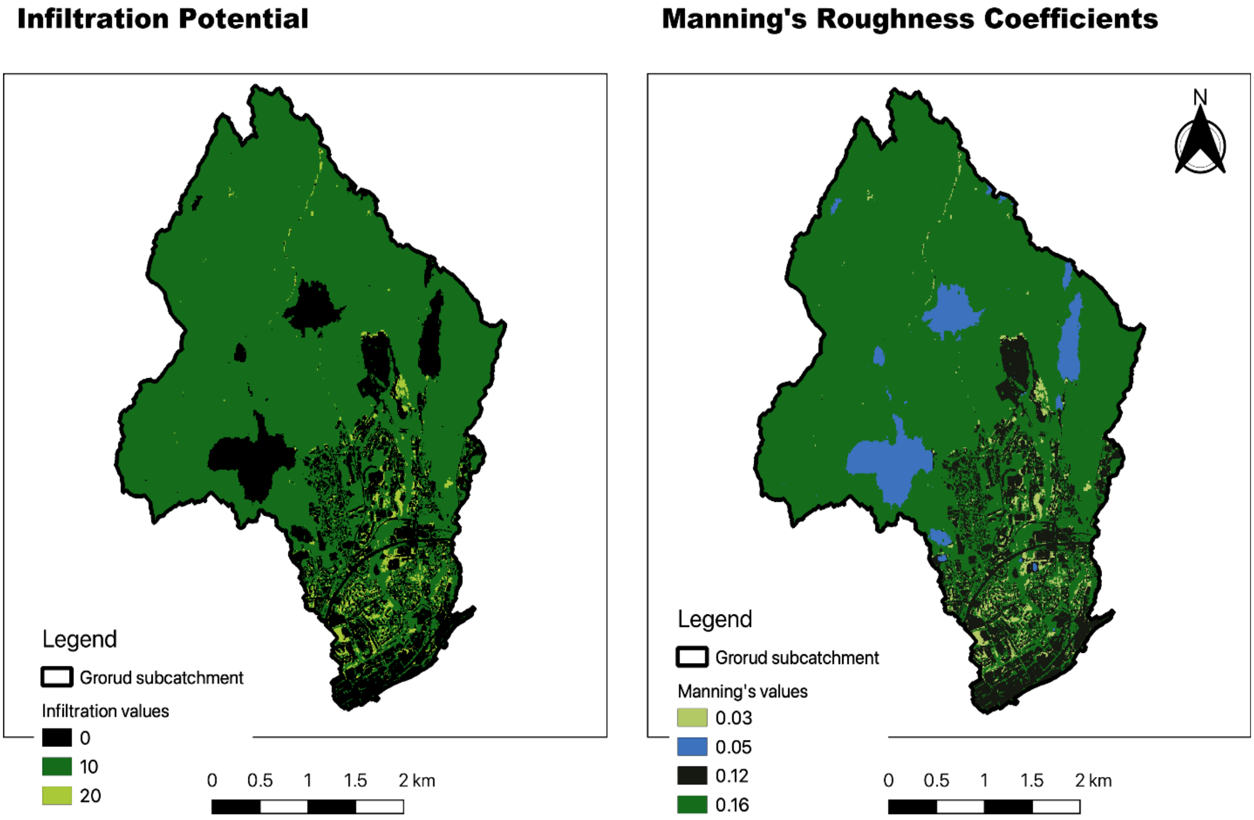
Digital Elevation Model

Land Cover for the Alna Catchment

*Fig. 5: 2 m Digital Elevation Model (left) and land cover data (right) for the study area.*

The required inputs for the SIMWE model are rainfall, terrain, infiltration rate and Manning's roughness coefficient. As mentioned before, the terrain inputs include the elevation, and the x- and y-derivatives of the slope directions. As shown in Figure 5 the Alna catchment, and particularly the Grorud subregion, are hilly with large variations of elevation over a small area, with a range from 3 to 420 m above sea level. This greatly influences the direction and velocity of surface runoff and is partially the reason for choosing this study area. The knowledge of land cover allows the creation of the Manning's roughness coefficient and infiltration rate rasters. These factors are related to each other, and so assumptions of each land cover type's Manning's and infiltration rate values can be made. This has to be done as there are currently no quantifiable Manning's roughness coefficient or infiltration rate maps for Oslo. The land cover data comes from Sentinel-2 as a 2 m spatial resolution imagery (see Figure 5). However, due to some areas of the Alna's catchment being out of the range of this data, these gaps are filled with Sentinel-2 10 m spatial resolution data (NINA, 2017). This is acceptable as the areas filled with this data were mainly large forest areas, where a finer spatial resolution does not affect the land cover (and hence Manning's roughness coeffcient and infiltration rate) categories. For the Manning's values, these were derived from a study by the Norwegian

Institute of Bioeconomy Research (NIBIO, 2018). Using the r.recode function in GRASS GIS, this allowed the Sentinel-2 land cover data to be reclassified according to the Manning's roughness coefficient and infiltration rate value of each land cover class, respectively (see Figure 6). Furthermore, these rasters are hybrids of descriptive infiltration capabilities and impermeable surfaces. This is based on the work of Li et al., 2020 who transformed the descriptive capabilities into quantitative infiltration capacities (see Table 1). This was done by simply linking each land-cover type with an infiltration capacity value, which was based on previous research (Li, et al., 2020). The impermeable surfaces are derived from the Sentinel-2 data and combined with rasterised polygons of roads and buildings found on the Norwegian common map (fkb) database (Norwegian Mapping Authority, 2005).


**Infiltration Potential**

**Manning's Roughness Coefficients**

*Fig. 6: Infiltration rate and Manning's roughness coefficient maps for the Grorud subcatchment used as inputs for the SIMWE model.*

*Table 1: Infiltration rate based on a descriptive infiltration capacity and impermeable surface, as quantified by Li et al., 2020.*

| | **Good** | **Middle** | **Little** | **None/Unclassified** | **Impermeable Surface** |
|---|---|---|---|---|---|
| **Infiltration Rate (mm/hr)** | 40 | 30 | 20 | 10 | 0 |

### 3.2.3. LID Implementation

*Table 2: Total area of the Grorud subcatchment and how much was converted to LID from impermeable land cover.*

| | **Area ($m^2$)** |
|---|---|
| **Grorud subcatchment** | 13,701,779.40 |
| **Impermeable land cover** | 4,271,251.00 |
| **Swales/Permeable pavement** | 1,588.37 |
| **Green roofs and other LIDs** | 212,001.00 |
| | |
| **Percentage impermeable land cover converted to LID** | 5% |

To facilitate LID implementation in the study area, it is important to consider where roads and buildings currently are to ensure the correct placing of LIDs. The road and building polygons (Norwegian Mapping Authority, 2005) were used here to help this decision-making process. The placement of LIDs is vital to urban stormwater management so that they can be as effective as possible without unnecessary excess expense required to cover areas that are not as at risk. When placing LIDs in this study, it was important to be realistic in deciding how much land cover can be achieved. A target of 10% maximum land cover change in the Grorud subcatchment was set, as this is approximate to what would be considered by policy makers in the Municipality of Oslo. In total, 5% change was achieved (see Table 2). It has been found that a land use conversion that results in the decrease of the impervious area by 5% is enough to achieve noticeable hydrological benefits (Palla and Gnecco, 2015). It is of interest to see how much reduction in surface runoff and pooling can be achieved under this minimum percentage change of impermeable surface.

The overall coverage of LIDs is shown in Figure 7 below, which displays where LIDs are placed in the urban area of Grorud, compared to the depth results from the first simulated storm event (pre-LID installation). The first targeted areas were depth and discharge hotspots, particularly near combined sewers as these are to be protected to prevent CSO events. Much of the combined sewer systems run directly underneath roads, with drains running from the road surface into the sewers to protect the roads from surface flooding. Due to this factor, it was decided to place swales alongside as many of the roads above the combined sewer systems, as this would aid in slowing down or even greatly reducing the amount of runoff into the sewers. This would protect against CSOs. Later, other hotspot areas were also considered, and it was decided that the implementation of green roofs across the southern half of the subcatchment would be useful. Based on previous research, these measures would aid in increasing the infiltration capacity of the district as a whole, since it is currently heavily urbanised with large areas of impermeable land cover. The Huken quarry in the north of Grorud is also converted entirely as an LID, to model the impact of the reconversion project currently being undertaken by the Municipality of Oslo, which was described in Chapter 3.1.2. (Municipality of Oslo, 2019).

