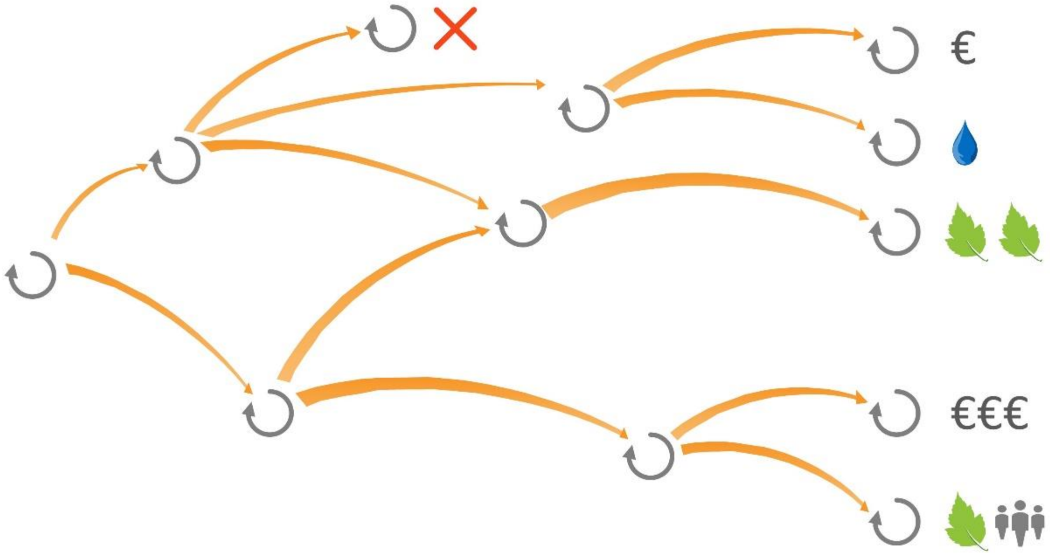
Opportunities to make Grefsen stormwater proof: developing adaptation pathways for the Grefsen district in Oslo, Norway



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Opportunities to make Grefsen stormwater proof: developing adaptation pathways for the Grefsen district in Oslo, Norway

A research thesis established for a MSc thesis at the Water Systems and Global Change Group of Wageningen University and Research

Illustration on front page inspired by Wise et al., (2014)

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ABSTRACT

While municipal ambitions in the field of urban water management are increasing, the pressure on the water system gradually grows due to climate change. Conventional strategies for adapting long-lived water infrastructure to climate change are often based on a ‘predict then build’ principle. Flexible strategies, on the other hand, are implemented in a step-by-step manner based on how the future unfolds. Therefore, they have a smaller risk of under- or over dimensioning of water infrastructure. This research uses a flexible approach, and creates adaptation pathways to make Grefsen – a district in the city of Oslo – stormwater proof until the end of this century. Special emphasis was placed on exploring strategies that use nature-based stormwater solutions. Results show that there are ample possibilities to reduce Grefsen’s water surplus on a large scale through nature-based stormwater solutions such as Low Impact Developments (LIDs) and wadis. However, some parts of Grefsen do not offer space to effectively deal with the water surplus with nature-based solutions, and therefore still require to be implemented in combination with technocratic measures such as underground storage facilities.

Further findings of this research show that, although authorities are committed to make Grefsen stormwater proof, the exact definition of stormwater proof is still lacking. This research explores 2 possible definitions and shows that the definition of stormwater proof has a substantial impact on what measures and pathways are required for a storm water proof Grefsen. The research also shows that Grefsen does not currently meet any of the possible definitions of stormwater proof and that a large storage deficit already exists today.

ACKNOWLEDGEMENTS

This research was written in the context of a thesis at the Water Systems and Global Change chair group as part of the Master International Land and Water Management at the University of Wageningen. For this thesis I went to Norway for three months where I was part of the New Water Ways (NWW) project team at the Norwegian Institute for Water Research's water and society department. The NWW project is established to explore innovative storm water solutions that go beyond conventional water management practices. In this way, a contribution is made to make Norwegian cities leading in sustainable urban water management by focusing on liveable, green and climate-proof stormwater solutions.

I felt right at home in Oslo and I really enjoyed the friendly colleagues, nice lunches and sporty ping pong matches. I would like to thank the people of the NWW project team and the people of the Water and Society department for both helping me with my thesis and for making my Norway adventure a very nice experience.

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CONTENT

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ABBREVIATIONS

ATP	Adaptation Turning Point
BGI	Blue Green Infrastructure
CSO	Combined Sewage Overflow
GHG	Greenhouse gasses
GIS	Geographic Information System
IDF	Intensity Duration Frequency
IPCC	Intergovernmental Panel on Climate Change
LID	Low Impact Development
M5 – M20	Precipitation events with a 5- and 20-year return interval, respectively
NWW	New Water Ways
RCP	Representative Concentration Pathway
SRES	Special Report on Emission Scenarios
SUD	Sustainable Urban Drainage
SWMM	Storm Water Management Model

CHAPTER 1. INTRODUCTION

According to the United Nations, 55% of the world's population lives in cities and an estimated 68% will be by 2050 (United Nations, 2018). This makes water management in cities a focal point of attention. The urban environment imposes great pressure on the water system. Urban water systems especially have difficulties coping with intense precipitation events. Generally, the majority of city area is paved which increases direct runoff, while discharging or storing runoff water is restricted by limited space in urban areas (Hollis, 1988; Chocat et al., 2007). Consequently, daily life is disrupted, water on the streets causes widespread damage and often sewers overflow in surface water, imposing high environmental costs (Finnemore et al., 1982; Price & Vojinovic, 2008; Tingsanchali, 2012). Mitigating these problems ask for the use of – often long lived – water infrastructure. Planning such infrastructural assets on the long term is done under the uncertainty of changing socio-political and climatic circumstances, which impedes robust decision making. One way of dealing with these uncertainties is to use a flexible planning approach (Haasnoot et al., 2013). This research uses such an approach, i.e. adaptation pathways, to explore possibilities to make Grefsen stormwater proof until the end of the century.

1.1 STORMWATER RELATED ISSUES IN GREFSEN

This research focusses on an urban catchment near the Akerselva river which covers most of Grefsen, a peri-urban area in the Norwegian capital of Oslo. The area covers approximately 1,33 km^2. The catchment boundaries that are used in this research are presented in Figure 1. Runoff water is discharged by a – mostly combined – sewer system that, when its maximum capacity is surpassed, can overflow into the Akerselva river.

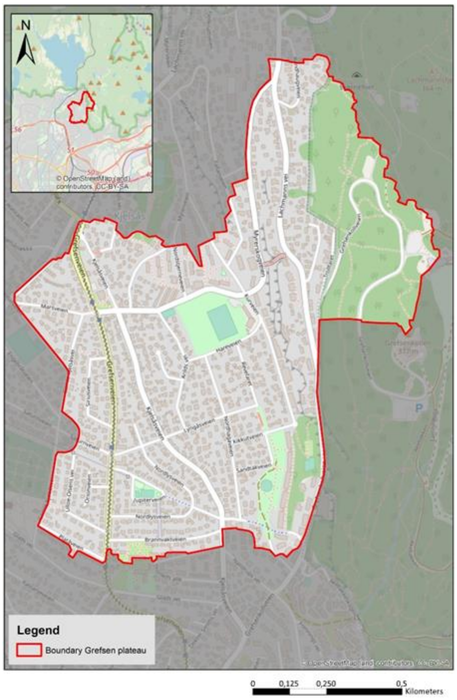


Figure 1. The catchment boundaries of the study area. In this research referred to as 'Grefsen'.

The municipality of Oslo currently indicate combined sewage overflows (CSOs) are the main stormwater related problem in Grefsen (Oslo Komunne, n.d. a). CSOs negatively affect the social and natural environment in multiple ways. To start with, they form a threat to the biological and chemical water quality. Sewage water generally contains high concentrations of nutrients that exacerbate eutrophication in the waterbodies it ends up in (Waaien et al., 2014). Moreover, the decomposition of organic matter from sewers in surface water is known to reduce the amount of dissolved oxygen (Hvitved-Jacobsen, 1982), sometimes resulting in the mortality of aquatic fauna (Mallin et al., 2007). Another problem is that CSOs introduce pathogens into surface water, which forms a risk for users of the water from the Akerselva and the downstream Oslo fjord (Arnone & Walling, 2006). Additionally, any other pollutant that can be found in sewage water can end up in the surface water. The Akerselva does not have enough resilience to deal with such pressures, as it currently has a poor ecological quality ratio, and thus fails to meet the European Water Framework Directive requirements (Oslo Kommune, 2017). Finally, CSOs for a threat to user interests. Intense precipitation events of short duration are mostly responsible for CSOs (Nilsen et al., 2011; Montalto et al., 2007). In Oslo, these events generally take place in summer when recreation is at its peak in the shape of swimming and fishing (Lindholm, 2011). Via the Akerselva, the CSOs from Grefsen form the source of pathogenic microbes and intestinal bacteria that are transported to the Oslo fjord (Rodrigues et al., 2012). During summer time the municipality considers the fjord unsuitable for swimming activities for 24 hours after a sewage overflow has taken place.

The current situation regarding CSOs is considered undesirable by the City of Oslo (Oslo Kommune, 2016). On top of that, the challenges presented by CSOs are likely to increase even more because of climate change. Norway's climate centre recently reported that short duration (<1 hour) intense rainfall events in Norway with a return interval between 5- to 200-years will potentially increase with a factor between 1,42 and respectively 1,55 by 2070 (Dyrrdal & Førland, 2019), exacerbating the issue of CSOs.

1.2 PROBLEM STATEMENT

The occurrence of CSOs and their potential to increase because of climate change resulted in a need to make the area stormwater proof on the long term. The conventional method for managing climate change related challenges, consists of trying to predict the future, designing adequate responses based on these predictions and implementing these responses. (Hallegatte et al., 2012; Manocha & Babovic, 2017). This approach makes it difficult to deviate from the established strategy and subsequently makes it hard to deal with uncertainty. Another approach mentioned in current literature regarding managing climatic uncertainty is to assume the worst-case scenario and design adaptation actions accordingly (Dyrrdal & Førland, 2019). This approach, however, brings a great risk of over dimensioning stormwater infrastructure.

Doing too little or taking action too late can lead to an undesirable amount of CSOs. At the same time, acting too soon or undertaking measures that are too extensive is expensive. Therefore, authors are increasingly pleading for more flexible approaches (e.g. Heinmiller, 2009; Hallegatte et al., 2012). Firstly, because the ‘step-by-step’ character of flexible approaches enables policy makers to keep options open for as long as possible. This is described by Rosenhead et al., (1972) and Rosenhead (1990) as an indicator for the robustness of strategies under high uncertainty. Secondly, flexible planning has proven to be useful for identifying ‘no-regret’ actions (Kingsborough et al., 2016). These are actions which – irrespective of how the future will unfold – will not create undesirable effects. A third reason for flexible approaches is that they can provide better insight in pathway’s that are being taken and the subsequent trajectory a city (or other) follows. (Gajjar et al., 2018). Following a certain trajectory can create path-dependency, which limits the options a city has in determining its future course of action. Heinmiller (2009) pleads that choices made in the past possibly limit the amount of future choice sets and thereby constraining the adaptation space. Gajjar et al. (2018) refer to a situation in which future adaptation options diminish, due to current choices of adaptation, as a ‘lock-in’. They conclude their argument by stating that identification of these lock-ins can help to avoid mal-adaptation in the future. This research therefore takes a flexible approach to making Grefsen stormwater proof.

1.3 OBJECTIVE

To summarize, uncertainty about future conditions have implications for the formulation of suitable response strategies to deal with excess stormwater, increasing the need for a flexible, step-by-step approach. This research will explore strategies to deal with stormwater by using adaptation pathways, which is such a flexible approach. In line with commitments of the Oslo municipality to green the city, special focus will be on how dealing with excess stormwater can be done by using nature-based stormwater solutions.

Considering the need for a flexible stormwater strategy and the relevance of nature-based stormwater solutions, the objective of this research is:

‘’to establish adaptation pathways that explore the possibilities for Grefsen to become and remain stormwater proof until 2100’’.

1.4 READING GUIDE

Chapter 2 further elaborates on the theory of adaptation pathways and its key characteristics. Chapter 3 explains the methodology and introduces the five research phases. Chapter 4 presents the research results. These findings are then discussed and put into the context of current literature in chapter 5. Finally, chapter 6 gives the research’s main conclusions.

CHAPTER 2. THEORETICAL BACKGROUND OF ADAPTATION PATHWAYS

The adaptation pathway approach has often been used to plan long term strategies and infrastructure. This chapter reflects on the scientific work that has been done regarding adaptation pathways, starting by why it is used, followed by an explanation of the concept its prime components such as turning points and climate scenarios.

2.1 A NEED FOR FLEXIBLE APPROACHES

Long term decision making in the context of climate change is regarded as very complex matter (Kingsborough et al., 2016). The main reason for this is the uncertainty that comes with climate change. Bosomworth et al. (2015, p.7) point out that ''*while the overall trend of a warming climate is clear, there are inherent uncertainties in climate change projections and their downscaling, which are compounded in attempts to specify impacts on biophysical systems, especially at local scales''*. In the majority of residential areas, climate change impacts require some degree of adaptation of climate related infrastructure and the built environment (Barbosa et al., 2012; Moore et al., 2016). In literature, multiple response strategies to a changing climate are described. For example, Bosomworth et al. (2015, p.7) indicate '*an optimal static response*', or basing strategies on the 'most likely scenario' as common reactions to climate change. Manocha & Babovic (2017, p.86) describe similar approaches by summarizing the traditional response as *''predict then build* ''. According to Dyrrdal & Førland (2019, p6.), Norway uses a *''precautionary principle''*, meaning that adaptation is planned to be able to cope with 'the worst-case scenario'. However, these approaches can still be insufficient, and are likely to be more expensive than necessary if the hypothesized scenario does not turn out to become a reality. Several authors therefore plead for more flexible planning approaches (Haasnoot et al., 2013; Wise et al., 2014; Manocha & Babovic 2017). According to Manocha & Babovic (2017, p. 87), *''robust decision making, adaptive policy making, adaptation pathways, dynamic adaptation policy pathways and real option analysis'',* are flexible approaches that deal with decision-making under great uncertainty. The same authors claim there is no definitive procedure to establish informed, long term policy making under great uncertainty. The concept used in this research is adaptation pathways. The following sections in this chapter explain the different components of the concept.

2.2 ADAPTATION PATHWAYS

As described by Werners et al. (2020), the concept of adaptation pathways has slight variations, i.e. 'the route map pathways approach' (Reeder and Ranger, 2011), 'dynamic adaptive policy pathways' (Haasnoot et al., 2013) and 'adaptation as part of pathways of change and response' (Wise et al., 2014). Despite there being slight variations in naming the concept, most definitions of adaptation pathways in papers reviewed in this research share central elements when describing the concept. Without exception authors speak of a 'sequencing of measures' (Haasnoot et al., 2012; Haasnoot et al., 2013; Ranger et al., 2013; Wise et al., 2014; Bosomworth et al., 2015; Tanaka et al., 2015; Kingsborough et al., 2016; Haasnoot et al., 2019; Werners et al., 2020), often in combination with the implication that this happens over a long period of time and in the context of uncertain future developments (Wise et al., 2014; Kingsborough et al., 2016; Haasnoot et al., 2019; Werners et al., 2020). The definition of adaptation pathways as described by Werners et al. (2020, p.1) will be adopted in this research. It reads: *''Adaptation pathways sequence measures over time, which allows for adaptive implementation depending on how the future unfolds, on the development of knowledge, and on stakeholder inputs and priorities''.* Figure 2 shows the current 'classic' conceptualisation of adaptation pathways as presented by Wise et al. (2014).

The adaptation pathway concept is used in different ways. Werners et al. (2020) explored the field of adaptation pathways in the context of climate change by comparing 31 papers that used the concept. They found that there are four main ways of operationalizing the concept. The first operationalization they call is quantitative pathway development, which is applied in cases with high data availability. These papers have a single, fixed objective and pathways are used to identify all strategies that could meet this policy objective. Usually only one climate

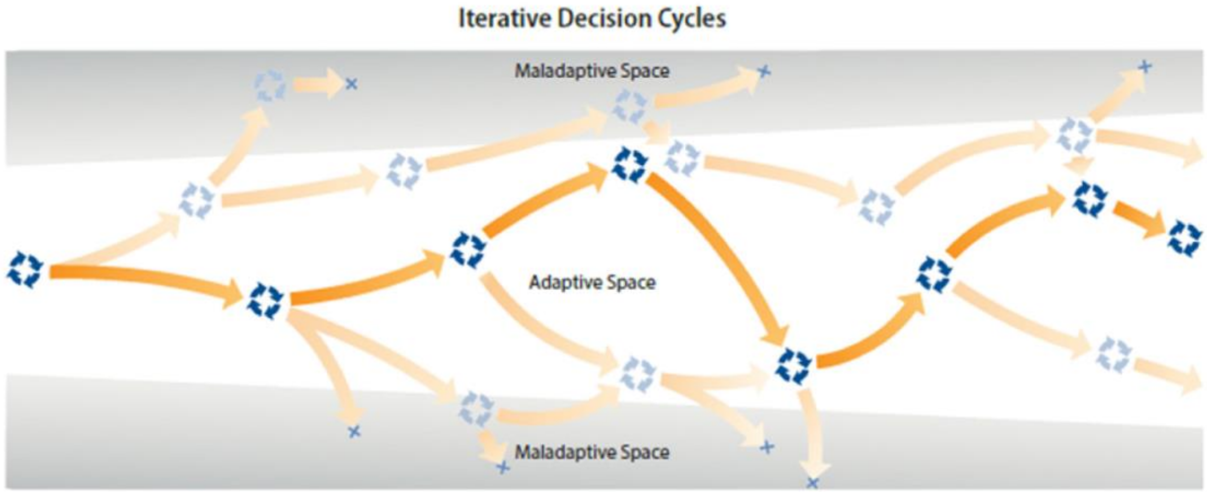


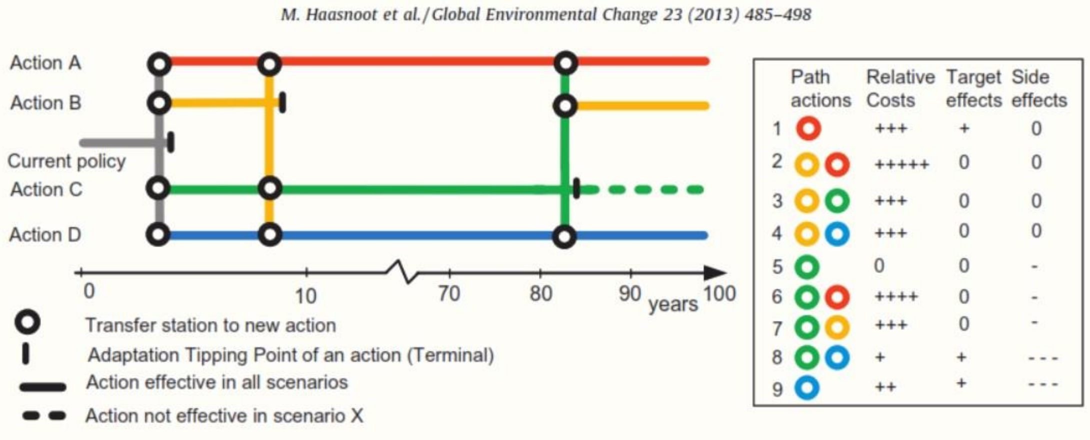
Figure 2. A conceptualization of adaptation pathways made by Andy Reisinger and presented by Wise et al. (2014). The original explanation of the figure by Wise et al., (2014, p.326) reads: ''A series of adaptive learning decision cycles over time with their lifetimes, where some chains of decisions lead to maladaptive outcomes over time, but there may be other alternatives that are adaptive. From the perspective of the current decision point at the left, a currently satisfactory pathway can be plotted through the future (strongest colour), but this must be re-vised at each decision point''.

parameter is used to define turning points (this topic is explained in section 2.3). Some papers (Haasnoot et al., 2019; Manocha & Babovic, 2017) extend this approach by conducting an economic valuation of the pathways. Box 1 provides a detailed example of the quantitative pathway approach. Secondly, Werners et al. (2020) describe a semi-quantitative pathway development approach. Similar to the first named pathway approach, semi-quantitative pathways have a high data demand. The difference is that also qualitative methods are used in the pathway appraisal. Thirdly, there are qualitative pathway approaches, which distinguishes from the first two types by being more focussed on society and institutions. Additionally, multiple goals can be part of the decision context. Fourthly, transformative pathway approaches have been reported. These differ from the first three approaches by starting out with describing a desirable future, and then use back casting to develop pathways to get to this future state.

2.3 ADAPTATION TURNING POINTS AND ADAPTATION TIPPING POINTS

Inseparable from adaptation pathways is the concept of tipping points. In the widest sense of the word, a tipping point refers to a situation in which changing conditions force a system from one regime into another (Scheffer, 2009). In the context of adaptation pathways, adaptation tipping points – also referred to as adaptation turning points or ATPs in short – are described by Manocha & Babovic (2017, p. 89) as ''*the physical boundary conditions where acceptable technical, environmental, societal or economic standards may be compromised, requiring implementation of new actions to meet the specified objective*''. Groot et al., (2017, p. 4) use a similar definition by defining ATPs as ''*the specific situation in which a decisive threshold in the performance of policies and practices is reached due to climate change. This includes the situation in which new practices have become more attractive than current practices*''. ATPs can be both a biophysical threshold – such as the failure of water infrastructure – or a socio-political threshold, such as increasing standards from society (Werners et al., 2013).

BOX 1



Path actions		Relative Costs	Target effects	Side effects
1	🔴	+++	+	0
2	🟠 🔴	+++++	0	0
3	🟠 🟢	+++	0	0
4	🟠 🔵	+++	0	0
5	🟢	0	0	-
6	🟢 🔴	++++	0	-
7	🟢 🟠	+++	0	-
8	🟢 🔵	+	+	- - -
9	🔵	++	+	- - -

Adaptation Pathways Map **Scorecard pathways**

The Figure above shows an example of the adaptation pathways constructed by Haasnoot et al., (2013). On the left, adaptation pathways are shown and, on the right, a table is presented which scores the pathways on costs, as well as target and side effects. The original explanation of the figure by Haasnoot et al., (2013, p.488) reads:

''An example of an Adaptation Pathways map (left) and a scorecard presenting the costs and benefits of the 9 possible pathways presented in the map. In the map, starting from the current situation, targets begin to be missed after four years. Following the grey lines of the current policy, one can see that there are four options. Actions A and D should be able to achieve the targets for the next 100 years in all climate scenarios. If Action B is chosen after the first four years, a tipping point is reached within about five years; a shift to one of the other three actions will then be needed to achieve the targets (follow the orange lines). If Action C is chosen after the first four years, a shift to Action A, B, or D will be needed in the case of Scenario X (follow the solid green lines). In all other scenarios, the targets will be achieved for the next 100 years (the dashed green line). The colours in the scorecard refer the actions A (red), B (orange), C (green), and D (blue).''

2.4 SCENARIOS

Scenarios are another important component necessary to construct adaptation pathways. If only one future scenario is used, the future is assumed to be fixed and uncertainty is not taken into account. This means there is no need for the flexible pathway approach. Using one scenario with a 'most likely' description of the future means falling back to the traditional adaptation approach. Some authors choose to develop their own scenarios if local characteristics are a major source of uncertainty. Examples are given by – among others – Manocha & Babovic (2017) and Kingsborough et al. (2017), who used climate scenarios in combination with land use scenarios, or population scenarios to establish tailor made scenarios for their case. In other cases, climate change is the only, or main uncertain pressure. In this case, standardized climate scenarios, or downscaled versions of those are used (Tanaka et al., 2015).Within the context of this research, changes in precipitation patterns are most relevant for urban water management. As shown in Figure 3, precipitation projections for Norway vary widely, suggesting that climate change is a major source of uncertainty (Hanssen-Bauer et al., 2017). The use of climate change scenarios originates from the Intergovernmental Panel on Climate Change (IPCC). They introduced the Special Report on Emission Scenarios (SRES), which was later replaced by Representative

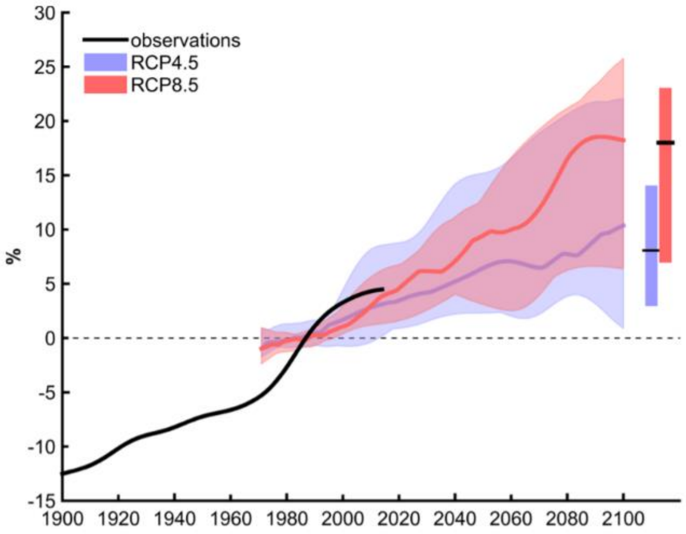


Figure 3. Precipitation projections for Norway according to Hanssen-Brauer et al., (2017). The original figure caption reads: ''annual precipitation over Norway as deviation (%) from the period 1971-2000. Black curve represents observations (1900-2014), red and blue curved lines show median values for the ensemble of ten RCM simulations for emission scenarios RCP 8.5 and RCP 4.5. All curves are smoothed. Shading indicates the spread between low and high climate simulation (10th and 90th-percentile). The box plot on the right shows projections up to 2071-2100 for both scenarios.'' (p.22)

Concentration Pathways (RCPs) (van Vuuren et al., 2011), which will be used in this research. In short RCPs describe the possible trajectories of additional radiative forcing in W/m^2 due to greenhouse gas (GHG) concentrations in the atmosphere based on assumptions about the economy, energy production and population growth (Wayne, 2013). RCPs serve as input for initialization of climate models, which use these scenarios to calculate climatic variables such as temperature and precipitation. Four narrative storylines can be distinguished:

- RCP2.6 was established by the makers of the IMAGE model and is the lowest emissions scenario where GHG emissions are reduced substantially. The radiative forcing in this scenario peaks at 3,1 W/m^2 in 2050, and then declines to 2,6 W/m^2 by the end of the century (Wayne, 2013). A CO_2 equivalent concentration of <490 p.p.m. is expected (van Vuuren et al., 2011)
- RCP 4.5 was established by the makers of the GCAM model and is a moderate emission scenario where radiative forcing gradually stabilizes shortly after the end of the century (Wayne, 2013). The stabilization corresponds with a radiative forcing of 4,5 W/m^2 and a CO_2 equivalent concentration of approximately 650 p.p.m. is expected (van Vuuren et al., 2011)
- RCP 6.0 was established by the makers of the AIM model. It is a higher emission scenario where radiative forcing – by the help of advanced technologies – stabilizes shortly after the end of the century. Here a radiative forcing of 6,0 W/m^2 is expected with a CO_2 equivalent concentration of approximately 850 p.p.m. (van Vuuren et al., 2011)
- RCP 8.5 is the highest emission concentration scenario where the CO_2 equivalent concentration keeps increasing till >1370 p.p.m. and a radiative forcing of 8,5 W/m^2 is reached by the end of the century (van Vuuren et al., 2011).

CHAPTER 3. METHODOLOGY

This research can be divided in five phases that have been executed mostly chronologically: i) finding background information and explore the research context; ii) calculating the adaptation need in the study area and relating this to turning points; iii) selecting adaptation actions for the construction of adaptation pathways; iv) constructing the adaptation pathways; v) making a cost overview of the pathways. Figure 4 visualises these phases. These research phases were inspired by- and adapted from Werners et al., (2018) and Werners et al., (2020). The main activities that have been carried out within each phase are described in the following sections.

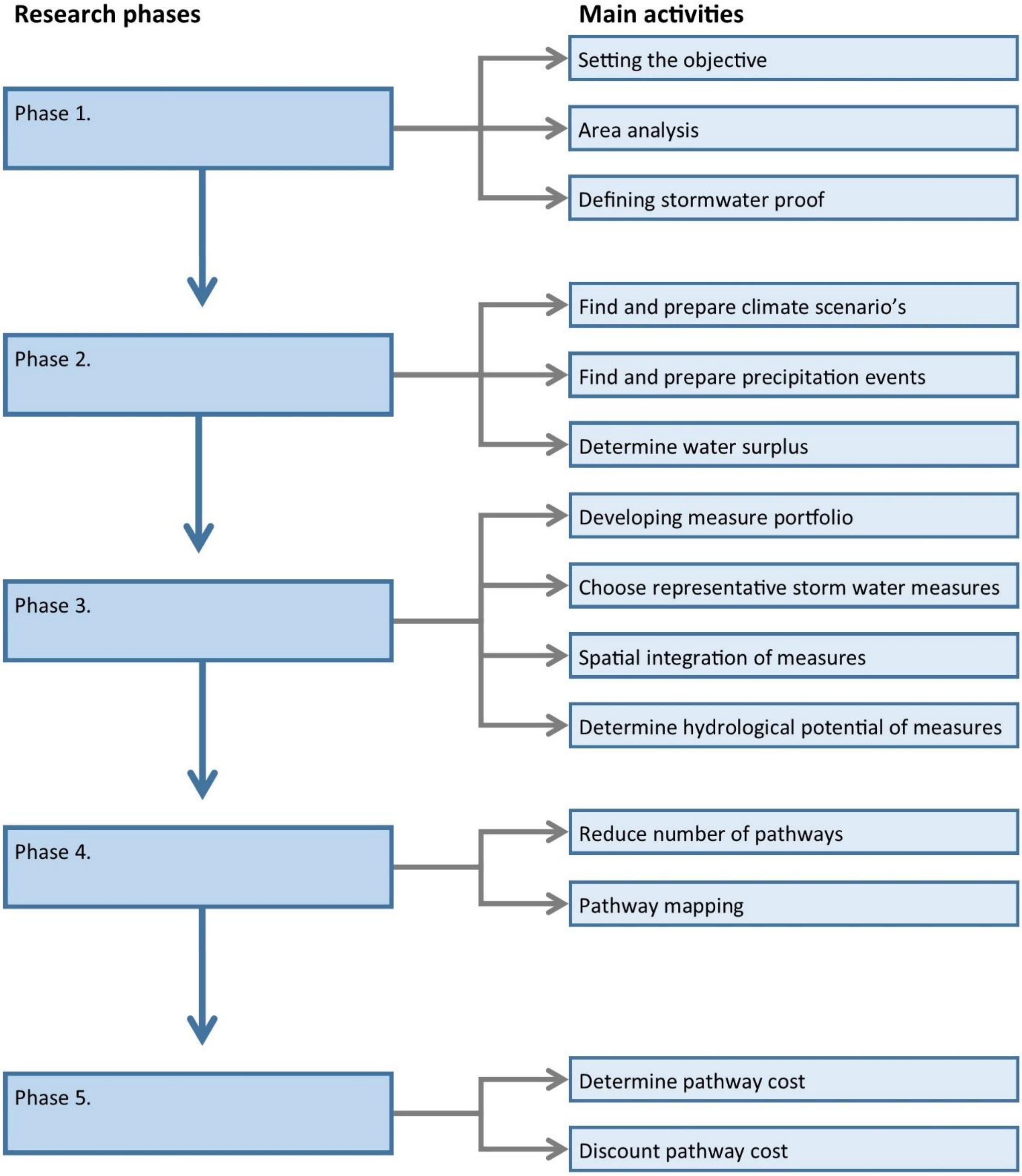


Figure 4. Research phases and main activities.