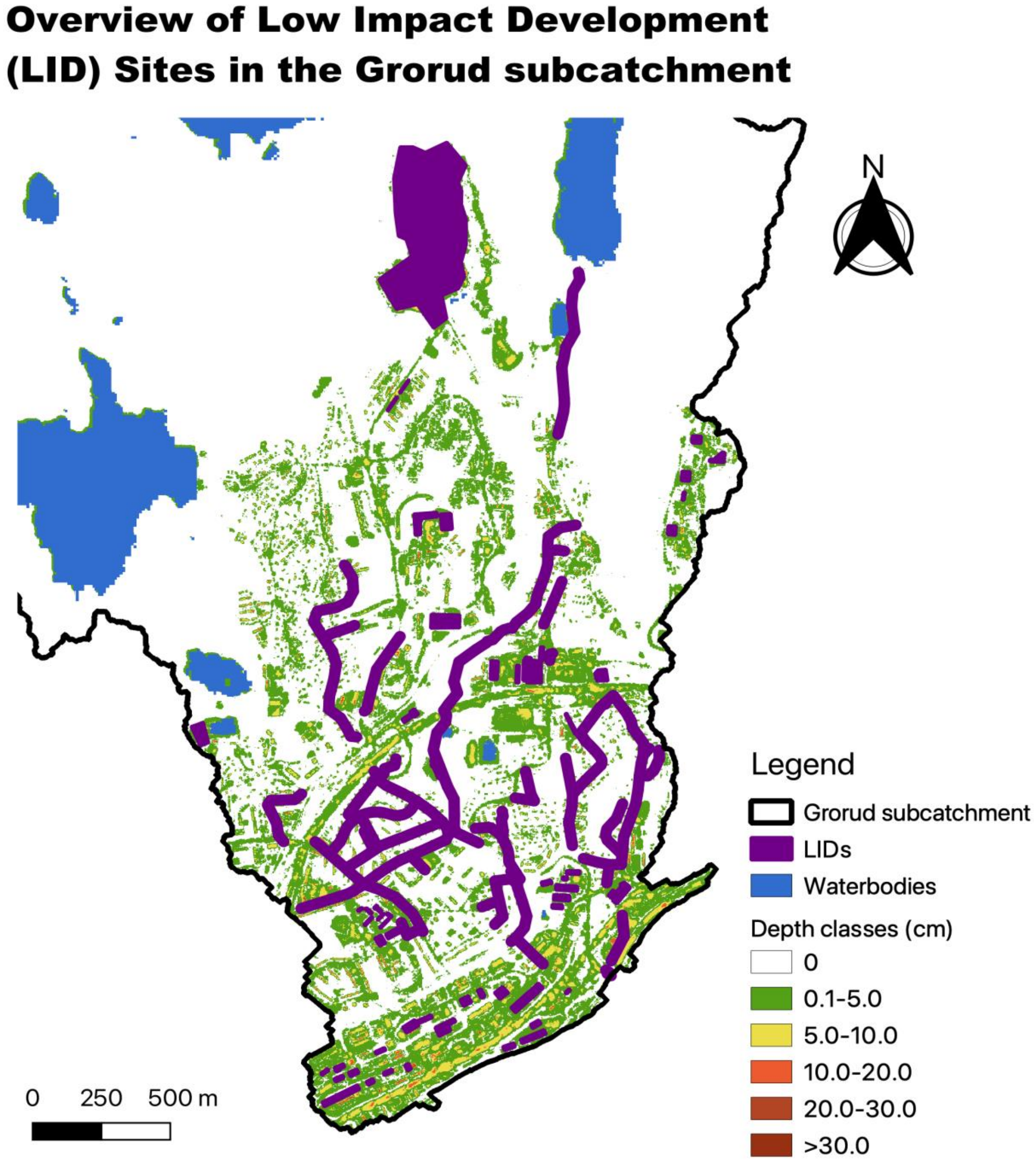


*Fig. 7: Total extent of LID (purple) implementation in the Grorud subcatchment. The locations are based on the first modelled depth results without LIDs. 5% of the total subcatchment area is converted.*

### 3.2.4. Design of Storm Events

Rainfall events for this model are based on predicted future rainfall events under RCP 8.5. This data is derived from historical rainfall measurements from the Blindern weather station, which has the longest time series data, and so is frequently used for the whole of Oslo. The rainfall data is therefore only available in a spatially uniform, rather than spatially distributed manner unlike the rest of the data used in this model. Based on the Oslo Municipality planning policy, rainfall events with a 20-year return period were applied in this study. In these SIMWE model runs, events of 30 minutes under RCP 8.5 conditions were used. Therefore, historical 20-year rainfall events of 30 minutes (53.4 mm/hr) were multiplied by a factor of 1.38 (for RCP 8.5 conditions), resulting in storm events of 66 mm/hr precipitation. The first model run is for the whole Alna catchment, without LIDs implemented, to identify areas vulnerable to flood risk, and the result of this showed Grorud as being at risk. SIMWE is then run again for this subcatchment, so that a more detailed investigation into flood risks in this smaller area can be undertaken. On this smaller scale, it is then appropriate to identify areas suitable for LID implementation. To determine what classifies as a flood risk in cities, it is important to use a quantitative classification system tailored to urban areas. However, in Norway there is neither an urban flood warning system nor a flood risk classification for critical urban flood sizes (Li et al., 2020). For this study, urban flood risk levels will be classified using the following system that is based on what the Municipality of Oslo deems as problematic. The city of Oslo generally considers urban flooding to be depths of >10 cm. Therefore, depths greater than this value will be coloured in varying shades of red, indicating the increasing levels of danger. Table 3 shows this classification of depths that will be used throughout this research:

*Table 3: Classification of urban flood risk, based on the water depth present in any given area.*

| **Depth Class** | **0** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|---|
| **Water Depth (cm)** | 0.0 | 0.1-5.0 | 5.0-10.0 | 10.0-20.0 | 20.0-30.0 | >30.0 |

## 3.3. Data Analysis

The SIMWE model is a physically based, spatially distributed model. Only six inputs are required: rainfall, terrain (elevation plus the derivatives of slope direction dx and dy), surface roughness and infiltration rate. The outputs are water depth and discharge. Depth is calculated using Equation 1, which describes how water depth is the product of rainfall excess rate and water flow. Discharge is calculated by Equation 2, which theorises that discharge is the result of the interactions between water depth and flow velocity. The velocity is calculated based on the Manning's roughness coefficients, slope angle and slope direction. In this study, despite analysing urban flood risk, the sewage drainage system is not taken into account. This is because the SIMWE model focuses purely on overland flow, due to its usage of elevation and topography as the main factors behind the tracking of fallen precipitation. Though SIMWE accounts for basic infiltration rates and speed of movement (using the Manning's roughness coefficient), complex underground pipe networks are unable to be used as inputs for this model. Therefore, underground and subsurface processes must be neglected in this study. As urban flooding usually occurs as shallow overland flow, the SIMWE model can still be a useful tool for this study. The spatial variation of water flow velocity with respect to depth can be neglected by using the bivariate of the fundamental Saint Venant equation for the continuity of flow (Mitasova et al., 2015):

*Equation 1:*

$$\frac{\partial h(\boldsymbol{r}, t)}{\partial t} = i_e(\boldsymbol{r}, t) - \nabla \cdot \boldsymbol{q}(\boldsymbol{r}, t)$$

where, $r = (x, y)$ is the position, $t$ is the time, $h(r,t)$ is the depth of overland flow, $i_e(r,t)$ is the rainfall excess = (rainfall - infiltration - vegetation interception), and $q(r,t)$ is the water flow per unit width ($m^3/s$) (Hofierka & Knutová, 2015). Using this method, it is therefore possible that the SIMWE model can calculate the water depth at a given time for each cell.

For discharge, this is calculated using the second Saint Venant continuity equation:

*Equation 2:*

$$\boldsymbol{q}(\boldsymbol{r}, t) = \boldsymbol{v}(\boldsymbol{r}, t)h(\boldsymbol{r}, t)$$

where, $v(r,t)$ is the flow velocity in the given position ($r$) and time ($t$). This is influenced by the Manning's $n$ values and the slope directions (dx and dy) (Hofierka & Knutová, 2015).

In GRASS GIS, the r.sim.water function was utilised to run SIMWE. The model was set to predict the depth and discharge values for the entire Alna catchment after a 30-minute storm with a 20-year return period under RCP 8.5 climate conditions. The output rasters of depth and discharge were then exported to QGIS for further analysis, as this GIS software has a more user-friendly interface. In QGIS, the raster to vector function was utilised for both depth and discharge to create a point cloud of data. By using the 'heatmap' symbology in QGIS, this then displayed hotspot areas within the Alna catchment, these results will be displayed in Chapter 4. It was clear that there were hotspot areas in the north of the catchment, in the Grorud and Stovner districts of Oslo, respectively. Targeting the upstream areas for LID implementation is also useful, as their impacts here should have a greater impact on reducing the stormwater runoff for the Alna, hence protecting the downstream culverts. This is not just important for deciding where to apply LIDs, but also to identify areas where interim storage areas for stormwater, such as artificial wetlands, can be implemented. This would be useful for satisfying the second stage of the Municipality of Oslo's stormwater management plan. In the event of discovering high runoff areas, floodways could also be considered as a potential solution for mitigating stormwater under the third stage of the stormwater management plan.

When deriving the Grorud subcatchment, it was necessary to identify all subcatchments for the main Alna catchment. This was done by using a QGIS plugin from the IHE Delft, known as 'calculate catchment from points'. This specialist module requires a DEM, and a points shapefile that is created by the user (IHE Delft, 2021). The shapefile was made by placing points at the confluences of tributaries along the course of the Alna. The points were then "snapped" to the river course, for greater accuracy. The final step involved using the 'delineate all subcatchments in a catchment' function, and this provided an accurate overview of all subcatchments for the Alna. Grorud was chosen over Stovner because the Alna flows directly through Grorud, whereas Stovner only includes a tributary of the river (Tokkerudbekken). Time constraints had to also be considered, and it was deemed that one subcatchment that is analysed in more detail would be more beneficial for the stakeholders of the Alna catchment than two which may have been "under-analysed" due to the short amount of time for this project. It would be interesting for future research to consider the Stovner region as the next study area to be analysed. This would then mean that the entire north-east and north-west subcatchments of the Alna will have been modelled and could provide further upstream mitigation to protect stormwater infrastructure further downstream.

Once the subcatchment was decided, all of the raster inputs for SIMWE were clipped to the boundary of Grorud, so that this could become the next focal point for the analysis. The same storm event as before was used, and again the depth and discharge maps were exported from GRASS GIS into QGIS to be converted to point maps. Hotspot analysis was again undertaken to identify flooding risk areas by using the heatmap symbology. LIDs were then "placed" in hotspot areas. This was done by creating buffer zones around the combined sewers in the catchment (see Figure 10) as these follow roads. Due to this, it makes it easy to implement LIDs such as permeable pavements or swales next to roads. As stated before, it is vital to protect combined sewers from overflowing so that is the main reason why LIDs were applied in those areas. Later, green roofs were also added to the southern half of Grorud, as there was still a large percentage of the overall subcatchment that could still be converted to LID under the targets stated in Chapter 3.2.3. To test the effectiveness of these measures, the input raster layers for SIMWE had to be reclassified again using the r.recode feature. Since LIDs are assumed to have similar Manning's roughness coefficient and infiltration capacities as grassy areas, the LIDs were rasterized and added to this land cover class. Once this was done, the model was again run with the same storm events as before the installation of LIDs. The effect of LID implementation on the depth and discharge maps was calculated to find the differences between both maps. This was done subtracting the number of pixels assigned to post-LID depth and discharge measurements from that of the pre-LID raster maps. The results of this will be described in the next chapter.

# 4. Results

## 4.1. Pre-LID Implementation

### 4.1.1. Alna Depth

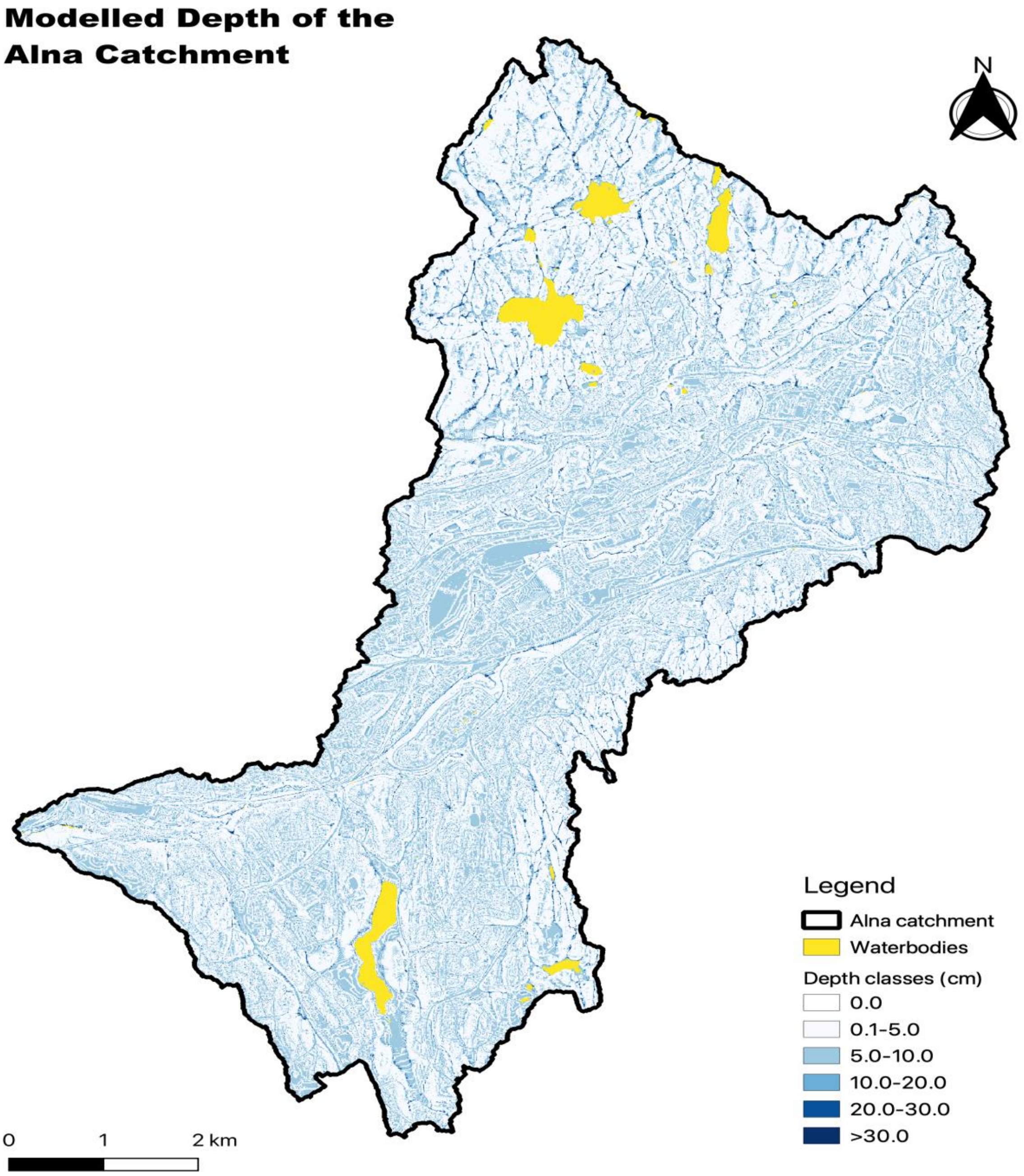


*Fig. 8: Results of the initial model run without LIDs for the whole Alna catchment, depth classes correspond to those outlined in Table 3.*

As shown in Figure 8, there is a wide-scale issue in water depth accumulation throughout the Alna catchment after the simulated 30-minute storm event of 66 mm/hr under RCP 8.5 climate scenarios. An initial warning is that this colour scheme does not follow the traffic light system for the depth classes as is shown in Table 3. That colour scheme was attempted to be used here, however the quality of the image produced by this was too low to be used as the final result. The lakes that are present in the catchment have been marked separately in yellow to improve clarity in analysing the results of urban surface accumulation. Doing this makes it clear that there are many areas that are inundated by at least 5-10 cm of water (Class 2), though this does not constitute as flooding. However, for Class 3 (10-20 cm depth), there are also widespread regions of concern. Even in this broad modelled area, impermeable areas such as roads are vulnerable to flooding. Since combined sewers follow many of these roads, the risk of CSOs is greatly increased as these pooled areas will only be drained by sewers due to the impermeable nature of roads and pavements. Also, important to note is that there are many industrial areas in the centre and north of the catchment that are also projected to be at risk from flooding. Hotspot analysis in Chapter 4.1.2. will further analyse these results and explain why Grorud was chosen as the subcatchment of interest.

### 4.1.2. Alna and Grorud Hotspot Analysis

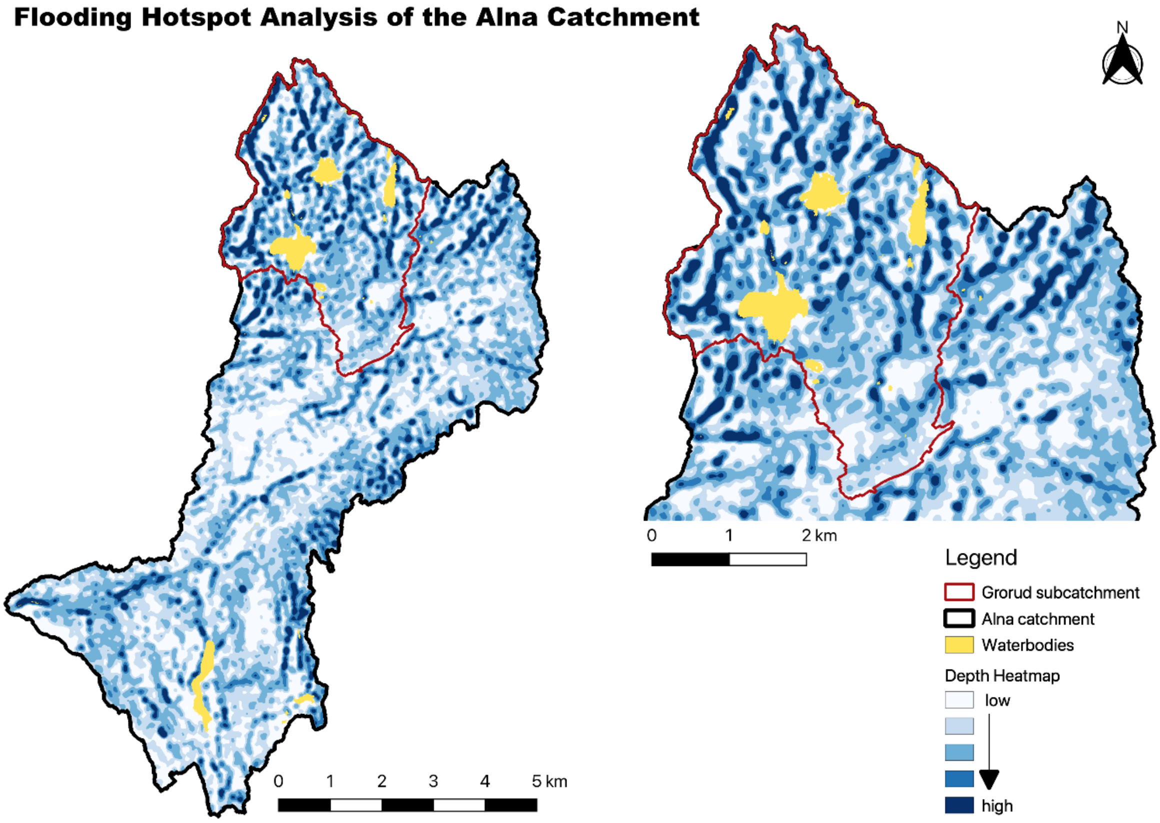


*Fig. 9: Hotspot analysis of water depth changes in the Alna (left) and Grorud (right) study areas after the simulated storm events.*

Shown in Figure 9 are the results of hotspot analysis showing water pooling in both study areas after the simulated storm. Whilst it is clear that there are plenty areas of concern across the whole Alna catchment, particular clusters of deep flooding depth pixels can be found in the Grorud subcatchment in the north-west. This is where the source of the Alna river is, and as mentioned before is an urbanised area with much of the river still flowing through culverts, and so is fed by stormwater runoff. To help make a positive impact throughout the rest of the catchment, it is important to focus on the upper reaches of a river so that less urban stormwater runoff and CSOs have a knock-on effect further downstream. In the case of the Alna, it is especially important to avoid repeated flooding events suffered in 2014 and 2015, and of course to protect the vulnerable Kværnerbyen culvert in the south of the Alna catchment. This hotspot analysis justifies the greater focus on Grorud as a subregion for LID implementation, as the urban and industrial nature of this district has a clear impact on water pooling during storm events. An additional note is that the Stovner district, in the north-east of the Alna catchment, is also predicted to be badly affected by the simulated storm event. As this also contains a tributary of the Alna, as well as important residential areas, Stovner would be a good case study for any future analysis of the Alna catchment.