3.1 DEFINING THE DECISION CONTEXT

Three main activities where done to set the context. Firstly, determining the objective. This started with consultation of New Water Ways (NWW) project team members to select a suitable research area in Oslo. Grefsen was chosen as a research area because a hydrological model of Grefsen was available, meaning a more detailed analysis of the adaptation need was possible. The need to make Grefsen stormwater proof emerged from the municipalities commitments as described in their climate adaptation strategy (Oslo Kommune, 2014) and action plan for stormwater management (Oslo Kommune, 2016) to make Oslo climate proof and to reduce sewer overflows, of which there are many in Grefsen.

Secondly, the study area was analysed. To establish the boundaries of the research area, the hydrological catchment of the AK 52 overflow weir was chosen as the boundary of the research area, as this is the main source of pollution that originates from Grefsen. This catchment area was extracted from a multi-flow direction from a digital elevation model by Dr. Hong Li (Hong Li, email communication 1-11-2019). The study area was further explored through the screening of municipal plans and strategical water management plans. The area was also explored using a Geographic Information System (GIS) – ArcMap version 10.4. This contributed to the gathering of background information that can be found in the introduction, and information that supports later research phases such as the selection of possible adaptation actions and estimating storage capacities of stormwater measures.

Thirdly, the concept of being 'stormwater proof' was defined and operationalized, as there are many ways to interpret this concept and different operational definitions are used by policymakers and researchers. Defining stormwater proof started with conducting a literature research to 'overflow' and 'water nuisance thresholds'. National and municipal policy documents were also screened, but stormwater related thresholds were not found for Oslo. Therefore, in consultation with a representative of the Oslo municipality and researchers of the NWW project, two definitions of stormwater proof have been established for this research: one using an ambitious and strict norm, and one using a less strict norm. These two definitions were chosen to cover a large range of uncertainty and ambiguity, associated with what it means to make an area stormwater proof. For defining stormwater proof, normative precipitation events are used. This is often done to assess the performance requirements of water infrastructure (Hong Li, personal communication, 19-11-2019). The duration of the precipitation event was set at 60 minutes in consultation with researchers of the NWW project (Hong Li, personal communication, 19-11-2019; Isabel Seifert-Dähnn, personal communication, 4-12-2019)

3.2 CALCULATING THE ADAPTATION NEED

Phase 2 consisted of calculating the adaptation need, which was operationalized as the water surplus created by a heavy precipitation event. This is the amount of water that surpasses the AK52 overflow weir, and thus the amount of water that needs to be stored or discharged to prevent Combined Sewage Overflows (CSOs). The following sections elaborate on the used precipitation events and scenarios, and on how a hydrological model was used to calculate the water surplus.

3.2.1 GENERATING AN ARTIFICIAL PRECIPITATION EVENT

In this study, an estimate has been made of how the intense – short duration precipitation events can increase over time. Firstly, various scenarios were realized in which uncertainties that affect the water surplus are covered. The expected development of precipitation events over time was then examined for each scenario. This is done according to a method as described by Førland et al. (2015) and Dyrrdal & Førland (2019), where a climate factor is multiplied by a statistical precipitation event of an existing time series. The result of this intermediate step is, for each scenario, a statistical precipitation event that is representative of a certain possible reality.

This research regarded climate change and how to define stormwater proof as the two main uncertainties that determine how much the water surplus will be in the future and thus, at what point in the future ATPs will be reached. Therefore, estimations for the future water surplus in Grefsen were made for four scenarios that describe potential realities: i) a low emission scenario with a low normative precipitation event to define stormwater proof; ii) a low emission scenario with a high normative precipitation event to define stormwater proof; iii) a high emission scenario with a low normative precipitation event to define stormwater proof; iv) a high emission scenario with a high normative precipitation event to define stormwater proof, see Figure 5.

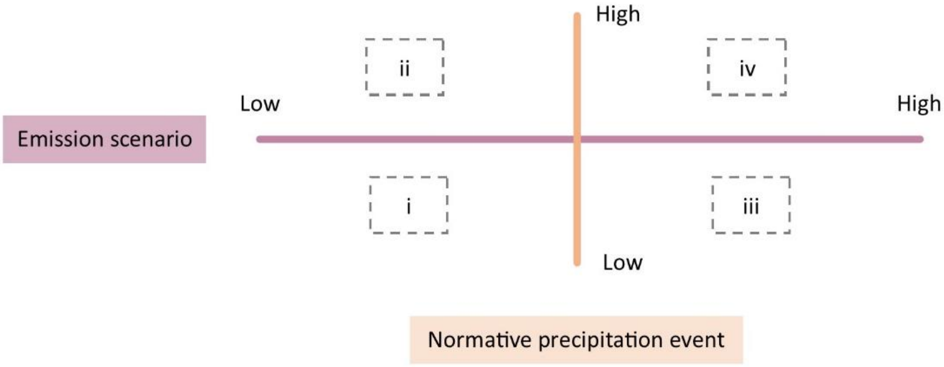


Figure 5. Using two emission scenarios and two normative precipitation events to define stormwater proof, leads to four scenarios for which artificial precipitation events were produced.

Because climate change does not set in abruptly at the end of the century, artificial precipitation events were generated for timesteps of ten years, up to 2100. This has been done by multiplying intensity-duration-frequency curves (hereafter referred to as IDF curves) with climate factors. An IDF curve is the cumulative precipitation of a hypothetical rainfall event with a certain frequency (Uijlenhoet et al., 2016). The IDF curves used here have been established based on precipitation data from the Blindern measuring station from 1968-2015 and can be found in the work of Ingebrightsen (2017, p.42) and Sorteberg et al. (2018, p.39). Blindern station is closest to Grefsen. Accumulated precipitation amounts for events with a return intervals of 2- and 200-years have been presented for durations of 5,10,15,20,30,45,60,120,180,360,720 and 1440 minutes. For this research, only precipitation events with a duration of 0 till 60 minutes were used in timesteps of 5 minutes. Values for timesteps that were unspecified in the afore mentioned reports were interpolated using a logarithmic function that was generated in Excel.

To get an indication of how future precipitation events will develop, climate factors were used. A climate factor is a number that represents the statistical increase of a precipitation event with a certain return interval at a given time. They are multiplied with IDF curves that are established with observed precipitation values in the area of interest. Climate factors were found for a high (RCP 8.5)- and a low (RCP 4.5) emission scenario by means of a literature research. The climate factors were taken from Førland et al. (2015) and Dyrrdal & Førland (2019) who used downscaling of regional climate models to a resolution of 12*12 km. Projected precipitation events for 2071-2100 with a certain return period are compared to observed precipitation in the period 1971-2000, obtained from Euro-Cordex. By dividing the projected precipitation with a given return period by observed precipitation, the climate factors were established by Førland et al. (2015) and Dyrrdal & Førland (2019). Variations between climate factors are generally ascribed to differences in location, return period, duration of the event and the climate scenarios. Because the found climate factors did not represent all event durations, return periods and timesteps, additional inter- and extrapolation steps were taken in this research.

- Climate factors for the 10-year time steps are established based on linear interpolation between the climate factor 1 in the year 2000, and the given climate factor for the year 2100. The year 2000 is used as a base year because both Førland et al. (2015) and Dyrrdal & Førland (2019) used Euro-Cordex data until this year;

- For RCP 4.5, data was only available for precipitation events with durations of 24 hours and 3 hours. Linear extrapolation was used to establish the climate factor for a 1 hour precipitation event;
- For RCP 4.5, data was only available for precipitation events with 5- and 200-year return intervals. Linear interpolation was performed to establish the required 20-year return interval.

3.2.2 DETERMINING THE WATER SURPLUS

To quantify the water surplus in Grefsen, results from the Stormwater Management Model (SWMM) were used. SWMM has been set up by Ina Storteig, she provided a detailed description of the model setup in her master thesis (Storteig, 2019). For each 10-year timestep up to 2100, four artificial precipitation events were used as input for the model that was set up by Sorteig (2019), one event for each scenario. The model simulated the discharge for every precipitation event for the AK 52 overflow weir (manhole 161143). The capacity of the sewer system at that point is 600 l / s (Storteig, 2019). All discharge values above this threshold lead to CSOs and are thus regarded as the water surplus.

A few alterations to the parameters were made so the SWMM was set up correctly for this research:

- All timeseries of precipitation were deleted and manually changed for the artificial precipitation events generated for this research;
- All other external climate files were changed to 'no data'. Evaporation was set on a constant value of 1 mm / day. This value coincides with expectations of Engeland et al. (2004).
- Model simulations have only been made for singular events with short duration, meaning the bulk of the event has been discharged after a few hours. The exact date is therefore irrelevant for the model outputs and was therefore – at random – changed from a time series to a fixed starting date of 12/12/2019 00:00, and a fixed end date of 12/12/2019 03:00.

3.3 SELECTING MEASURES FOR PATHWAYS

Selecting stormwater measures for pathway construction started with compiling a portfolio of the different adaptation measures that could be taken. To establish this portfolio I looked into learning cases of NIVA's NWW project: Amsterdam and Copenhagen. Amsterdam in particular has a well described toolbox that included a large variety of stormwater measures. To ensure that the portfolio constructed here contained all applicable stormwater measures, an additional literature scan was made. Search terms as 'LID' (Low Impact Developments), 'SUDS (Sustainable Urban Drainage systems)', BGIs (Blue-Green Infrastructure) and 'stormwater measures', were used to scan the first two pages of search results in Google Scholar and the Wageningen University library. Articles provided extensive lists of stormwater measures, but these measures were not marginally diverging in comparison to the Amsterdam rainproof toolbox (Rodak et al., 2019; Alves et al., 2018; Jotte et al., 2017; Ahamed, 2017). The measure portfolio is presented in Appendix B and consists of a set list of all possible stormwater measures that can be taken in Grefsen. Additionally, the measure portfolio contains considerations that were made for picking a small number of stormwater measures that represent the broad variety of stormwater measures that will be used to construct the adaptation pathways.

As some measures overlap in their functionality and because the integration of too many measures would result in too many pathways, the assessment was limited to seven stormwater measures. For the selection, measures have been categorised in 'traditional', 'technical' stormwater solutions, and 'nature-based' stormwater solutions. Later, additional subcategories were made based on the functions of measures: retain, infiltrate and discharge stormwater, resulting in six sub categories. The end selection has been made in consultation with Isabel Seifert-Dähnn (personal communication, 1-11-2019). Measures adhere to the following criteria:

- Realize little overlap between measures in functionality and in applicable locations;

- Fair representation of green and innovative measures because of Oslo's vision of a green city (Oslo Kommune b, n.d.) and its ambition to use green measures to tackle stormwater related issues (Oslo Kommune 2014).

An estimation of the storage potential of each measure in the end selection was also made. This was done according to two principles: 'the maximum potential', or 'demand and supply'. The first named principle is primarily focussed on measures that can only provide a limited contribution to storing the total water surplus. The maximum and / or plausible storage capacity has been estimated by means of a literature study. Additionally, GIS was used to estimate the feasibility of spatial implementation of measures. The latter named principle is focussed on large-scale measures of a technical nature, which have a relatively high physical limit for water storage. The storage capacity was determined by setting the storage amount equal to the water surplus in the worst-case scenario. Using the proposed dimensions, the measures have been drawn in a map of Grefsen with the help of GIS to check as to whether spatial implementation is indeed feasible, see Appendix A. For both principles used, the knowledge gaps were filled with assumptions that have been crosschecked with Isabel Seifert-Dähnn (Isabel Seifert-Dähnn, personal communication, 16-12-2020).

3.4 PATHWAY CONSTRUCTION

To ensure the pathways are easily understood, the pathways were visualized using a tree structure instead of conventional adaptation pathway figures as shown in box 1, section 2.3. The pathways have been manually ensembled. Firstly a figure was made that showed all combinations. Next, pathways were excluded based on the following considerations:

- Water surpluses were modelled for each scenario in time steps of ten years. Pathways have been constructed with the assumption that the water surplus must be reduced by adding up measure capacities. There are two exceptions to this. Water squares and wadis have a large storage capacity, but a small additional technocratic measure is required to store water that falls on lower elevated areas than the proposed wadi / water square locations;
- Because expanding the capacity of a sewer system would require a complete renovation, this measure is not combined with other stormwater measures that are presented in the pathways. Also, as it is the traditional way of dealing with stormwater, it is not combined with other measures to provide contrast to nature-based solutions;
- To reduce pathway complexity, low impact developments (green roofs, raingardens and rain barrels) have been merged into a measure package specified as 'LIDs';
- When a follow-up measure is being chosen, earlier taken measures remain functional;
- Because a large gap exists between the current situation and the required storage facility, the period until 2030 is considered a transition period in which measures can be planned and constructed.

3.5 ECONOMIC VALUATION OF PATHWAYS

To put the pathways into perspective, a rough estimation of the costs were made. The cost estimate includes the following parameters: life expectancy, implementation costs, project management costs and maintenance costs. The life expectancy was estimated based on literature and by comparing the measure to similar cases that have already been implemented. The same was done for the implementation cost. Additionally, a gardener and contractor were consulted to estimate costs for soil transportation and implementation of rain gardens. Project management costs were obtained by estimating the required number of working hours for stakeholder consultation based on the extent of the measure and the required stakeholder involvement. All labour hours were multiplied by a set wage of 500 NOK / hour (Intermediair, 2019). Maintenance costs were determined through literature research and consultation of a gardener. The obtained numbers were not always presented in NOK, so the following exchange rates have been used to convert the costs to NOK:

- 1 EUR = 10,16 NOK
- 1 USD = 9,20 NOK
- 1 DDK = 1,35 NOK

The year in which a certain water surplus is reached varies between scenarios. Therefore, the timing of measures varies as well, meaning that interest and inflation are an additional factor to take into account when calculating the nominal cost of adaptation pathways. The scenario is also determining for the range in which the water surplus falls, meaning that in some scenarios not all stormwater measures need to be implemented. Hence, the costs are calculated for each pathway in all four scenarios until 2100. A discount rate of 1,4 is used which is advised by the Stern review (Hagen et al., 2012).

CHAPTER 4. RESULTS

This chapter presents the results from the 5 phases outlined in the methodology. Firstly, the definition of stormwater proof is given. Secondly, the future water surplus is described in relation to both climate change scenarios and the ways of defining stormwater proof. Thirdly, the measures that were used to construct the adaptation pathways are presented. Finally, the adaptation pathways including cost estimates are described.

4.1 DEFINING STORMWATER PROOF FOR GREFSEN

As elaborated on in section 1.1, Combined Sewage Overflows (CSOs) are the main stormwater related problem in Grefsen. There is a clear need to reduce both the overflow quantity to improve water quality, as well as the overflow frequency to limit nuisance for recreation. However, the question remains of what constitutes an acceptable amount of overflows and what does not? To identify pathways that are effective at making Grefsen stormwater proof, this term needs to be defined by translating problems to performance thresholds.

National documents indicate that CSO norms are set by the municipality (VA-Norm, n.d. a), but at a municipal level, only design guidelines were found (VA-Norm, n.d. b). To my knowledge the municipality did not formulate quantitative goals for the reduction of sewer overflows. Targets do exist for emission flows to the Akerselva (Hult, 2015) and pollutant concentrations in the Akerselva (Oslo Kommune, 2018) , but these values depend on the quality of water supplied and biophysical processes in the water and river bed (Hayatsu et al., 2008). Hence, they cannot be used directly to formulate reduction goals of water quantities that run over the AK52 overflow weir. On an abstract level the municipality does have a vision regarding CSOs, which is less concrete but shows the issue is on the political agenda. The municipality website states that 'sewer overflows must be reduced as much as possible' (Oslo Kommune, n.d.). According to a municipality representative, the current policy regarding urban water management is that no damage and / or negative effects of a catchment may be inflicted in downstream areas. However, the municipality representative also indicated that – as a rule of thumb – a CSO event once every three years is considered acceptable (Bent Baskerud, personal communication, 16-12-2020). These statements vary and all can be interpreted differently, therefore no unambiguous goal regarding the reduction of CSO events came forward during this research. As a result, this study was not able to use a legal quantitative threshold for CSOs in order to design adaptation pathways for Grefsen.

As no quantitative target exists, this research describes two ways to define stormwater proof. This was done to cover the range of uncertainty caused by the choice of definition, and to show the effect of using different definitions. Normative precipitation events are used to define stormwater proof as this is customary in design values for water infrastructure, and because it simplifies modelling. The first definition represents a high and ambitious norm and is set in consultation with experts from the New Water Ways (NWW) project (Isabel Seifert-Dähnn and Hong Li, personal communication, 19-12-2019) and reads:

Grefsen is stormwater proof if no CSO takes place during a 60- minute precipitation event with a return interval of 20 years.

To provide contrast, the return interval is set on 5 years for the second definition of stormwater proof, meaning the second definition of storm water proof reads:

Grefsen is stormwater proof if no CSO takes place during a 60- minute precipitation event with a return interval of 5 years.

In some cases this report refers to these events as M20, and M5 precipitation events, respectively.

4.2 THE ADAPTATION NEED

4.2.1 THE IMPACT OF CLIMATE CHANGE

To construct pathways, it is necessary to calculate the water surplus induced by heavy precipitation in the area over time and for different scenarios. As explained in more detail in the previous chapter, this is done by using Intensity Duration Frequency (IDF) curves, which are multiplied by climate factors. As a base year, the IDF curves for Blindern 1968-2015 are used, see Table 1.

Table 1. 5-Minute interval data for IDF curves of Blindern (Ingebrightsen (2017, p.42). Values are presented in mm for a 5- and 20-year return interval.

t (min)	5 year return interval	20 year return interval
5	7,60	10,1
10	11,4	15,1
15	14,2	19,3
20	16,6	22,6
30	19,7	27,0
45	23,4	32,4
60	25,3	35,1

For Norway, two studies present climate factors that can be used for this research. The first study was done by Førland et al. (2015) who presented climate factors on a regional scale and as national averages. For the regions only climate factors for 3-hour precipitation events with a return interval of 200 years are presented for both RCP 4.5 and RCP 8.5. As national averages they present climate factors for 3-hour and 24-hour M5 and M200 events in scenarios RCP 4.5 and RCP 8.5. Results for the national average provide the most elaborate information, but this is not location specific. However, the 3-hour events for the region of Østlandet – which includes Oslo – do compare to the 3-hour events as a national average. The climate factors for the region are 1,17 and 1,37 with respect to 1,19 and 1,38 as a national average. Therefore, the climate factors of the national average are deemed most representative for scenario RCP 4.5 and are further used in this research. Because climate factors are neither for a 20-year return interval precipitation event nor for 60-minute precipitation events, the climate factors of Førland et al. (2015) are linearly inter- and extrapolated which resulted in the climate factors for RCP 4.5 as presented in Table 2.

Continuing on the work of Førland et al. (2015), Dyrrdal & Førland (2019) established climate factors for precipitation durations of 1, 3, 6 and 12 hours, for events with a return interval between 5 years and 200 years. These factors have been established for mainland Norway in scenario RCP 8.5. The report shows both national means and median values. Because scenario RCP 8.5 assumes relatively large increases in precipitation in the regions of Oppland, Troms and Finnmark, the mean values are high compared to the median. Since it can be diverted from visualisations in the Appendix that projections for Oslo are more moderate, the median climate factors are chosen to work with (Dyrrdal & Førland, 2019, p.20). The climate factors that are used in this research are presented in Table 2.

Table 2. Climate factors for the year 2100 in scenario RCP 4.5 and RCP 8.5 for precipitation events with a 5- and 20-year return interval.

	5 year return interval	20 year return interval
RCP 4.5 Førland et al. (2015)	1,16	1,16
RCP 8.5 Dyrrdal & Førland (2019)	1,36	1,38

Climate change is a growing pressure that will not abruptly set in at the end of the century. Therefore, climate factors are calculated in timesteps of 10 years. Climate factors for these timesteps are determined based on linear interpolation between the year 2000 and 2100. The year 2000 has a climate factor of 1, because climate factors of Førland et al. (2015) and Dyrrdal & Førland (2019) were compared with observed precipitation data up to this year. Therefore, 2000 is the base year. Climate factors for all timesteps are presented in Table 3.

Table 3. Climate factors for 60-minute precipitation events with a return interval of 5- and 20-years for RCP 4.5 and RCP 8.5 in time steps of 10 years until 2100.

RCP4.5				RCP8.5			
5 year return interval		**20 year return interval**		**5 year return interval**		**20 year return interval**	
Known X	Known Y	Known X	Known Y	Known X	Known Y	Known X	Known Y
2000	1,00	2000	1,00	2000	1,00	2000	1,00
2100	1,16	2100	1,16	2100	1,36	2100	1,38
New X	Predicted Y	New X	Predicted Y	New X	Predicted Y	New X	Predicted Y
2020	1,04	2020	1,04	2020	1,08	2020	1,07
2030	1,05	2030	1,05	2030	1,11	2030	1,11
2040	1,07	2040	1,06	2040	1,14	2040	1,15
2050	1,08	2050	1,08	2050	1,18	2050	1,19
2060	1,10	2060	1,10	2060	1,22	2060	1,23
2070	1,11	2070	1,11	2070	1,25	2070	1,27
2080	1,13	2080	1,13	2080	1,29	2080	1,30
2090	1,15	2090	1,14	2090	1,32	2090	1,34
2100	1,16	2100	1,16	2100	1,36	2100	1,38

Each of the above showed climate factors is multiplied with the corresponding IDF curve. This leads to the future projections of IDF curves as presented in Figure 6 and Figure 7.

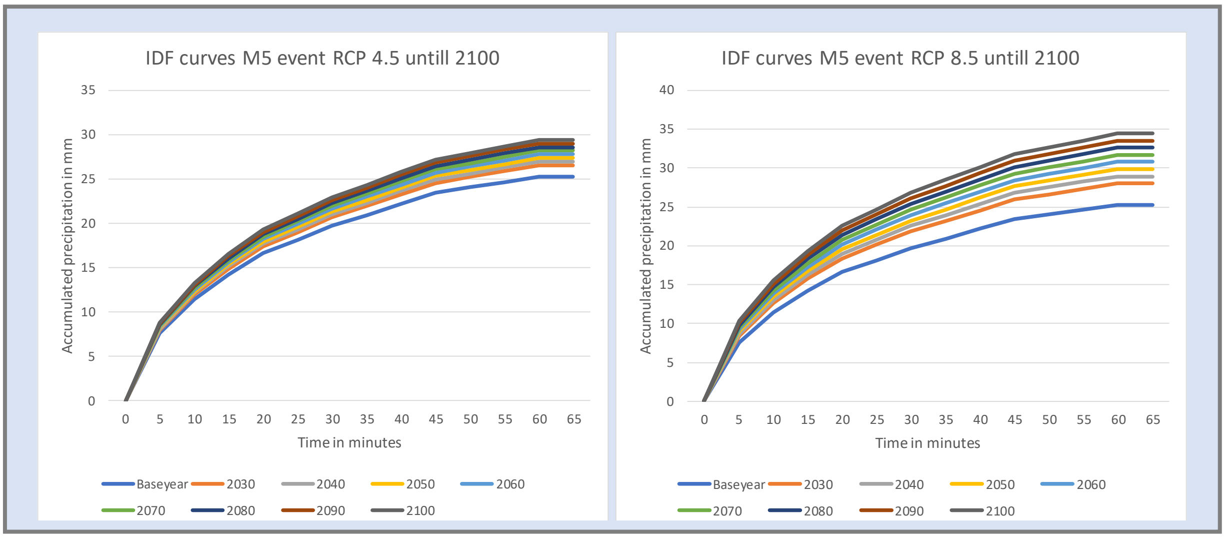


Figure 6. Newly generated IDF curves for precipitation events with a 5-year return interval in scenarios RCP 4.5 and RCP 8.5. in time steps of 10 years.

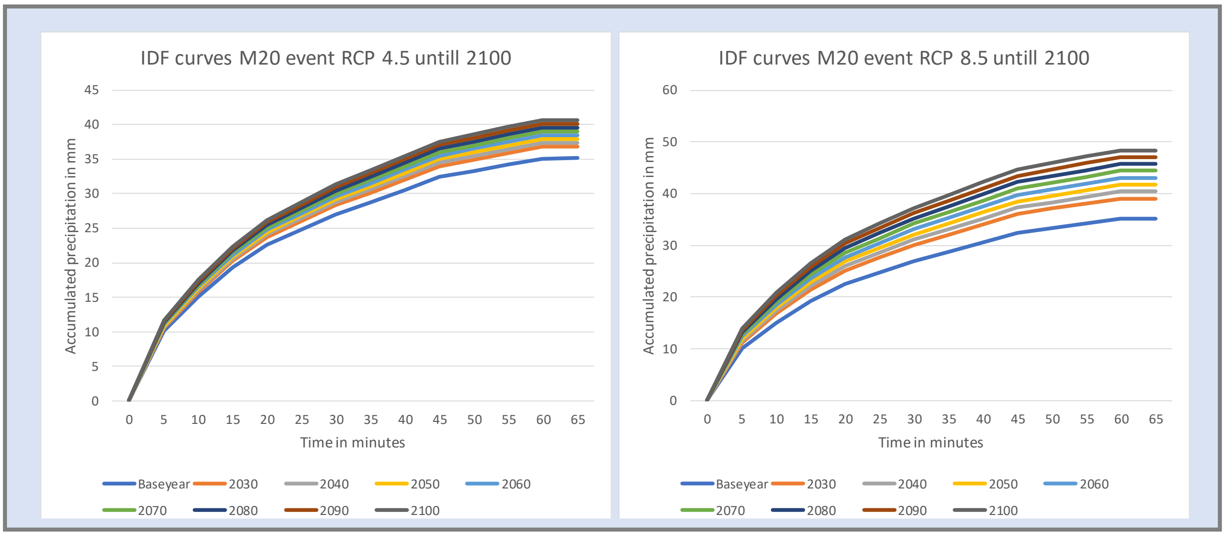


Figure 7. Newly generated IDF curves for precipitation events with a 20-year return interval for scenarios RCP 4.5 and RCP 8.5 in time steps of 10 years.

4.2.2 MODELLING OF THE WATER SURPLUS

The precipitation events that are presented in Figure 6 and Figure 7 were imported in SWMM. For each precipitation event this resulted in a graph where discharge is set against the elapsed time. The surface under the graph, minus the critical discharge for the AK 52 to overflow of 600 l / s, was calculated to establish the total CSO volume. The number that remained is the water surplus at that given time. The course of the water surplus in different scenarios is presented in Figure 8. Model outcomes and exact water surplus figures are presented in Appendix E. Two things can be observed from Figure 8: i) the two definitions of stormwater proof induce a larger difference between scenarios than the difference between RCP 4.5 and RCP 8.5 at the end of the century; ii) in both cases of defining stormwater proof the water surplus is marginally larger than the variety's that are induced by climatic influence and the normative precipitation event. When stormwater proof is formulated using a normative event with a 5-year return interval the water surplus in 2020 ranges from 9.336 m^2 to 9.801 m^2. When stormwater proof is formulated using a normative event with a 20-year return interval the water surplus in 2020 ranges from 13.524 m^2 to 14.219 m^2. Thus, a major gap already exists between the current situation and a situation that can be classified as stormwater proof. This means that Grefsen currently is not stormwater proof.

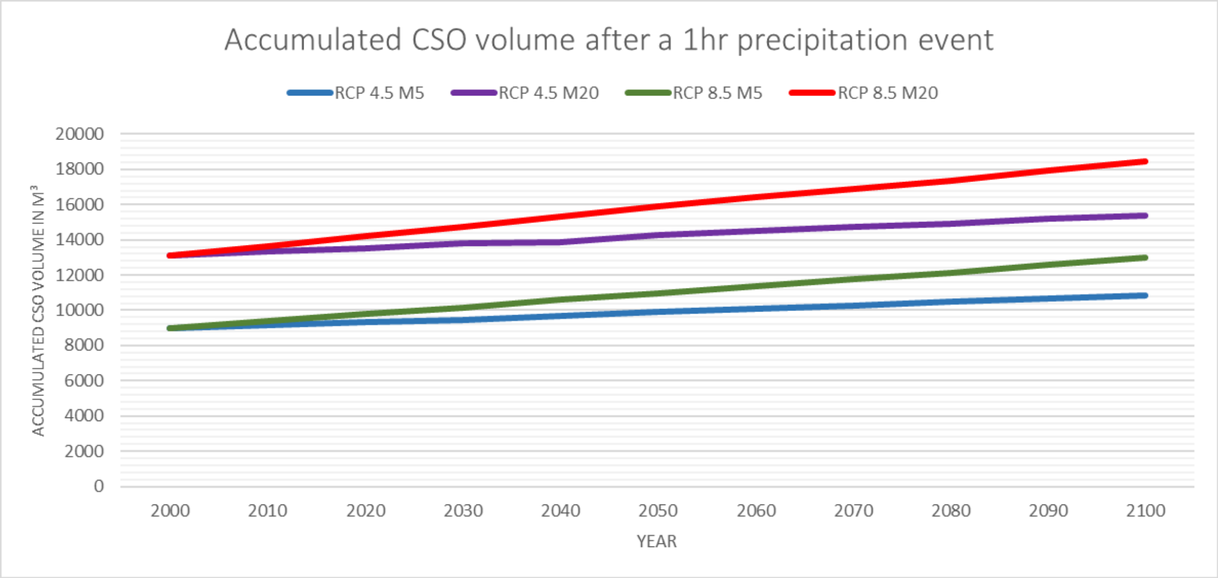


Figure 8. The water surplus for a 5-year (M5)- and 20-year (M20) return interval precipitation event for scenarios RCP 4.5 and RCP 8.5 until 2100. The vertical axis presents the accumulated CSO volume. This is the amount of water that flows over the AK 52 overflow weir and is thus the water surplus.

4.3 STORMWATER MEASURE PORTFOLIO

A scan of NWW learning cases Amsterdam and Copenhagen and a literature study were done to identify all relevant stormwater measures to consider when making Grefsen stormwater proof. Not all these measures are used in the construction of pathways. The section below presents seven measures that were used for pathway construction. The total list of stormwater measures as well as the considerations that were made to select a small number of these can be found in Appendix B. This section briefly describes the basic functioning of the short-listed stormwater measures as well as main characteristics. Where applicable, proposed spatial implementations can be found in Appendix A. Assumptions on dimensions and the storage capacity can be found in Appendix C. Assumptions and calculations on costs can be found in Appendix D.