### 4.1.3. Alna Discharge

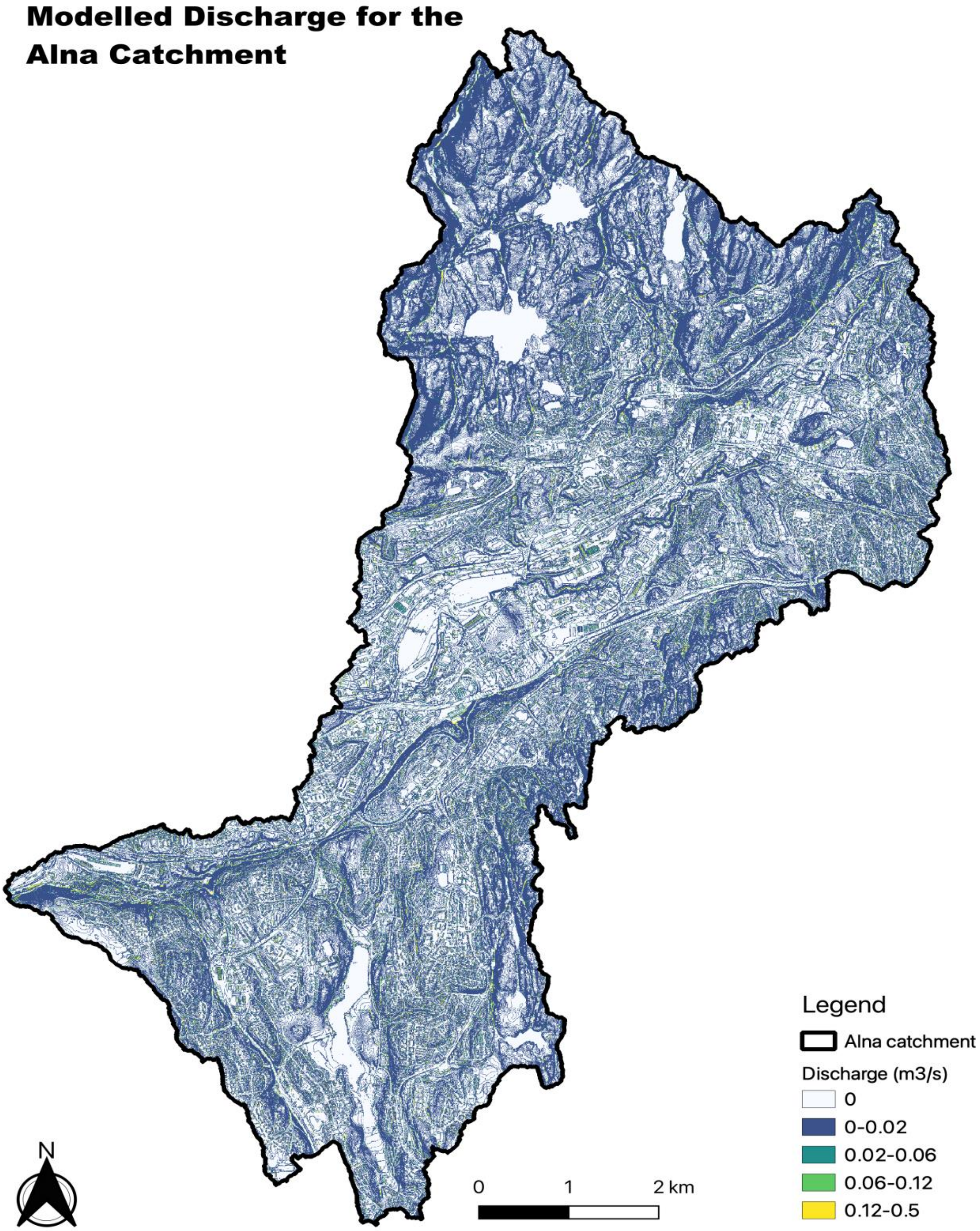


*Fig. 10: Discharge results for the entire Alna catchment before LID implementation*

Figure 10 shows how discharge was modelled across the entire Alna catchment after the simulated storm event. There are similarities to Figure 8 as where there are increases in discharges also results in an increase in depth. This result shows that the relationship between these two factors is co-dependent, increased discharge causes a faster movement of surface runoff across impermeable areas. Once these streams of water hit a barrier e.g., a building, then the water pools around these structures. What is also important to note is that the discharge is typically higher in areas of increased impermeability, as well as in areas that are considered hilly, which is to be expected. It is common knowledge that rain falling on impermeable areas will run faster due to both less infiltration occurring and also smoother surfaces being more prominent here. Hilly areas result in faster discharge values due to there being more extreme slope values present here. In the north of the Alna catchment, towards the Grorud subcatchment, there is also high levels of discharge shown. Therefore, these results underline the importance of implementing LIDs in the Grorud subcatchment, as reducing this will lower the risk of CSOs and urban flooding.

### 4.2. LID Implementation

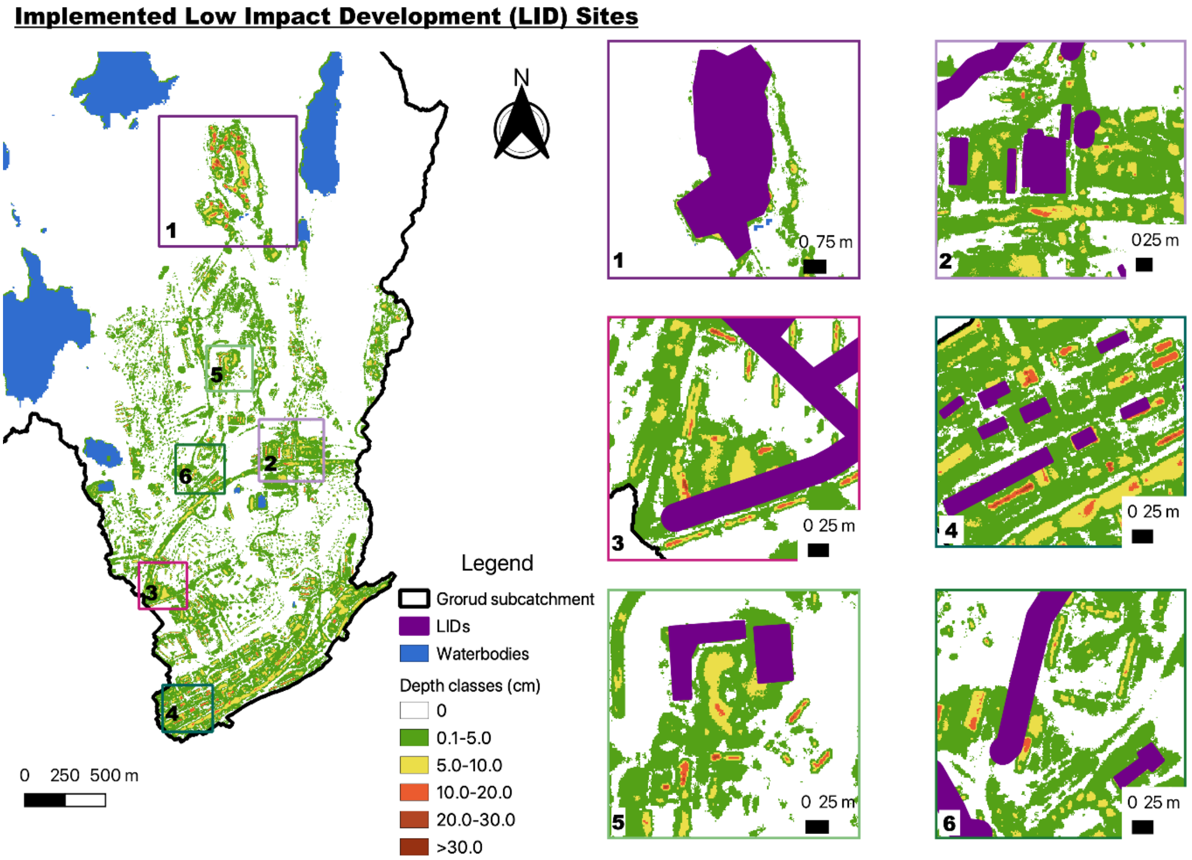


*Fig. 11: Examples of identified flood risk locations suitable for LID implementation, based on the first modelled depth results without LIDs. Displayed is a mix of generic LID measures (represented by purple lines), green roofs (shown by polygons) and the development of the Huken quarry (Site 1). Depth classes refer to those outlined in Table 3.*

Shown in Figure 11 are some specific target areas for LID implementation. These are just some example sites, as LID measures are actually more widespread in the final model (as shown in Figure 7). All LID locations were chosen based on either being under at least 20 cm depth of water or in close proximity to the combined sewers. For the generic measures that are near to the combined sewers, these would be interpreted as being swales (for wider areas), or other LIDs such as permeable pavement. Since the combined sewers are mainly following roads, these LIDs were placed by using a buffer in QGIS around the shapefile of combined sewers in Grorud. The buffer dedicates 10 m either side of the combined sewer (and therefore the roads) to LID measures. This is done to reduce the amount of stormwater runoff onto the roads, causing flooding here, and also to protect the drains leading to the combined sewers from overflowing. In the case of Huken quarry (Site 1), this was targeted as it is a planned conversion from impermeable to forest, with the reopening of the Aurevannsbekken tributary of the Alna. Therefore, it was deemed interesting to model the projected impacts of this plan. Green roofs are placed on buildings that are in areas currently at risk of flooding and of high levels of surface runoff. Many of these buildings are either residential or industrial, therefore it would be necessary for the city of Oslo to intervene and encourage the owners of these private properties to implement these measures. As stated in Chapter 2.3., these measures are simple to install, are relatively inexpensive, and aesthetically pleasing. Therefore, green roofs could be a simple but effective LID to employ.