Green roofs

A green roof generally contains a layer of substrate in which vegetation can grow and water can be stored, followed by drainage- and a protective layer (Amsterdam Rainproof, 2020a). Any precipitation falling on the roof will be either stored or delayed in discharge compared to a conventional roof. Green roofs are available in multiple variants: intensive green roofs, extensive green roofs and polder roofs. Because the extensive green roofs have the most applicability possibilities (it is the cheapest variant, can be implemented on most existing roofs, low maintenance, light weighted), this is the type of green roof that will be used for pathway construction.

Based on assumptions that are presented in the calculations of the storage potential, a surface of approximately 142.000 m^2 is available for green roof implementation. An estimated 2.214 m^3 can be stored during a single precipitation event. The costs for this measure are estimated to be 115,6 million NOK for implementation and 1,7 million NOK / year for maintenance.

Wadi / raingarden

A wadi is a vegetated ditch or field which is funded on substrate with high infiltration and storage capacity (Amsterdam Rainproof, 2020b). When precipitation falls, the wadi fills up with water. Additionally, a box with gravel is usually installed under the wadi to increase retention capacity and speed up infiltration. The substrate allows the water to slowly infiltrate to the surrounding soil. In some cases, a drain is installed under the gravel box to empty the wadi, but given the low ground water table and high infiltration properties of Grefsen (Storteig, 2019), this alternative is not chosen. A raingarden in essence is the same as a wadi albeit that they are implemented in gardens, mostly on a small scale. The main assumption for implementation within this research is that raingardens are implemented on a small scale on private property, whereas wadis are implemented on a larger scale on public ground. Figure 9 illustrates the basic idea of a wadi.

In case of the assumed dimensions as presented in Appendix C, 23.780 m^2 of surface area is available for wadi implementation and 681 raingardens can be implemented. This corresponds with 7.490 m^3 and respectively 224 m^3 of storage capacity. The costs for wadis are approximately 12 million NOK for implementation and 16.000 NOK / year in maintenance. Implementation costs for raingardens are estimated on 11,2 million, whereas maintenance costs are set on 170.250 NOK / year.

Rain barrel

A rain barrel catches and temporarily stores water from roofs via disconnected drain pipes (Amsterdam Rainproof, 2020c). When the maximum capacity is reached, the barrel will overflow. After a precipitation event the barrel can be emptied manually or the water can be stored for later use. Current developments are to fit rain barrels with an electronic operating system that empties barrels based on precipitation forecasts (Oberascher et al., 2018). Figure 9 illustrates the idea of a rain barrel.

Assumed is that 681 rain barrels can be implemented, leading to a storage capacity of 136 m^3. Costs are estimated to be 623.000 NOK for implementation and 170.250 NOK / year for maintenance.

Water square

A water square is a square which is lower than its surroundings. A system of curbs and gutters lead water from the surroundings to the square which stores the water (Amsterdam Rainproof, 2020d). When a precipitation event is over, the remaining water can be pumped out or discharged under gravity. Under dry conditions squares can fulfil a social function and are available for playing children and anyone who wants to enjoy the square. The water square has different varieties. Examples are the 'urban' Benthem water square in Rotterdam and the 'green' Enghaveparken in Copenhagen. Figure 9 illustrates part of the 'Benthem water square' in Rotterdam.

The water square foreseen for Grefsen can initially store 9.706 m^3, but storage can be expanded to 15.694 m^3. Implementation cost are 28,4 million NOK and 17,5 million NOK for an additional expansion. Maintenance costs are estimated to be 48.000 NOK / year.

Infiltration crates

Infiltration crates can be described as permeable underground boxes where water is temporarily stored and then infiltrated into the surrounding soil (Amsterdam Rainproof, 2020e). Figure 9 illustrates infiltration crates under a road. Water from the road is collected at the curb after which it enters the crates. Water can freely infiltrate, and when the maximum capacity of the boxes is met, it overflows to a drainage pipe. The structural integrity of infiltration crates allow them to be implemented on various locations: under fields; roads; parking spaces etc.

Infiltration crates are divided in units to increase applicability in pathways. One unit can store 2.769 m^3. Costs for implementation are expected to be approximately 39,6 million NOK. Annual inspection is expected to cost 4.000 NOK / infiltration crate unit.

Separate sewer system with increased capacity

Changing the sewer system to a separate sewer system would stop the occurrence of CSOs. In order to deal with the increased discharge because of the set definitions for stormwater proof and increasing pressure caused by climate change, the drain system for runoff water in Grefsen itself to the AK 52 needs to be increased in capacity. The drain at manhole 161143 needs to be able to discharge at an additional 7 m^3 / s compared to the current system. This corresponds with a water surplus reduction of 18.461 m^3. The implementation costs for this operation are estimated to be 22,8 million NOK plus an additional 4.000 NOK / year for inspection and maintenance.

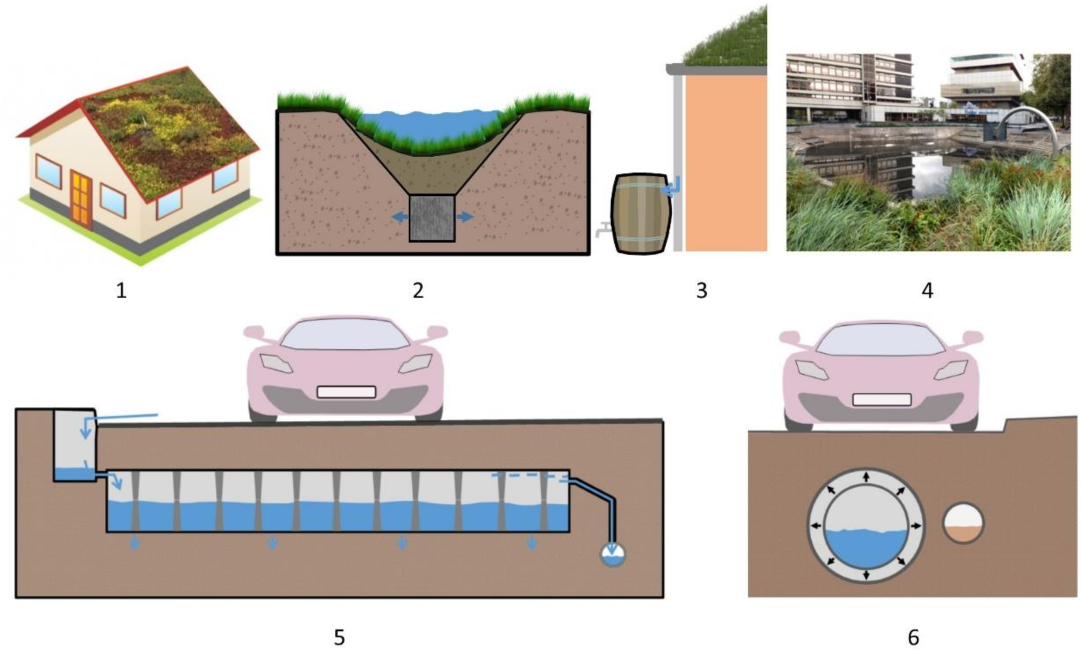


Figure 9. Measure illustrations from left to right: 1) green roof; 2) wadi / rain garden; 3) rain barrel; 4) water square, photo taken by De Urbanisten (sd); 5) infiltration crates; 6) separate sewer system with increased capacity.

4.4 MAPPING ADAPTATION PATHWAYS

This section introduces the adaptation pathways to make Grefsen stormwater proof. Firstly, a general description of the pathways is given, supported by a detailed description of the most nature-based pathway possible. Secondly, the rough, estimated costs are presented and differences among pathways are explained.

4.4.1 THE PATHWAYS

Figure 10 presents possible adaptation pathways for Grefsen to become and remain stormwater proof. Two general remarks can be made about the Figure. First, a transition period is included in the design of the figure. As elaborated on in section 4.2.2, the existing water system does not meet the established definitions of stormwater proof under current precipitation conditions. To bring the current water infrastructure to a desired performance level, large scale measures need to be taken, e.g. a wadi in combination with in infiltration crate unit, a water square or changes to the sewer system. To establish such measures major time consuming steps have to be taken in decision making, planning and designing of measures, and the actual construction of water infrastructure. Therefore, it is unlikely that actions will be taken on the short term. Hence, a transition phase that lasts until 2030 has been included in the figure. The transition period between 2020 and 2030 is meant to plan and construct adaptation actions, meaning that Grefsen will not be stormwater proof in this period. From 2030 onwards, measures are implemented, to make and keep Grefsen stormwater proof from that point.

Secondly, the pathways do not necessarily consist of all measures that are shown in a pathway. All measures that make a pathway are only run through in sequence, if the pathway starts with a return interval of 5 years as a normative event, and later scales the normative event up to a 20-year return interval normative event. If the definition of stormwater proof does not change over time, a smaller part of the pathway is used, meaning that in practice the total number of available pathways is lower. To get the best understanding of how the adaptation pathways figure works, see section 4.4.2 where an example is given for pathway C4.

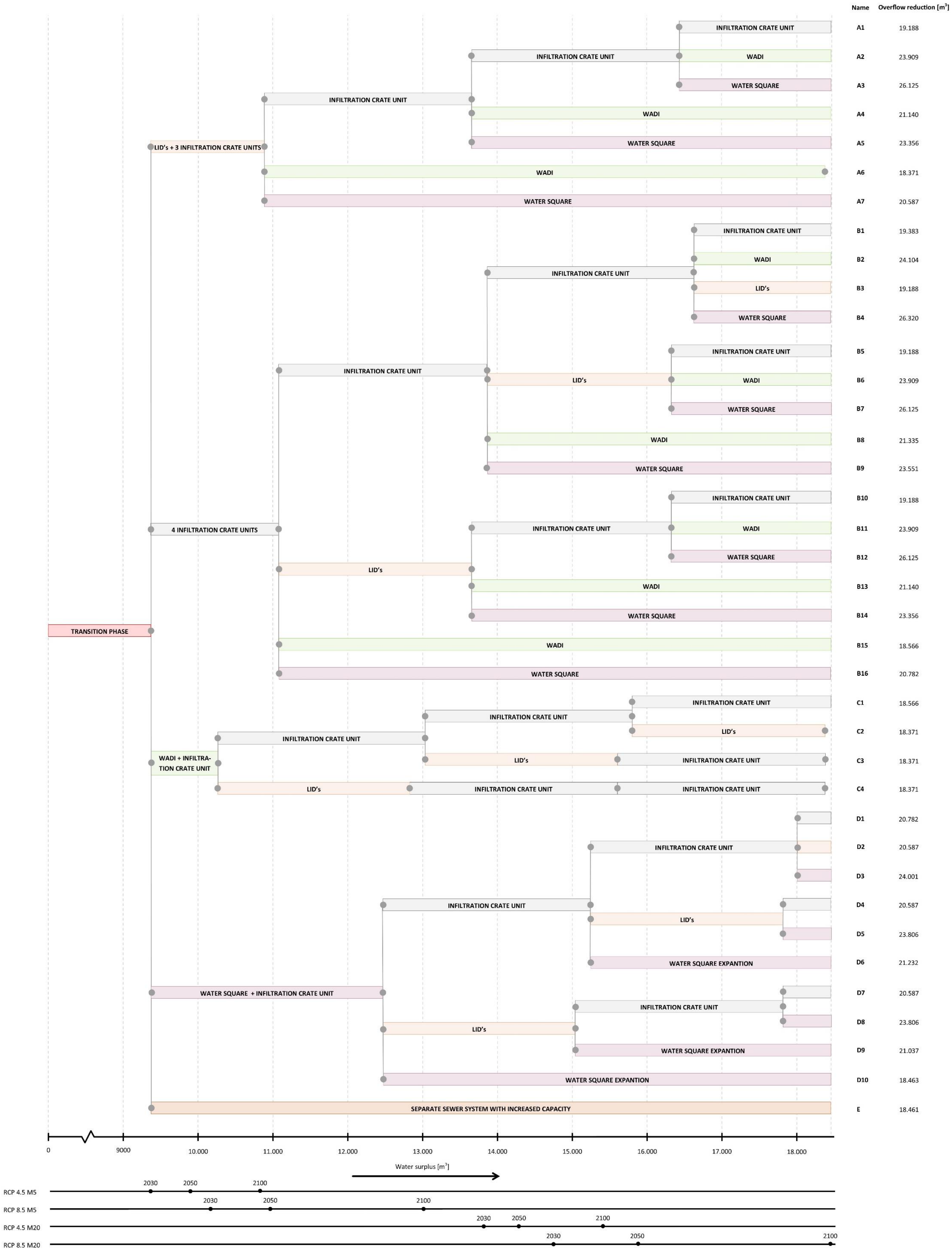


Figure 10. Possible adaptation pathways for Grefsen.

Pathways A1 till A7 start with the implementation of Low Impact Developments (LIDs) with three additional infiltration crate units. When the future water surplus increases, additional infiltration crate units can be implemented in a step-wise manner. At each decision point either a water square or a wadi can be implemented, which makes the area stormwater proof until the end of the century. Note that when a follow up measure is taken, earlier taken measures will remain functional. For example: when the turning point of LIDs in pathway A7 is reached and an additional water square is implemented, LIDs remain functional.

Pathways B1 till B16 start with 4 infiltration crate units. When the demand for storage surpasses the storage capacity of these measures, extra infiltration crates, LIDs, a wadi, or a water square can be chosen as follow up measure. Infiltration crates and LIDs can be implemented in a step-wise manner after that. Wadis or a water square directly prepares Grefsen for 'the worst-case scenario'.

Pathways C1 till C4 start with the implementation of wadis and one infiltration crate unit. Part of the study area has a lower elevation than potential implementation locations for wadis, meaning an additional solution is required in this lower elevated area to establish an effective pathway (see Appendix A). This is also the case for the water square. Because the wadi and water square compete for the same implementation location, pathways beginning with C, do not include a water square. Follow up measures consist of additional infiltration crate units and LIDs. Pathways beginning with C are relatively similar, but differ in the timing of LID implementation.

Pathways D1 till D10 start with a water square and one infiltration crate unit. Possible follow up actions can be infiltration crate units or LIDs, where the timing of LIDs causes divergence between pathways. A third possibility is to expand the water square, this can be done at each available decision point. This research does not consider combinations with wadis because the implementation locations for wadis and a water square overlap, see Appendix A.

Pathway E is not combined with other measures, because it is included to provide contrast to nature-based pathways. This pathway is designed for the worst-case scenario as alterations to the sewer system requires reimplementing the measure. There are no turning points included in pathway E, the sewer system is designed to deal with the maximum possible water surplus until 2100.

4.4.2 A PRACTICAL EXAMPLE

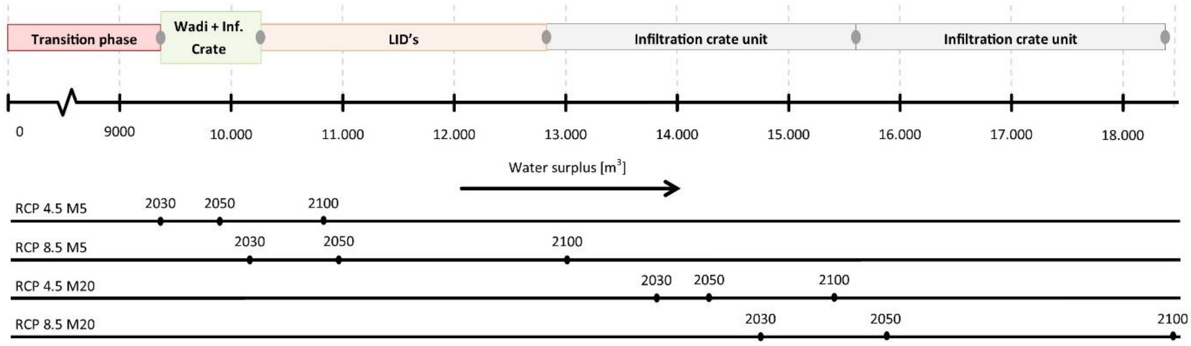


Figure 11. Pathway C4. The figure has similar axes to figure 10. The upper horizontal axe constitutes the water surplus. the lowest four horizontal axes constitute the scenario time lines to see in which year a particular water surplus value is reached.

The Figure above shows pathway C4. The water surplus axis and scenario axes are similar to the axes shown in Figure 10. The first horizontal axis shows the water surplus if no alterations to the current water system would be made. This equals the storage deficit. The water surplus can range from 0 m^3 to 18.461 m^3. The maximum water surplus is to be expected in 2100 under scenario RCP 8.5 with a 20-year return interval for the normative precipitation event, see Appendix E for model outcomes. The scenario axes below the water surplus show at what point in time a certain water surplus is reached. For example, when looking at an M5 precipitation event in RCP 8.5, the water surplus is approximately 11.000 m^3 in 2050. To illustrate: one pathway can be operationalized in four ways. This depends on the scenario. The section below discusses how pathway C4 is operationalized in all four scenarios.

The first scenario applies to RCP 4.5 where stormwater proof is defined by using a return interval of 5 years for a precipitation event. In this scenario the water surplus in 2030 would be 9.461 m^3 if no alterations to the current water infrastructure would be made. So, this is the amount of water that needs to be stored or discharged. The first measures to take are large scale implementation of wadis in combination with an infiltration crate unit. The implementation of these measures will take until 2030, after that point they will be functional. This measure combination can store 10.259 m^3 which is more than is required in 2030. Therefore this combination of measures is in this scenario able to keep Grefsen stormwater proof 2060. At that point the water surplus surpasses the total storage capacity of the wadis and an infiltration crate unit, meaning an additional action needs to be taken. In pathway C4 LIDs are used as an additional measure, which ensures a stormwater proof Grefsen until the end of the century.

The second scenario also uses a 5-year return interval as a normative precipitation event, but applies to RCP 8.5. Here, the water surplus is 10.170 m^3 in 2030. A combination of wadis with an infiltration crate unit is not able to store this amount. To prevent a situation in which a follow up measure needs to be taken just briefly after 2030, LIDs as an additional measure are also already implemented in the transition phase and functional from 2030. In 2095 an extra infiltration crate unit needs to be implemented so that Grefsen is stormwater proof until the end of the century.

The third scenario uses a 20-year return interval as a normative precipitation event in RCP 4.5. Here, the initial transition between the current water system and a stormwater proof Grefsen is substantially larger. A water surplus of 13.815 m^3 is expected for 2030. Directly after the transition phase wadis + an infiltration crate unit, LIDs and an additional infiltration crate unit have to be realized to manage the expected water surplus for 2030. This is enough to remain stormwater proof until 2100.

The fourth scenario uses the same 20-year return interval as a normative precipitation event but uses RCP 8.5 as a climate scenario. Here the combination of wadis and a infiltration crate unit, LIDs and an additional infiltration crate unit is used to bridge the transition phase, but this combination of measures only keeps Grefsen stormwater proof until 2040. At this point an additional infiltration crate unit needs to be installed, so that Grefsen is stormwater proof until 2100.

4.4.3 ECONOMIC VALUATION OF PATHWAYS

Table 4 presents the costs of each pathways until 2100 in million NOK. Basic assumptions for measure costs and all calculations can be found in Appendix D. The Table indicates for each scenario the most expensive (grey) and the cheapest pathway (green). When stormwater proof is defined using a precipitation event return interval of 5 years in scenario RCP 4.5, the costs of all pathways beginning with A are up to 5 times as expensive as alternative pathways. In the other scenarios the pathways that keep using infiltration crates as additional measures remain the highest in cost. The high costs are mostly attributed to LIDs, that turn out to be relatively expensive in implementation, as well as in maintenance. Because LIDs as a measure can only store 2.574 m^3 of water, support from other measures is required. In the most expensive pathways, support of LIDs is entirely done by using infiltration crates. These measures are relatively expensive to implement as they are constructed underground. Additionally, the life expectancy of infiltration crates is estimated to be 50 years, meaning that early implemented infiltration crates have high exchange costs in the future.

Table 4. Pathway cost in million NOK for all scenarios.

	5 year return interval		20 year return interval	
Pathways	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
A1	400,7	442,0	502,3	525,4
A2	400,7	442,0	502,3	509,6
A3	400,7	442,0	502,3	519,7
A4	400,7	442,0	464,4	464,4
A5	400,7	442,0	478,5	478,5
A6	400,7	411,1	413,6	413,6
A7	400,7	422,4	427,7	427,7
B1	203,2	244,4	304,8	326,3
B2	203,2	244,4	304,8	311,5
B3	203,2	244,4	304,8	404,4
B4	203,2	244,4	304,8	321,0
B5	203,2	244,4	401,1	424,2
B6	203,2	244,4	401,1	408,3
B7	203,2	244,4	401,1	418,5
B8	203,2	244,4	266,8	266,8
B9	203,2	244,4	281,0	281,0
B10	203,2	397,0	502,3	525,4
B11	203,2	397,0	502,3	509,6
B12	203,2	397,0	502,3	519,7
B13	203,2	397,0	464,4	464,4
B14	203,2	397,0	478,5	478,5
B15	203,2	213,5	216,0	216,0
B16	203,2	224,9	230,2	230,2
C1	86,7	114,4	165,2	191,8
C2	86,7	114,4	165,2	298,4
C3	86,7	114,4	362,8	403,0
C4	173,9	310,5	347,1	388,3
D1	77,7	94,1	142,7	203,0
D2	77,7	94,1	142,7	240,2
D3	77,7	94,1	142,7	195,0
D4	77,7	94,1	177,6	352,6
D5	77,7	94,1	177,6	344,2
D6	77,7	94,1	134,9	143,5
D7	77,7	141,3	341,3	388,7
D8	77,7	141,3	341,3	380,3
D9	77,7	141,3	326,1	342,2
D10	77,7	85,2	95,1	95,1
E	201,5	201,5	201,5	201,5

CHAPTER 5. DISCUSSION

This chapter reflects on the obtained results by first looking at methodological choices that have influenced the end result, followed by a reflection on the adaptation need. Lastly a personal view is given on what pathways are attractive at this moment.

5.1 METHODOLOGICAL CHOICES

This paragraph reflects on methodological choices that were made during the research and how this influences the end result.

5.1.1 ALTERNATIVE WAYS TO DEFINE STORMWATER PROOF

According to Werners et al. (2020), the focus on a specific policy objective or an uncontested goal – as I do in this research – is an important element in making quantitative and semi quantitative pathways. However, an unambiguous definition of stormwater proof did not present itself during this research. To cover the uncertainty surrounding the definition, and to show the effect of using different definitions for the adaptation pathways, two ways of defining stormwater proof were taken up: '*Grefsen is stormwater proof if no Combined Sewage Overflow (CSO) takes place during a 60-minute precipitation event with a return interval of 5 years'* – and – '*Grefsen is stormwater proof if no CSO takes place during a 60-minute precipitation event with a return interval of 20 years'*. As there are still uncertainties surrounding these definitions, there are three implications to discuss that affect the end results of this research: i) the elements that are used to establish the definition of storm water proof; ii) the values that were chosen as a normative event and for event duration; iii) the matter of constructing adaptation pathways with two possible definitions of stormwater proof. The following section discusses all these implications.

A first factor that had a large influence on the outcomes are the elements that were used to establish the definition of stormwater proof. The elements used in the definition are CSOs as a main problem, and the use of a normative precipitation event to indicate the required level of performance. Both elements could have been chosen differently. Using CSOs as a central theme in the definition of stormwater proof was done because the municipality pointed CSOs out as the main stormwater related problem in Grefsen (Oslo Komunne, n.d. a). Factors as damage to property and water on the streets were not used to define stormwater proof. These are usually factors that have a larger influence on the everyday life of citizens. Therefore, it is likely that the return interval of the normative event that defines stormwater proof would have been larger if these factors were included in the definition. This would have resulted in a larger adaptation need, and therefore a smaller role for nature-based measures, as discussed further in this section.

The use of a normative precipitation event to indicate the required level of performance is another element that was used in the definition of stormwater proof. Alternative definitions of stormwater proof could have included a specific number of overflows, volume of sewage that flows into the Akerselva or even pollution restrictions in the Akerselva. These alternative definitions could address the problem of pollution even more specifically. However, a specific volume or frequency would not have changed the results directly as artificial precipitation events were used to calculate the water surplus. A normative event is still required in this case to test the water system. If the definition of stormwater proof would have included restrictions on emissions to – or concentrations in – the Akerselva, the definition of stormwater proof would have been more variable. Emissions to- and concentrations in surface water are variable and largely dependent on factors such as the quality of the received water and the bio-chemical processes in the river bed and water, meaning the allowed overflows can vary in a matter of days (Klemetson, 1985; Mulliss, 1996). In this case the quantity of CSOs that is allowed is variable over time. What this means for the adaptation pathways is that the range in which adaptation actions fall is larger because a larger uncertainty is to be covered.

A second factor that had a large influence on the outcomes were the values that were actually chosen to define stormwater proof. Both the normative events of a 5- or 20-year return interval respectively, as well as the event duration of 60 minutes could have been chosen differently. In case a lower return interval was chosen to define stormwater proof, or a shorter event duration, the water surplus would have been lower as well. In case a higher return interval was chosen to define stormwater proof, or a longer event duration, the water surplus would have been larger. This is important for the role of nature-based solutions in the adaptation pathways. Estimations of the storage capacity of nature-based solutions such as Low Impact Developments (LIDs) and wadis were made based on what was physically possible, whereas the storage capacity for technocratic measures was estimated based on how much storage was required. So, the smaller the water surplus, the more prominent the role of nature-based solutions can be. The larger the water surplus, the more prominent the role of technocratic solutions will be, because these measures have fewer limitations to cope with large quantities of water.

A third factor that had a large influence on the outcomes is the matter of constructing adaptation pathways with two possible definitions of stormwater proof. Having multiple ways of defining stormwater proof has two effects: i) it increases the range within which the adaptation measures fall; ii) it makes the starting point and thus the size of the initial transition to a stormwater proof situation as described in 5.2 more uncertain. Figure 12 shows that the difference in future water surplus for M5 and M20 precipitation events (indicated in purple) in the same climate scenario is substantially larger than the difference in water surplus resulting from different climate scenarios RCP 4.5 and RCP 8.5 (indicated in yellow). Thus, these results show that the definition of stormwater proof results in more uncertainty regarding the water surplus (and therefore the required adaptation measures) than climate change. But whereas climate change induces a gradually increasing pressure, the difference in normative events causes an abrupt change in the stormwater surplus. This research accounts for multiple ways of defining stormwater proof, but the scenarios do not include a situation where the normative event is up-or downgraded, nor are the pathways described in that way. I do, however, consider it a realistic option that a normative precipitation event does not remain the same until 2100 due to changing policies, economics, natural factors and societies perspective on what is acceptable in terms of CSOs and what is not.

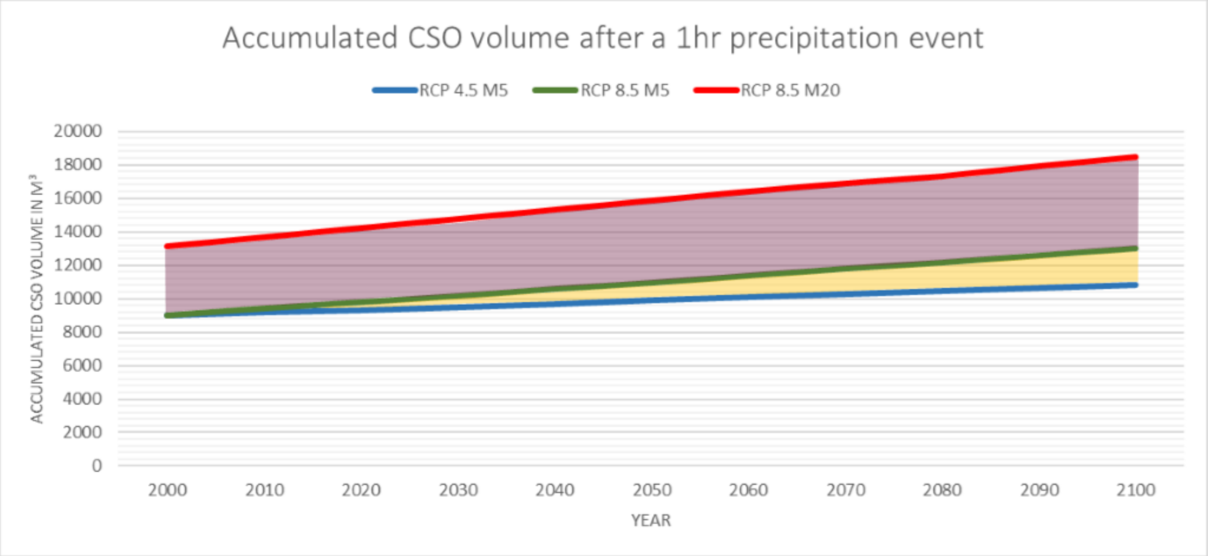


Figure 12. The area marked in purple indicates the difference between the water surplus of a 5-year precipitation event and a 20-year precipitation event in climate scenario RCP 8.5. The yellow area indicates climate induced variability in the water surplus for a 5-year event in RCP 4.5 and RCP 8.5. This figure shows that different ways of defining stormwater proof causes a substantially larger spread than climate variability.

5.1.2 Choosing representative measures

Assumptions were made regarding both the choice of stormwater measures and defining the measure properties. These choices were made using basic criteria and this resulted in some degree of subjectivity. Therefore, future studies might find another set of adaptation actions fits better to their results. What eventually matters most is that the variety of stormwater measures is represented, which can be done in multiple ways. Increasing the representation of stormwater measures can only be done by including more measures in the analysis. However, this would have resulted in a large number of pathways, leading to significant overlap and complicating the analysis. Instead, the choice made in this research to focus on seven measures that were determined in consultation with experts resulted in a comprehensive overview of adaptation measures for Grefsen.

Additionally, there is uncertainty regarding how the measures chosen here would function in the field. This influences which measures are most suitable for different areas in Grefsen. A few examples: if infiltrating water turns out to be problematic because of soil properties, infiltration crates are less suitable. In that case regular underground storage that can empty in the sewer could be an alternative. In case of wadis and raingardens, low infiltration capabilities require additional drainage so that water is delayed before reaching the sewer. However, the flexibility of several of these measures means the difference between the theoretical functioning of a measure and its actual water storage capacity and / or functioning can be minimized. For example, in case the water storage of green roofs turns out to be lower, other LID parameters - such as the size of the rain gardens - can be adjusted to compensate for the reduced storage. Therefore, field testing as well as flexible implementation are a vital part of making Grefsen stormwater proof.

To summarize, different choices could have been made in choosing adaptation measures and making estimates for their storage potential, but adjusting parameters such as the size of LID measures allow to still get the same results. Different measures and their functioning do not necessarily change the course of the pathways, but only the associated costs. It is recommended that future studies conduct a sensitivity analysis to compare the impact of using different measures, but this was beyond the scope of the current research.