### 4.2.1. Grorud Depth – Pre- and Post-LID Installation

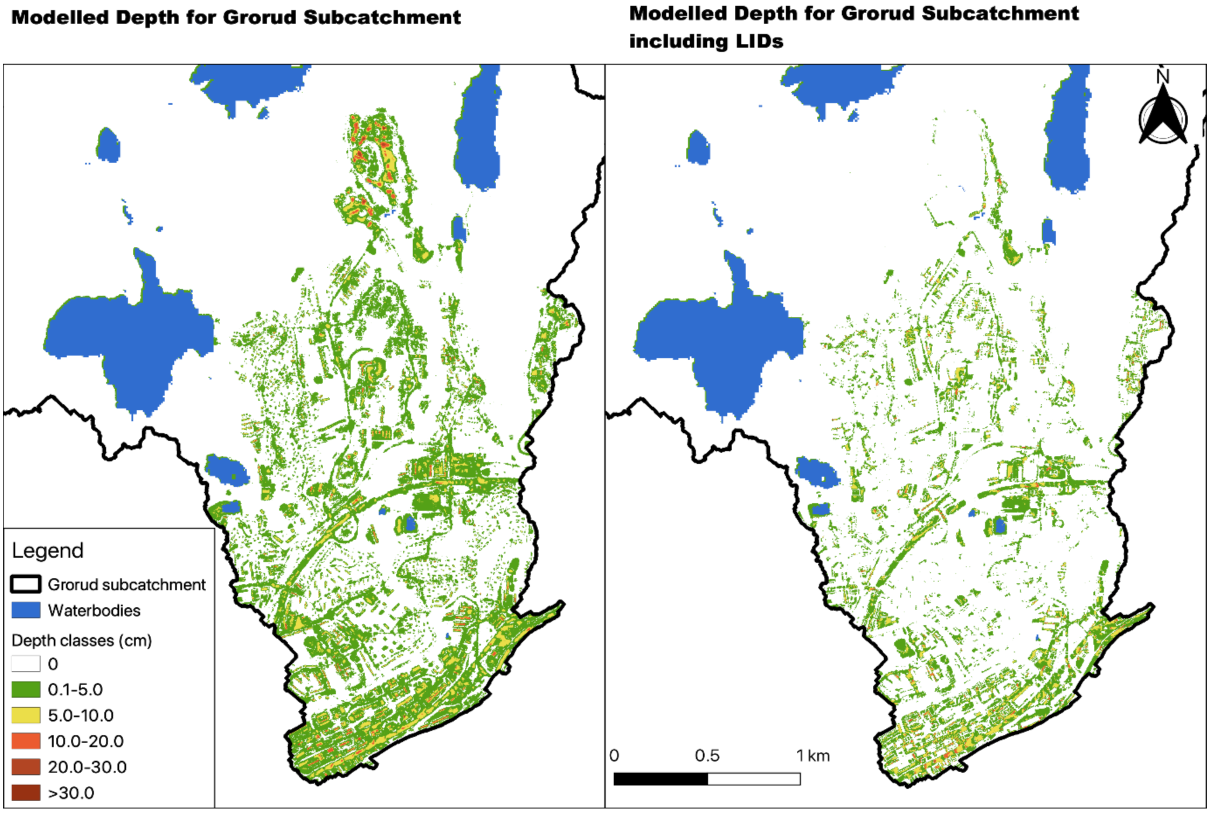


*Fig. 12: Comparison between the depth values for the urban region of Grorud subcatchment before (left) and after (right) LID implementation in 5% of the catchment area. Depth classes refer to those outlined in Table 3.*

Figure 12 shows the results of both modelling runs, before and after LID implementation. This model was run with a 30-minute storm event of 66 mm/hr under RCP 8.5 climate scenario. The first simulation shows that there is widespread pooling across the whole subcatchment, in particular at the Huken quarry and throughout the urban area of Grorud. Post-LID implementation shows some positive results. Compared to the initial model run, areas of pooling appear to be greatly reduced across the whole subcatchment. Previous sites of concern near combined sewers and on the roofs of buildings have had their water inundation depths reduced to almost 0 cm. In addition to this, the immediate vicinities of these measures show strong reductions in depth and discharge, as expected. Furthermore, the implementation of the Huken reconversion project suggests that this will be highly beneficial in reducing pooling in the northern part of the catchment. In the centre of Grorud, the Trondheimsveien road is shown clearly as a band of pooling across the middle of the urban area. This is one of the busiest roads in Norway (alongside the Østre Akervei) and so it is good to see that post-LID installation helps fragment and reduce the incidence of pooling on this road. In the southern half of Grorud, near the main industrial areas, there have been clear reductions of pooling. Many minor areas have been reduced from Class 3 (10-20 cm depth) to Class 2 (5-

10 cm depth), which is vital for protecting the combined sewer systems and to protect industries and roads (particularly the Østre Akervei) from becoming inundated. Below, the hotspot analysis in Figure 13 provides further details into the improvements in water depth reduction post-LID implementation.

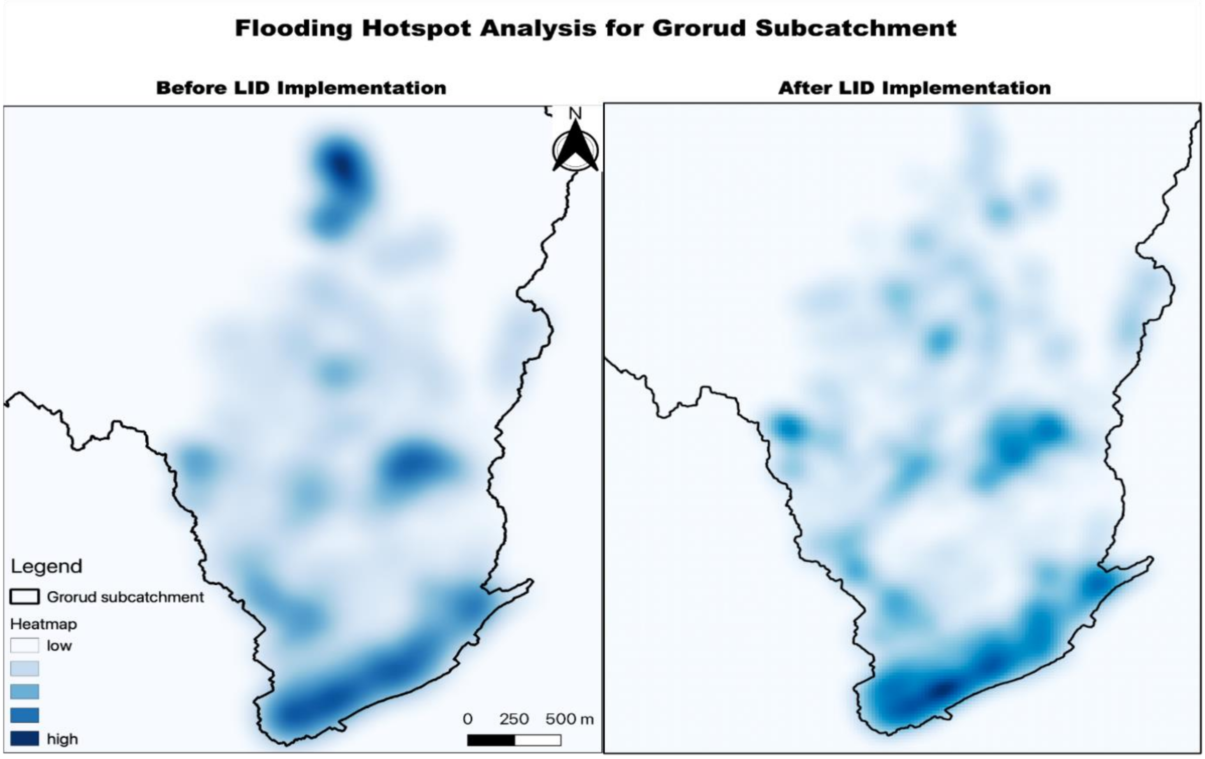


*Fig. 13: Hotspot analysis of the Grorud urban area pre- (left) and post-LID (right) installation.*

Further hotspot analysis, undertaken in the same way as in Chapter 4.1.2., demonstrates again the effectiveness of implementing LIDs in the Grorud subcatchment. Due to the nature of the hotspot symbology in QGIS, the blurred appearance does make it quite difficult to focus on more localised flooding hotspots, meaning that this type of analysis is more useful on the broader scale. What Figure 13 shows is that in the north of the subcatchment, where the Huken redevelopment project is, pooling is projected to be reduced once the quarry is converted to a more permeable surface. In the middle of the subcatchment, there has been a further reduction in hotspots, with a greater fragmentation of previously dark blue areas (high levels of pooling) to lighter blue regions. This represents still relatively high levels of pooling, however the reductions are clear enough to show a successful implementation. In the south of Grorud, particularly near the train station, there is also some reduction of pooling, but it is not as clear as in other areas. Here though runs the railway tracks, and also the Østre Akervei road. As these are two examples of highly important transport infrastructure, it is not possible to convert these areas to LID, which explains why flooding hotspots still remain. The green roofs close to the road have had a minor positive effect, but with further LID implementation next to the Østre Akervei (e.g. permeable pavements), it could be possible to protect this road from flooding, and hence the combined sewers from overflowing. Figure 14 below displays the quantifiable decreases in the percentage of pixels present across all depth classes. This alleviates any fears of weak LID performance, which could be assumed when only looking at the hotspot analysis.