5.1.3 DETERMINATION OF THE WATER SURPLUS AND HOW THIS IS REDUCED BY STORMWATER MEASURES

The determination of the effectiveness of the pathways has been theoretically rather than practically. There are a number of remarks to be made on how the water surplus was calculated and how it is assumed to be reduced by stormwater measures. Firstly, the water surplus calculations involved some uncertainty. The water surplus was calculated by modelling the effect of statistical precipitation events on the current spatial situation and existing water infrastructure. Thus, it is implicitly assumed that future changes in the built up environment will have a neutral influence on the discharge of stormwater. However, future infrastructure changes could impact the discharge of stormwater. When possible future changes in the build environment are also included, the uncertainty surrounding changes in the future water surplus could be different than predicted here. Secondly, the ability of measures to reduce the water surplus. The main assumption here was that the water surplus is reduced by the exact quantity of storage that stormwater measures can offer. However, the measures are not modelled. The statement whether a measure can work in practice is therefore less valid. There are a number of issues that could lead to a reduced storage capacity in practice:

- Storage facilities can already be (partly) saturated as a result of earlier precipitation events. Future studies can use models that do not only look at single precipitation events to examine the effectiveness of water storage of certain measures;
- Because measures were not modelled, runoff patterns are also neglected. Some measures can be situated in such a way that in reality the expected amount of stormwater cannot be supplied to a storage facility.

As a result, this uncertainty could mean that a measure cannot meet the estimated storage capacity. In this case, additional measures are required, alternative measures must be used, or costs may be higher. Therefore, it is recommended that future studies simulate the functioning of stormwater measures in Grefsen.

5.1.4 IMPLICATIONS OF THE COST ESTIMATES

The objective of this study was to explore pathways for Grefsen to become and remain stormwater proof. Being stormwater proof was operationalized in such a way that it accounted for the financial feasibility of adaptation measures. However, the economic appraisal was not the primary focus here, and the main conclusion of this research does not change because of cost estimates. The cost estimates role in this research was to put the pathways into perspective and to get an indication of whether green adaptation strategies could be a viable alternative to technocratic stormwater solutions. This insight is affected by the discount rate used and limited by the lack of a benefit analysis. The discount rate is considered low by some economists (Hagen et al., 2012). A higher discount rate affects the pathway cost because in various cases high cost measures are implemented on a longer term. Additionally, some measures such as LIDs and infiltration crates have maintenance cost that are almost equivalent to the implementation costs every 50 years. A higher discount rate would result in lower total pathway costs.

The conclusions are also limited because additional monetary and societal benefits of green measures were not considered. The costs are therefore not entirely representative for the real value of pathways. It is known that green measures such as LIDs have various benefits such as increased biodiversity, energy savings, awareness raising and positive effects on spatial quality. However, there are also co-benefits of technocratic solutions that should not be overlooked. For example, a separate sewer system for example reduces costs for water purification, because the current combined system also transports ‘clean’ rainwater. Future studies are advised to take this into account.

Besides there being possible benefits, there is also the issue of cost distribution. The results of this research showed that pathways with LIDs have the highest costs. What is not taken into account however is that maintenance costs for LIDs are mostly on account of private owners, whereas costs for measures in public space is usually for the municipality. This cost distribution is also important for what are attractive adaptation actions from the municipalities point of view and should be included in future studies.

5.2 TRANSITIONING TOWARDS STORMWATER PROOF WITH RESPECT TO CLIMATE CHANGE UNCERTAINTY

The adaptation pathways approach is used– by authors that use the concept in a similar manner – to anticipate increasing pressures that over time render strategies ineffective or lead to system failure. For example, Haasnoot et al. (2019) study revolves around uncertainty regarding future performance of long lived – climate change sensitive infrastructure. Kingsborough et al. (2014) look at long-term adaptation pathways that deal with the increasing urban heat island effect due to climate change. Manocha & Babovich (2017) use the adaptation pathway concept for the planning of urban drainage infrastructure under the uncertainty of socio-economic developments and climate change. Tanaka et al, (2015) look at the course of adaptation for food production with respect to the progress of climate change. The main assumption in the above mentioned studies is that the current situation is still acceptable, and that uncertain and external factors – such as climate change – gradually increase pressure on existing infrastructure or management practices until the existing infrastructure or management practices drop below a deceive performance level that requires change. This principle is visualised in Figure 13.

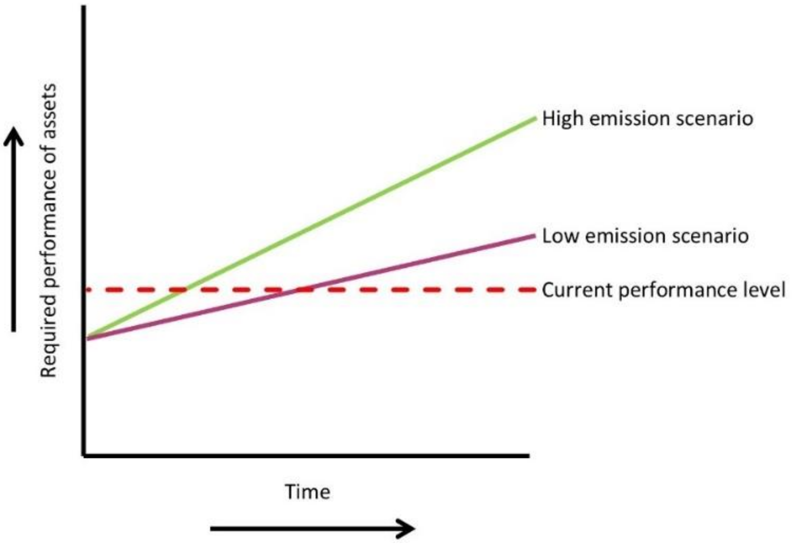


Figure 13. An illustration of the context in which quantitative adaptation pathways is used in comparative studies. The current performance level of assets is sufficient at the start of the graph. It is the gradually increasing pressure of climate change that at some point in the future causes assets to not perform adequately anymore.

The results of this research show that Grefsen does not currently meet the definitions of stormwater proof, and that – in contrast to literature on quantitative pathways – major action is required at the start of each pathway (Kingsborough et al., 2014; Tanaka et al., 2015; Manocha & Babovich, 2017; Haasnoot et al., 2019). This transition casts a shadow over the relatively small uncertainty caused by future climate change. For a precipitation event with a return period of 5 years, the choice between a low- and high emission scenario results in a maximum water surplus difference of 2.182 m^3, whereas at least 9.336 m^3 of storage is needed to even meet the adaptation need in 2020. When looking at a 20-year return period normative event, climate change variability leads to a maximum water surplus difference of 3.060 m^3, whereas the initial transition to make Grefsen stormwater proof at this moment requires at least 13.524 m^3 of storage. These large differences between the initial transition to become stormwater proof and the differences between a low- and high emission scenario are visualised in Figure 14. For both definitions of stormwater proof pressure from climate change gradually increases pressure on the water system, as it does in other reviewed literature (Kingsborough et al., 2014; Tanaka et al., 2015; Manocha & Babovich, 2017; Haasnoot et al., 2019). The difference is that this literature would have a starting point at an accumulated CSO volume of 0 m^3. Thus, in this case the current system would function as desired and climate change would be the factor that causes a failure of the system to meet the required demands. However, here it was found that first the large gap between the current – and desired situation needs to be closed. This has a great impact on the adaptation pathways and the eventual added value of using a quantitative adaptation pathway approach to deal with climate change. Because the initial transition is relatively large compared to the climate change induced range of water storage shortage, measures in the pathways are dimensioned to deal with large quantities of water. Hence, these measures operate in a larger value domain than the difference in water surplus brought about by climatic uncertainty. Measures for pathways in this research are specified to store water in this large value domain. As a result, a single measure is often enough to cover the complete domain of climatic uncertainty. Therefore, the traditional pathway idea of a sequences of measures to deal with the increasing climatic pressure is less applicable here.

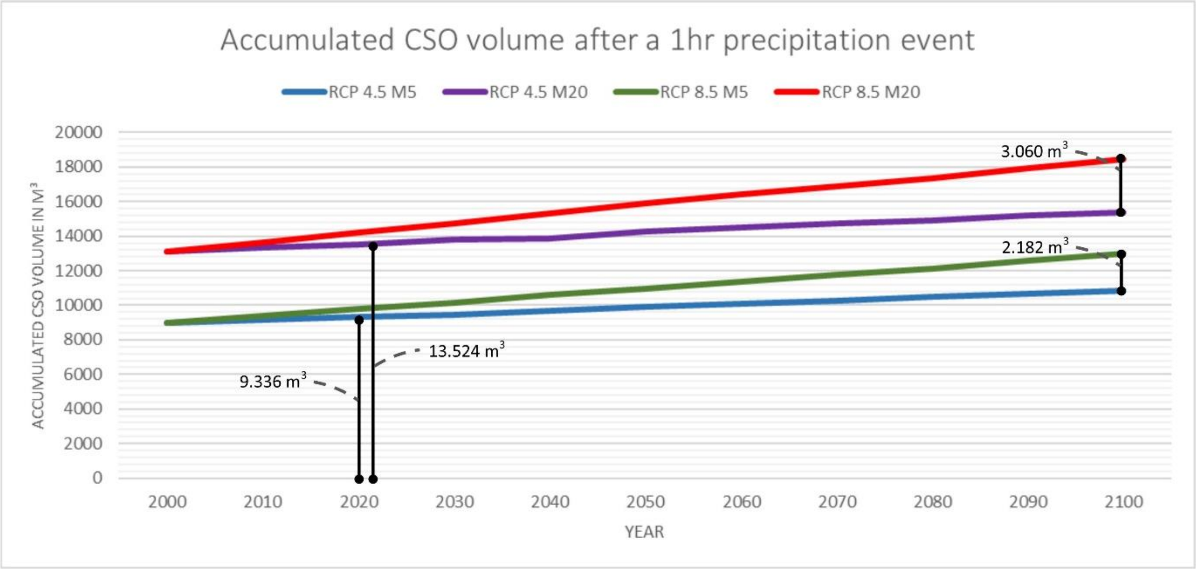


Figure 14. The relative difference between the initial transition to become stormwater proof in 2020 and the maximum climate induced variability in accumulated CSO volume in 2100.

5.3 PATHWAYS THAT STAND OUT

The purpose of this study was to explore possible options for Grefsen to become and remain stormwater proof until the end of the century. In this thesis, 38 pathways are presented that are expected to ensure a stormwater proof Grefsen. The next course of action was to assess what actions need to be taken now based on the results presented in this research. Therefore, I first reflect on pathways that stand out from the perspective of urban greening, costs or enhancing flexibility.

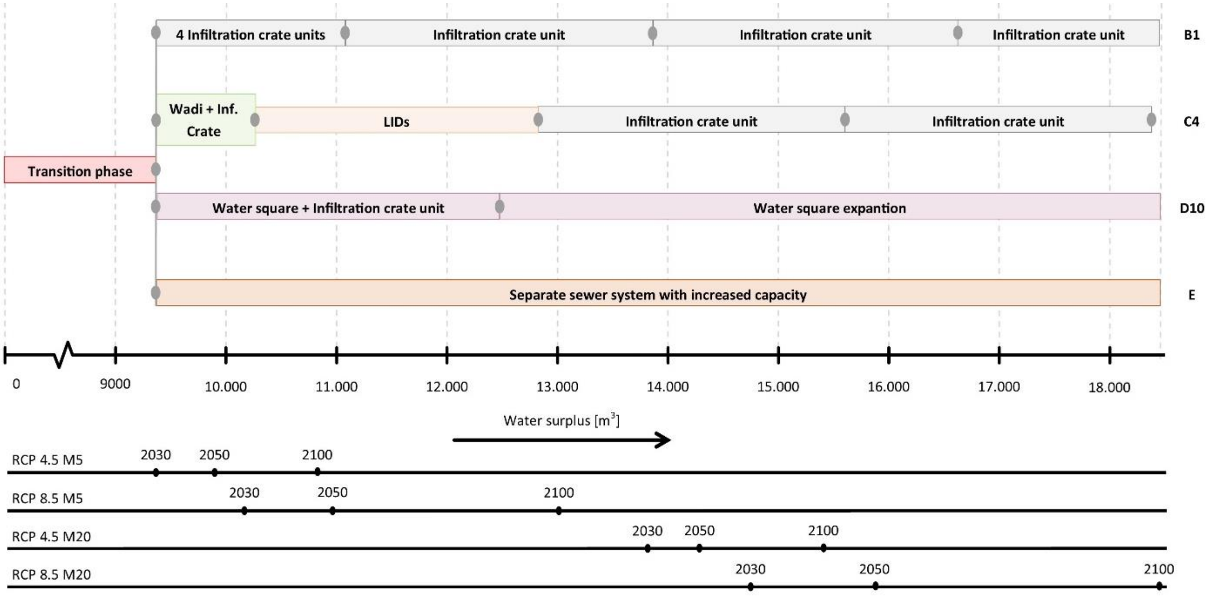


Figure 15. Adaptation pathways that stand out from the perspective of urban greening, costs or enhancing flexibility.

The first pathway that stands out is pathway B1. This pathway consists entirely of infiltration crates and thus has many possibilities for spatial implementation. This measure can be implemented under various surfaces while preserving the existing functionality of the area. Also, infiltration crates can be implemented with great flexibility: they can be installed in phases and they can be combined with most of the presented stormwater measures. On top of that, it is possible to diverge from the storage units as described in this research, meaning a reactive approach to climatic changes and changing policies is also a possibility.

The second pathway that stands out is pathway C4. This pathway is most in line with the commitments of the municipality of Oslo to enhance urban greening. Pathways C4 is the greenest pathway possible. It starts with a wadi, which requires support from infiltration crates in the lowest elevated parts of Grefsen. Pathway C4 contains the same measures as pathway A6, but wadis are implemented from the start, followed by LIDs. Thus, in scenarios where the water surplus remains relatively limited, nature-based solutions are well-suited adaptation measures. If the circumstances require more storage, infiltration crates will be used to deal with the remaining water surplus.

Another interesting pathway is D10. This pathway consists of two water squares in combination with an infiltration crate unit. This pathway stands out because it has the lowest expected costs due to relatively low maintenance- and renovation costs. Another benefit is that water squares can be designed to enhance urban greening and fulfil other functions.

The last pathway to reflect upon is pathway E. This pathway consists of increasing the capacity of the sewer system and subsequently discharging runoff water as quickly as possible. This approach is viewed by multiple authors as the traditional way of dealing with stormwater, and is therefore included for comparison to nature-based solutions (Holman-Dodds et al., 2003; Che et al., 2014). This traditional approach to stormwater management has been regarded as less cost effective than new and innovative stormwater solutions such as BGIs (Blue Green Infrastructure) and LIDs (Montalto et al., 2007; Houle et al., 2013). The Oslo municipality even stated that 'LID solutions are often cheaper than an underground pipe system. Society could save up to 50% costs by using these measures' (Oslo Kommune, n.d.). Based on the results of this study however, it appears that in this case dealing with the water surplus by means of a sewer system is – relative to green infrastructure – a viable alternative, and even cheaper than most other pathways. Especially when LIDs are used the costs increase substantially. However, it must be noted that this research only considered the total life cycle cost, and not additional benefits unrelated to stormwater management, and that LID maintenance costs are not for the municipality to bear. Nonetheless, a traditional way of dealing with stormwater does prove itself to be relatively low in cost while simultaneously being able to deal with the large value domain water surplus.

5.4 RECOMMENDATIONS

There are various interesting adaptation pathways to make and keep Grefsen stormwater proof until 2100. However, as discussed in this chapter, there are several factors that obstruct recommending the best pathway at this moment. Therefore, it is advised to first resolve methodological issues such as how to define stormwater proof. If the range in which adaptation actions can fall is narrowed down, even more 'to the point' pathways are possible. An unambiguous definition of stormwater proof will also lead to the definitive range of the water surplus. Based on the results of this research I expect that, even with an unambiguous definition of stormwater proof, the water surplus will be in the same large value domain as it is at the moment. This means that the main focus of making Grefsen stormwater proof is still on filling 'the storage gap' that currently exists. If an unambiguous definition of stormwater proof means that pathways as presented in this research are no longer relevant, it is advisable to use transitional adaptation pathways, instead of the quantitative adaptation pathway approach as used in this research.