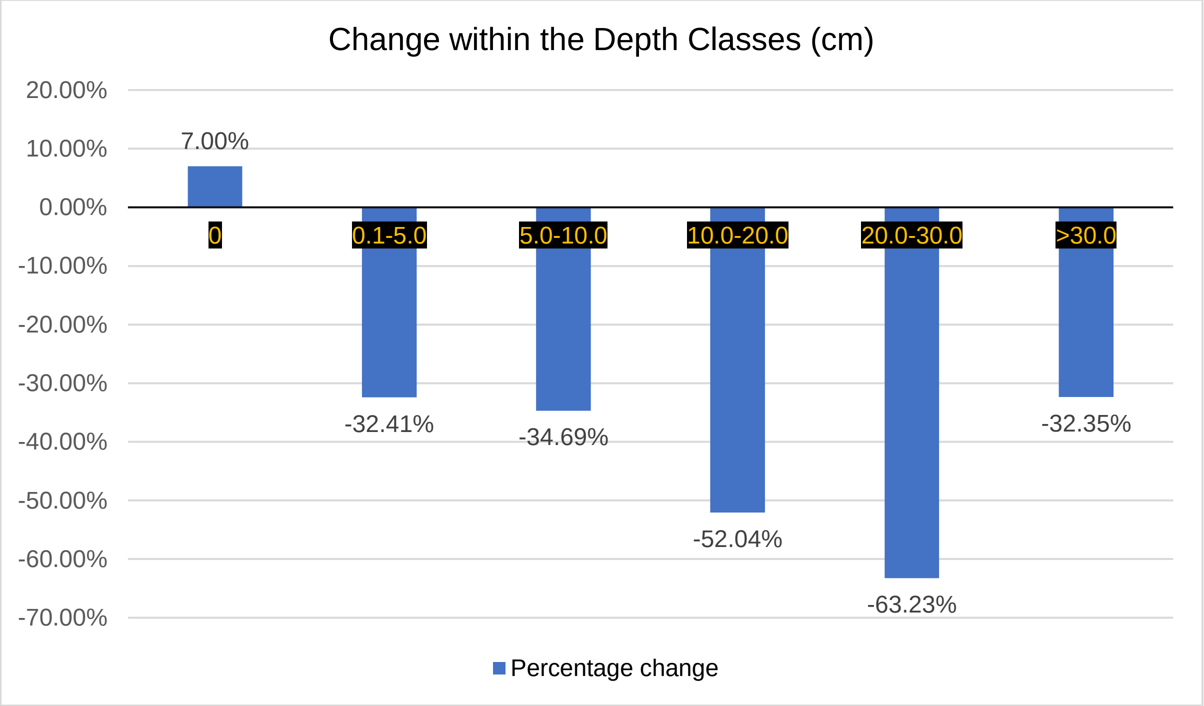


*Fig. 14: Graph showing the percentage change in depth classes (in cm) as a result of LID implementation.*

Figure 14 shows the impact that implementing LIDs has had on the number of pixels present in each depth class in the Grorud subcatchment. These results are positive as they show a decrease across all depth classes. All classes that contain pixels representing more than 10 cm of inundation (considered by the Municipality of Oslo to be urban flooding) were significantly reduced post-LID installation. Pixels symbolising depths between 10 and 20 cm were reduced by 52.04%, and the largest decrease of 63.23% came in Class 4, which corresponds to pixels with a range of 20-30 cm depth. There were also large decreases in pixels representing inundation of 0.1-5.0 cm and 5.0-10.0 cm of 32.41% and 34.69%, respectively. This therefore indicates that LIDs would result in an average reduction of 42.94% across all depth classes. For depth classes considered to represent urban flooding (>10 cm), there is an average decrease of 49.20% and hence considerably minimising urban flooding in Grorud under RCP 8.5 climate conditions and a 30-minute storm with a 20-year return period. These data are based on comparisons to the water depth values derived from Figure 10, which shows the comparison of pre- and post-LID implementation. This confirms that all depth classes in the pre-LID results have experienced substantial decreases in the percentage of individual pixels present in each class after running the model with LIDs installed. The exception to this is the class representing 0 cm inundation. There was a 7% gain in this class, which could be considered to be a small increase in relation to the larger decreases amongst other classes. However, since the number of pixels representing 0 cm depth was by far the largest class, the percentage increase is therefore expected to be small.

### 4.2.2. Grorud Discharge: Pre- and Post-LID Installation

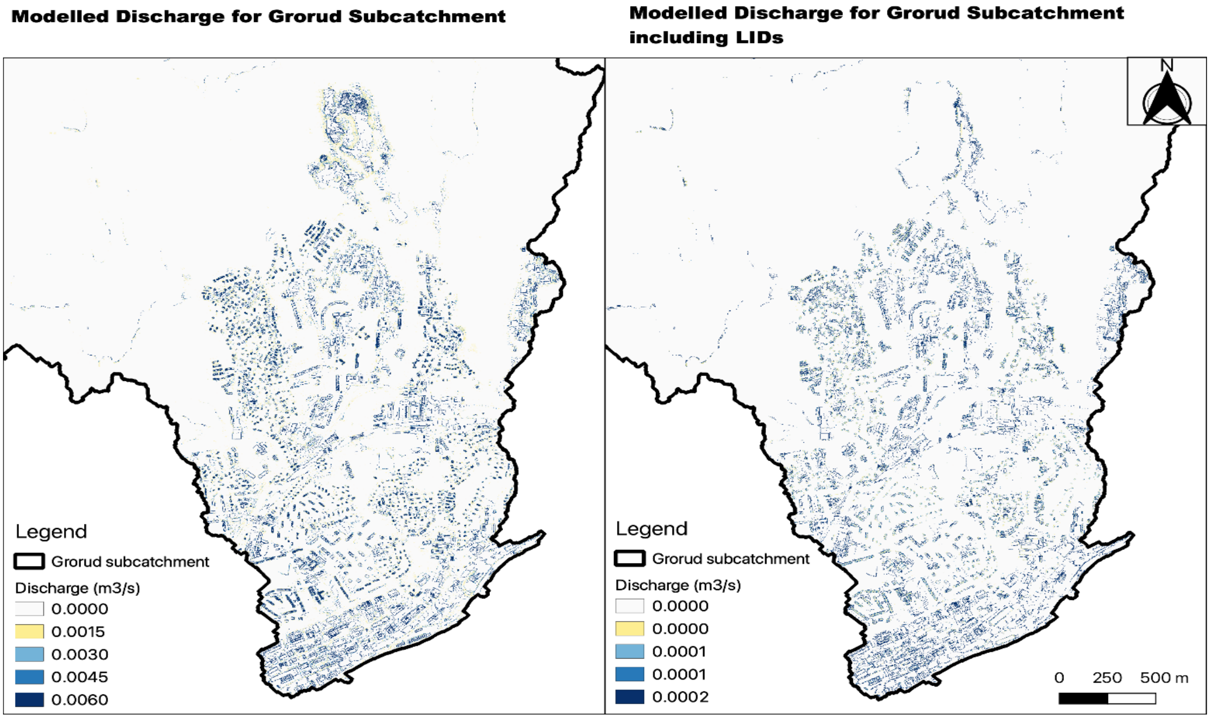


*Fig. 15: Comparison between the discharge values with focus on the urban areas of the Grorud subcatchment before (left) and after (right) LID implementation in 5% of the catchment area.*

As shown in Figure 15, there has again been success in reducing discharge after the implementation of LID measures. After the initial simulation, there are clear regions of higher than desired discharge associated with impermeable areas. Roads and roofs are particularly affected, which is mainly due to their impermeability as well as their slope angles encouraging the movement of water away from them. This also resulted in greater pooling which is shown in the depth results map in Figure 12. After LID application, the reduction of discharge is clear to see across Grorud. At the Huken site in the north, there is a stark slowing down of surface water flow, and as a result surrounding areas are also affected less severely. The same can be said for the southern half of the catchment area in the industrial region. Here, green roofs and LID measures such as swales and permeable pavements are predicted to decrease runoff substantially. Pre-LID installation, the minimum non-zero discharge measured was 0.0015 $m^3/s$, whereas the post-LID results show that the maximum discharge values are 0.002 $m^3/s$.

As a result, less runoff is detected across the entire catchment, and therefore also at the subcatchment outlet. This large reduction also affected how the legends could be displayed in Figure 15, the values were so different that they could not be compared using the same classification system that is shown in the pre-LID results. Further discussions into the meaning of these results, and how they fit into the contemporary debates surrounding this research will continue in the next chapter.

## 5. Discussion

This chapter will discuss the results from the previous section and delve further into what the results show in relation to the aims and objectives, and why these data have presented themselves in this way. Each subsection will be broken down in order to answer the research questions presented in Chapter 1.2. The impact of LIDs on the depth and discharge values for Grorud will be discussed, before moving on to comparing these results with other case studies. This chapter then concludes with an evaluation of all methods, with an input of thoughts about the limitations of the study itself.

### 5.1. Spatial variabilities of flooding hotspots in the Alna catchment

For the first sub-research question “What are the spatial variabilities in flooding hotspots in the Alna catchment?”, SIMWE was run for a 20-year flood event to predict where these hotspots would occur. As shown in Figure 8, the analysis brought up some interesting results. Throughout the entire Alna catchment, there were many flooding hotspots predicted, particularly in areas of heavy, impermeable land cover. This is to be expected, as catchments with only small amounts of green space inevitably suffer stormwater flooding impacts (Zhou et al., 2014). To reduce knock-on effects at the southern part of the Alna catchment (where the Kværnerbyen culvert is located), it was decided to mitigate the flooding hotspots identified in the northern areas in the Grorud district of Oslo. In the north-east of the Alna catchment, which is in the Stovner district of Oslo, there are also flooding hotspots predicted. This area was also considered for further study, however time constraints meant that Grorud was chosen for further study. Stovner does not contain the Alna itself, but a tributary (Tokkerudbekken) that is also covered near the confluence with the Alna and is also fed by stormwater drains (Pedersen and Bendiksen, 2005). There are further areas in the middle of the Alna catchment that are also predicted to be vulnerable to urban flooding. These include the Alna train station, in the Alnabru district, which is predicted to suffer flooding of 10-20 cm under the simulated storm conditions. The effect of this also influenced the hotspot analysis map and suggested that this region would be suitable for LID implementation. However, it is not possible to convert railway tracks to LIDs so this region was discarded in favour of the Grorud catchment. Furthermore, there were fewer combined sewage systems in this area, and fewer outlet points to the Alna, so LID implementation here would not be as important as in Grorud. According to the results shown in Figures 8 and 10, most of the Alna catchment and the depth and discharges pointing towards large-scale urban flooding under RCP 8.5 climate scenarios. Much of the catchment is predicted to be inundated with at least 10 cm of water, with some areas covered by more than 20 cm water.

The first hotspot analysis for the Alna catchment in Figure 9 confirms these risk areas, particularly in Grorud in the north-west of the catchment. Further to this, the discharge values across the impervious areas of Alna catchment (shown in Figure 10) are also quite high, with many pixels predicting values of between 0.0891 and 0.1188 $m^3/s$, which is somewhat fast for urban surface runoff. The combination of high pooling and fast discharge means that there is therefore a predicted risk that this region of Oslo could be under threat from severe urban flooding under future climate conditions. Key industrial areas are at particular risk, since these areas are impermeable it is highly probable that damage and disruption to economic activities will occur under the simulated storm scenarios. The Grorud subcatchment is a prime example of this, and so measures must be taken to mitigate these risks. With increased urban flooding comes increased surface runoff into the Alna river, and so as a result there is an elevated threat of exacerbated levels of pollutants entering the Alna that may be washed away from industrial areas. This is a common problem in urban areas, as the higher percentage of urban areas causes an increase in hydrological response, and therefore more pollutants transported with runoff (Dittmer et al., 2020). Further to this, the vast network of combined sewer systems in the Alna catchment (and Grorud in particular) is also at risk from combined sewer overflows during these flood events.

These results predicting increased depth and discharge of urban stormwater backs up the concerns of the Municipality of Oslo, who identified CSOs as a major threat to the health of the Alna (Municipality of Oslo, 2016). This has happened before in other places, as the study of Nie et al. (2009) found that increased urban runoff is likely to result in increased incidence of CSO events, ranging from 36% to exponential growth, depending on how much precipitation increases by over time (Nie et al., 2009). There are other studies that show the link between increased precipitation and greater incidence of CSOs. In the Shingashi region of Tokyo, the sewage system is served completely by combined sewers. Research from Yu et al. (2013) found that extreme rainfall events resulted in the increased risk of CSO incidents occurring (Yu et al., 2013). This is concerning for Oslo, as the current sewage and culvert systems for the Alna and its catchment are already suffering from CSO events under current precipitation events. In 2014 and 2015, the combined sewers and culvert systems of the Alna were overwhelmed, particularly at Kværnerbyen near the mouth of the Alna which suffered extensive damage as a result of both events (VAV, 2016). Though the Municipality of Oslo is intending on a large programme of reopening previously covered up rivers (VAV, 2016), this will take a long time and therefore it is important to mitigate CSOs in the short to medium term, so that further damage to the culverts does not happen. The results from the Grorud subcatchment study provide a promising outlook for the usage of LIDs that will allow this objective to be achieved.

### 5.2. Impact of LIDs on the Grorud subcatchment

In answering the main research question “What is the impact of implementing LIDs on reducing urban flooding in the Alna catchment?”, the SIMWE model was run under the same storm conditions as the initial model for identifying hotspots in the Grorud subcatchment. However, this time LID measures were included as part of the infiltration rate and Manning’s roughness coefficient components of the model. To be as realistic as possible in analysing the effects of LIDs on depth and discharge (and hence reducing CSO risks), only 5% of the Grorud subcatchment was targeted for conversion from impermeable surface to LID. This is half of the 10% maximum allowed under current government policy. As shown in Figure 10, there are clear indications that utilising LIDs in this region could be beneficial for Oslo. These LIDs have reduced the overall depth and discharges across most of the study sub-region, which is to be expected, as this is their intended impact. The results in Figures 12 and 15 confirm what other studies have shown, and that is a 5% conversion of impervious surface area to LID is enough to notice a distinct improvement in the depth and discharge of urban surface flooding (Palla and Gnecco, 2015). What is even more interesting is looking closer at the immediate vicinities of each LID measure. Buffer zones were created around combined sewer pipes and converted to LID. As these pipes also coincided with where roads are also located, it can be assumed that swales or permeable pavements either side of these roads could be the choice of LID in these cases. Here, the impact of LIDs was clear. There were reductions in pooling and discharge, of the immediate vicinity of the LID (see Figure 15), which is to be expected (Martin-Mikle et al., 2015).

The pre- and post-LID hotspot analyses for Grorud in Figure 13 indicate further that there was a reduction of pooling across most of the subcatchment, particularly where the Huken quarry redevelopment is taking place. However, for the rest of Grorud there appears to be very little difference in pre- and post-LID installation. This could be due to the clustering caused by the applying the heatmap symbology in QGIS, where values of relatively similar number may not be easily differentiated at a fine spatial scale. With the Østre Akervei road running through this area (this road is without LID conversions), it could therefore be also interpreted that this has influenced the hotspot analysis to focus more on this impermeable surface. There could be a perception of weak LID performance in this study can be shown in the heatmap in Figure (13).

In the southern part of Grorud near the station shows that green roofs had little impact in reducing pooling here. Østre Akervei obviously cannot be converted due to its importance as a major road. Therefore, hotspot analysis is much more useful at a broader catchment scale, as opposed to a localised one. In Figure 14, the quantifiable demonstration of the reduction in flooding across all depth classes is much clearer. The graph shows that there is an average reduction of pixels representing these classes of approximately 42.94%, suggesting that LIDs will reduce pooling across Grorud by this amount. For the depth classes representing flooding (>10 cm), this is even higher, with an average reduction of 49.20% across all of these classes. Even more impressive is that, in some places of the study area, the model predicted complete absorption of stormwater. This answers the second sub-research question: "How does the implementation of LIDs change water depth and discharge?". Such large reductions in pooling and discharge are to be expected when LIDs are correctly placed. Other studies have all found that using LID techniques can reduce the incidence of flooding in localised areas by up to 50%, particularly in the case of green roofs (Berghage et al., 2009; Jackisch and Weiler, 2015). For reductions of this scale to occur across an entire subcatchment is rare, and so some of the results of this study could be considered to be overexaggerated. As this study is the first of this type to use the SIMWE model for assessing LIDs for mitigating urban surface flooding, it is therefore difficult to compare these results with other studies.

Zero runoff and pooling are of course unrealistic, and is a sign of model limitations, which will be further described in Chapter 5.3. However, the general effectiveness of these LID types (swales and permeable pavements) is quite well-researched, so are still viable options for Oslo to consider. Permeable pavements have been considered as LID measures in California. Multiple studies there have determined that if these are implemented correctly, then there is a possibility that all pavement stormwater runoff could be captured without surface ponding or overflow (Li et al., 2013). The results of this study are therefore corroborated by this previous research, and whilst idealistic to suggest that permeable pavements will eliminate all ponding, it is safe to assume that effective reduction in surface runoff will occur if implemented correctly. This would then mean a reduction in the risk of CSOs, as much of the ponding that would normally occur around combined sewers would be mitigated against significantly. There is of course the counter to this, as there are doubts as to the extent that permeable pavements can handle storm-level rates of precipitation. Research in the Netherlands found that only 4 out of 16 newly installed permeable pavements met the minimum infiltration capacity standard of 194 mm/hr, and so would become oversaturated sooner than expected (Boogaard and Lucke, 2019). Though this is considerably higher precipitation rates than used in this study (66 mm/hr), it does demonstrate the importance in ensuring that permeable pavements chosen in Oslo would need to be tested thoroughly before implementation. The application of green roofs is also part of the successful results generated by the SIMWE model. Theoretically, these grass surfaces on the tops of buildings should slow down or stop stormwater runoff completely. The results of this study show that ponding on tops of buildings will be decreased by the use of green roofs, as well as the runoff. However, there are still incidents of pooling and surface runoff in the immediate vicinities of these green roofs, but this is negligible compared to the results without LID measures. This is expected as studies have shown that green roofs are not 100% successful at capturing rainwater. Rather, they have instead been shown to be approximately 50% effective (Berghage et al., 2009). This means that runoff is still reduced, and therefore peak flows across the whole catchment are also slowed down.

LIDs in general have associated issues with 50% or less effectiveness. They mostly succeed in the initial stage of a storm in dampening the peak runoff rates that would otherwise result in flash flooding, which is obviously a positive feature (Skagen et al., 2020). However, a common problem is that when modelling these LIDs, it is under the conditions of one storm under certain conditions. The effectiveness of LIDs reduces greatly when faced with an immediate successive storm. For many, the infiltration capacity is not strong enough to cope with this second event and so become oversaturated (Skagen et al., 2020). This would then result in runoff occurring, and under severe conditions may result in the overwhelming of a combined sewer system, just later than if there were no LIDs in place. Another important factor to consider is the effect that converting the Huken quarry into green space. As this project is already underway, these results should also provide some encouragement to decision makers and stakeholders in this part of the Alna catchment. This follows the example of many other cities in converting former brownfield sites into green space. In Berlin, the former Tempelhof Airport and former railway yard "Gleisdreieck" are both successful examples of a city government interacting with local people to provide recreational areas that benefit both humans and nature (Kabisch, 2019). In London, the Barking Riverside brownfield was redeveloped with the intention of improving habitat function and also providing extra space for stormwater storage (Connop et al., 2016). As shown from the results of this study, the Huken reconversion should aid in the collection of surface stormwater, and so these other examples back up the results of this study.

Finally, the most important aspect of these results is that they would satisfy the Municipality of Oslo's goals at reducing the rate of urban flooding and protect the Alna from further pollution caused by CSOs (Municipality of Oslo, 2016). These results are in line with the aforementioned study from Martin-Mikle et al., 2015. Simulated prioritised LID placing at impermeable flooding hotspots is predicted to result in large reductions of both ponding and surface runoff. Also, based on Martin-Mikle et al., 2015, reducing surface runoff in urban areas should lead to less sediment and nutrient loading into the Alna during storm events. The reduced runoff and pooling should provide better protection against the occurrence of CSOs, again resulting in less nutrient loading from the many combined sewer systems present in Grorud. This study has shown that with the careful installation of LID techniques, it is possible to make significant reductions in pooling and discharge compared to the current grey infrastructure that is present in Grorud. This backs up the results of other studies, where even under unfavourable conditions, LIDs placed directly at a flooding hotspot site is a suitable alternative to conventional stormwater management methods (Jackisch and Weiler, 2015). The study of Jackish and Weiler identified areas of weakness for LIDs, and what should be considered for future LID installation. Weak performance for LIDs generally related to underground storage, antecedent conditions, storm characteristics and seasonal freezing periods (Jacksich and Weiler, 2017). This could be an issue for Oslo to deal with, as annual freezing that occurs could pose a threat to LIDs if they are not chosen and maintained correctly. Finally, prioritised LID implementation should also hopefully reduce the damage to the culverts further downstream, which has occurred under smaller precipitation events to the one simulated in this study. The reduction in surface discharge across Grorud leads to less runoff entering the Alna in the upper courses. This would hopefully reduce the overall discharge of the Alna itself, and this theoretically lowers the threat of the Alna damaging the vulnerable culverts, such as the previously damaged one at Kværnerbyen.

### 5.3. Limitations of this study

Whilst this research has generated some very interesting findings into the impact of LID measures on the pooling and discharge of urban stormwater in the Grorud subcatchment of the Alna river, there are of course limitations to consider when determining the overall value of this study. The DEM is a potential source of errors and reduction in the quality of the overall results. Firstly, as the data for this is derived from a digital surface model (DSM), the DEM neglects any subsurface features, not just tunnels but, importantly in this study, pipes such as sewer networks and culverts. As much of the Alna river runs underground through these culverts, the actual impact of surface runoff on the discharge of the river cannot be quantified using only the DEM. As the DEM is the basis of SIMWE model, this is therefore a limitation of the model as a whole. To try and solve this issue, it would be interesting for further simulations to be run, but instead using a different hydrological model which is able to account for these issues such as the well-known Storm Water Management Model (SWMM). This model is able to evaluate grey stormwater infrastructure such as pipes, combined and sanitary sewers, and also storm drains (EPA, n.d.). The greater complexity of this model was one of the main reasons that it was not used in this study, as well as the fact that this study was building upon previous work using the SIMWE model in Oslo.

A further issue with the SIMWE model is, that whilst the DEM was set at a 1 m spatial resolution, to run the model efficiently this had to be reduced to 2 m spatial resolution. This was because at such a fine spatial resolution, running the model caused some technical difficulties. In fact, decreasing the resolution of the DEM from 1 m to 2 m reduced the processing time when running SIMWE by half, from 2 hours to 1, when running the larger Alna catchment. This also allowed the DEM to match the resolution of the land cover-derived features such as the infiltration rate and Manning's roughness coefficient rasters. Overall, there was a reduction in the capacity for the SIMWE model to operate at the finest possible spatial resolution, both through the DEM issues but also the technical capacity of the model does not allow 0.5 m spatial resolution simulations to be run.

Another limitation in SIMWE comes from the fact that soil saturation is not considered in the model. Due to the lack of quantitative data from the Norwegian databases, infiltration rate and Manning's roughness coefficient values have been assumed based on previous studies. The same is also true for the LID infiltration capacity and Manning's roughness values. These limitations reduce the overall quality of the results of this study. As a result, infiltration rate is deemed to be uniform throughout the entire model simulation, whereas in reality soil could be saturated earlier than expected (Li et al., 2020). This is a very important limitation to consider, as over time the infiltration capacity gradually (or suddenly, depending on the land cover), resulting in dynamic rates of saturation over the modelled area. Like much of southern Norway, in Oslo the ground remains frozen for much of the autumn and winter, and due to this across there are large annual variations in the infiltration capacity of some land cover types (Kværnø and Øygarden, 2006). Many soils undergo several freezing and thawing processes, and thus there is a wide variation of infiltration capabilities which can result in the erosion of some soils due to overland flooding (Lundberg et al., 2016). To further compound this issue, rain is the predominant precipitation in Oslo during this time, and so the risk of surface flooding is even greater during this time.

A final limitation is that the actual waterbodies, particularly the Alna, are not accounted for. Therefore, it is not possible to see the impact of LIDs on the discharge of the River Alna itself. This would be difficult for most hydrological models though, as much of the Alna is still covered up and so is not present on land cover maps, and this also impacts any models which require a DEM of the study region. However, despite these limitations, SIMWE remains suitable for designing storm events of extreme precipitation. In this situation, one would then assume that soils and sewage systems were already saturated (Li et al., 2020).

### 5.4. Considerations for future research

It is important to remember that this research is one of the first of its kind for using the SIMWE model, and also in researching the impact of LIDs on the Grorud region of Oslo. Therefore, moving forward it would be important to perform more in-depth analyses of both the Alna catchment and Grorud district. One way to do this is to run the SIMWE model for longer storm events, such as a one-hour event rather than for just 30 minutes. As mentioned in Chapter 5.3., personal technical limitations in laptop capacity played a big part in reducing the ability to run longer storms due to increased data processing times. This storm was also one with a return period of 20 years, it would be beneficial for future studies to also consider storm events with 50 and perhaps even 100-year return periods. As storms are predicted to become more erratic in Oslo, it is therefore important that a wider variety of storm events are modelled so that more risk areas can be identified. Future research in the same study area could also benefit from further increasing the percentage area of converted impervious area to LID measures. In this study, 5% was achieved, which is the minimum required to achieve noticeable hydrological benefits. However, it would be interesting to see how much more of a difference could be made by doubling the percentage of converted areas to 10% (the maximum value set out by the Municipality of Oslo). This comparison would then open discussions as to the cost versus benefits of converting 5% or 10% of the Grorud subcatchment, or if a middle ground scenario would be the optimal solution.

Furthermore, other regions of the Oslo urban districts could also be modelled, particularly those that contain more residential areas. Since many of these areas have not been targeted before (with the exception of Grefsen), it would be beneficial to model the risk posed to homeowners so that LID measures can be offered to these people. The aforementioned Stovner district is one such possibility. This research identified this area as containing a lot of predicted flood risk areas, however time constraints left this subcatchment out of the final study. Finally, it would be useful to perform analyses comparing different LID measures against each other, as well as modelling what occurs when these LIDs are placed in different areas to what was done in this research. This would involve implementing different LIDs in the same regions and determine their effectiveness in stormwater runoff mitigation using SIMWE. LIDs that perform well in this modelling would then undergo a cost-benefit analysis to deduce what measures would be finally used in the catchment.

## 6. Conclusions

To conclude, this study has shown that the implementation of LIDs would be an effective method of mitigating CSOs and other flood-associated risks in the urban region of Grorud. By converting 5% of the subcatchment impervious surfaces to LID measures, this study has shown that during a 30-minute storm under RCP 8.5 conditions with a 20-year return period should reduce flooding of more than 10 cm depth by an average of 49.20%, and an average of 42.94% across all defined depth classes. This answers the main research question of what the impact is of implementing LIDs on reducing urban flooding in the Alna catchment. Though Grorud is a small subcatchment, the promising results from this study could be extended to the rest of the larger catchment. By reducing the discharge and depth of urban stormwater runoff, one could expect a reduction in the pollution and discharge of the Alna during ever increasingly erratic storm events in Oslo. Of course, it is important to consider the limitations of this study. For one, these are basic predictions using a 2D overland flow hydrological model. Another limitation is the lack of quantifiable infiltration rate and Manning's roughness coefficient values for Oslo. Therefore, it would be advisable for the Municipality of Oslo to fund research to be able to give other researchers more accurate data that would improve the reliability of SIMWE. However, the effectiveness of this model in other studies dictates that SIMWE should also be used as a simple, effective tool for urban flood risk modelling. As it easier and faster building requirements, and with faster running times compared to the more popular SWMM and MIKE Series models, SIMWE is potentially a better way for governments to run localised analyses for districts of concern in any settlement. Though it would be advisable to at first run these more complex models alongside SIMWE to confirm its effectiveness. To conclude, these encouraging LID results should be considered for further research. As previous studies have shown, LIDs can produce ecologically beneficial, cost-effective solutions to flooding problems, even in complex urban settlements. If used appropriately, these measures could provide a greener, aesthetically pleasing way of mitigating some of the biggest threats to Oslo.

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