Besides dealing with these structural issues it is recommended to include field testing and modelling of measures in future research. This increases accuracy of estimations for real-life functioning of stormwater measures. Furthermore, additional research is required to put pathways into perspective. Legal and social feasibility are not accounted for in this research, but these factors are vital in decision making. Also, the economic appraisal needs to be improved by first looking into (monetarized) benefits of pathways, as well as the distribution of costs and benefits.

CHAPTER 6. CONCLUSION

Uncertainty about future conditions complicate the formulation of suitable response strategies to deal with excess stormwater, increasing the need for a flexible, step-by-step approach. This research therefore had the objective *''to establish adaptation pathways that explore the possibilities for Grefsen to become and remain stormwater proof until 2100''.* In line with the commitments of the municipality to make Oslo greener, there was a special focus on dealing with excess stormwater by using nature-based and vegetated stormwater solutions.

The 38 adaptation pathways found in this research have shown that both technocratic and nature-based solutions can be implemented to vastly reduce the expected future water surplus, and thus reduce Combined Sewage Overflows (CSOs). The large-scale implementation of wadis in particular can be used to substantially reduce CSOs while also 'greening' Oslo. Pathways that consist of only of nature-based solutions are not enough to make and keep Grefsen stormwater proof. Low Impact Developments (LIDs) do not have the required storage capacity to make Grefsen stormwater proof and wadis always require support from infiltration crates because of limitations in spatial implementation. Thus, whereas there are ample options to include nature-based stormwater solutions in adaptation pathways, these measures always need to be implemented in combination with a technocratic stormwater solution in order to make Grefsen stormwater proof.

Besides exploring the possibilities for Grefsen to become and remain stormwater proof by using nature-based solutions, further useful insights can be gained from this research. These can be summarized as follows:

- Large differences in costs exist between the pathways. Pathways that include LIDs are usually more expensive whereas a pathways that uses water squares is – by a large margin – the cheapest way to reduce the water surplus and make Grefsen stormwater proof. A traditional stormwater management approach that uses an enlarged sewer system designed be able to deal with the most severe precipitation event and climate change scenario, can compete with most pathways in terms of costs. In all cases, information on the benefits and the distribution of costs can shed light on whether a pathway is actually viable.
- Using a step-by-step approach and enhancing flexibility can be done optimally by using infiltration crates. They can be used on a large variety of locations, they can often be combined with other measures, and one does not necessarily have to stick to the specific unit quantities used in this research. It is therefore possible to respond effectively and reactively to adaptation needs induced by climate change.
- No unambiguous definition of stormwater proof exists yet. The range of potential definitions of stormwater proof presented in this research induces a larger difference in the water surplus than variations in water surplus because of differences in climate scenarios.
- For both ways of defining stormwater proof, a large transition is required from the current situation to a desired situation. This resulted in pathways that operate in a large value domain, whereas the range of the water surpluses for different climate scenarios belongs to a relatively small value domain.

Several recommendations were made with regard to the results of this research. These can be summarized as follows:

- Perform further research on how stormwater proof can be defined and establish an unambiguous definition of stormwater proof;
- The emphasis of current water management should be on the transition that needs to be made to make Grefsen stormwater proof at this moment, as they are currently not stormwater proof. Challenges caused by climate change can be taken into account when choosing adaptation measures, but are not the main priority yet;
- Include field testing and modelling of stormwater measures in future research to increase the accuracy of storage estimations;

- Legal and social feasibility are not accounted for in this research, but are vital in decision making. Additional research on the feasibility is therefore required;
- In order to make a conscientious decision on what adaptation pathways to take, (monetarized) benefits as well as the distribution of benefits and costs should be studied.

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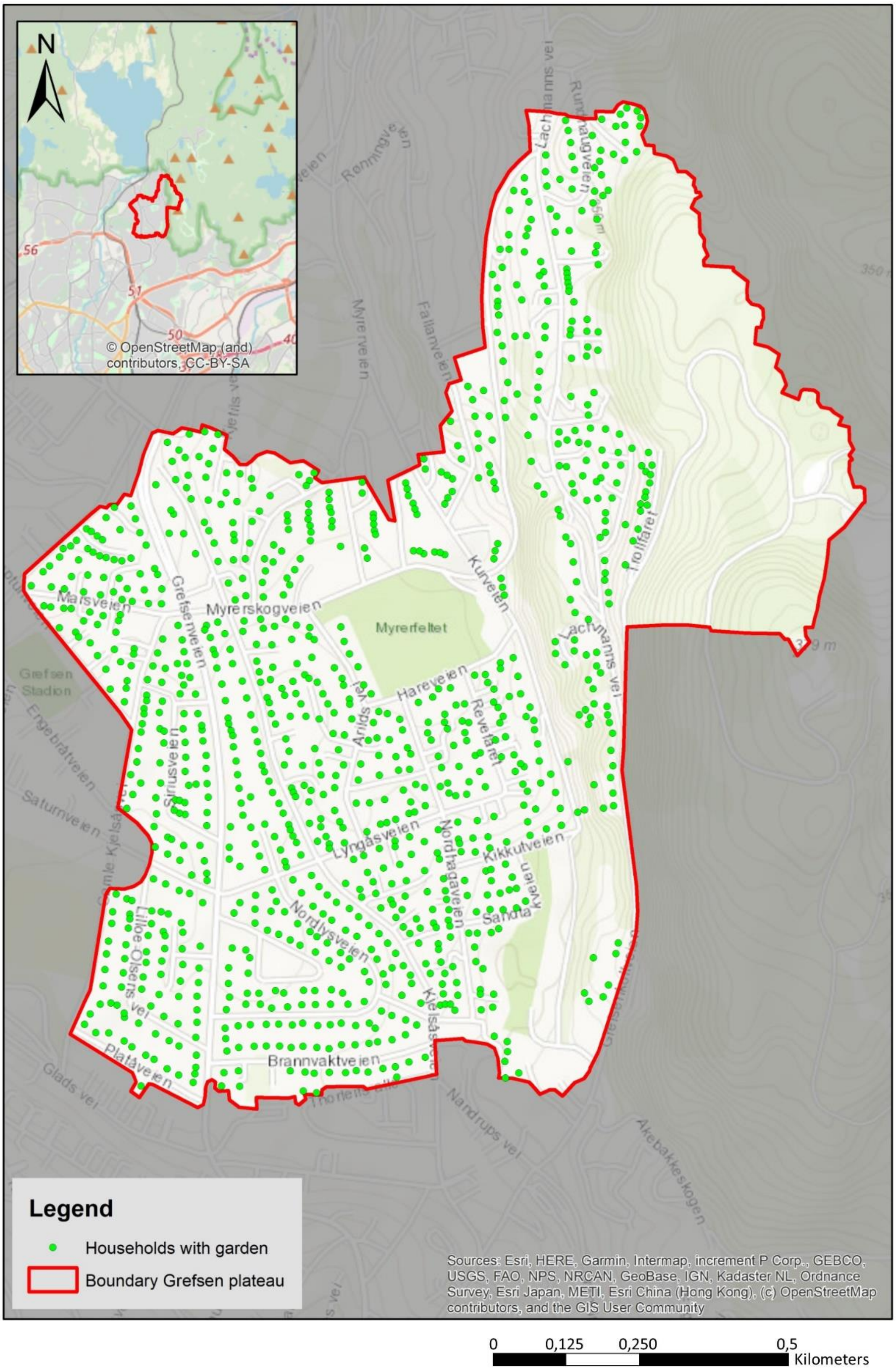
APPENDIX A. MAPS OF GREFSEN

Figure 16. Roofs in Grefsen.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 17. Households with garden in Grefsen.

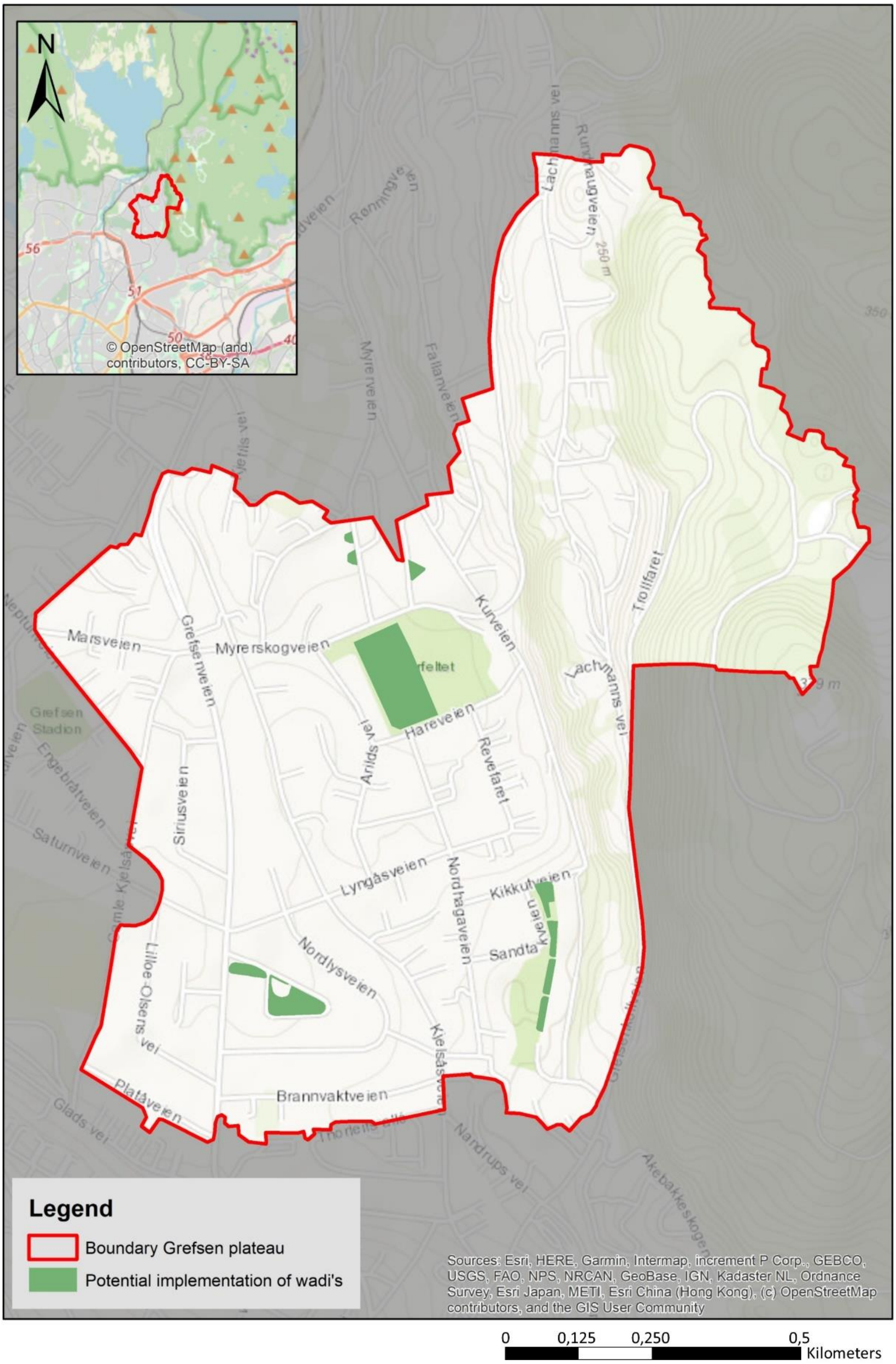
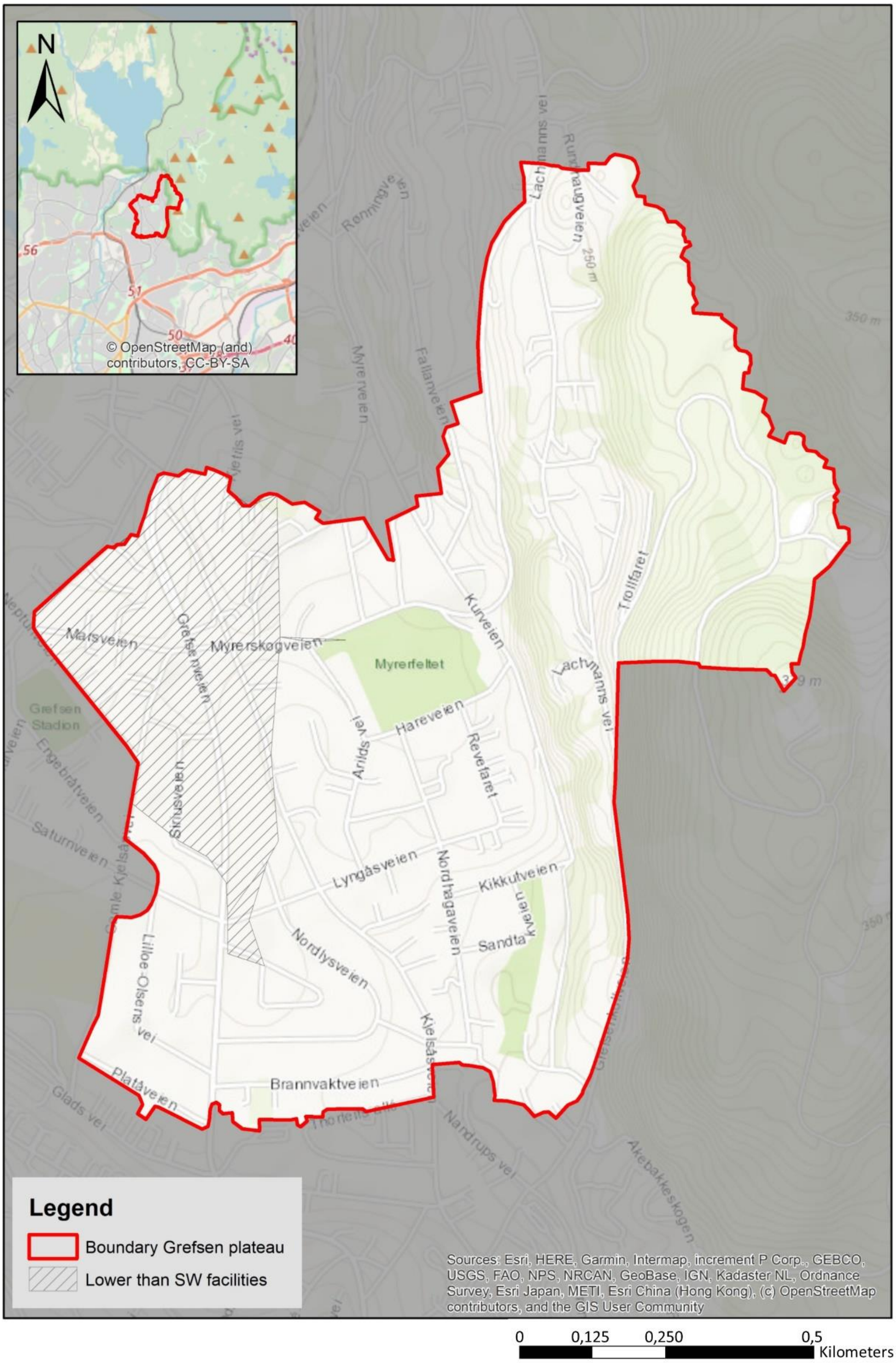


Figure 18. Proposed implementation locations for wadis.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 19. approximately 15 % of Grefsen has a lower elevation than potential implementation locations for large scale wadis or water squares.

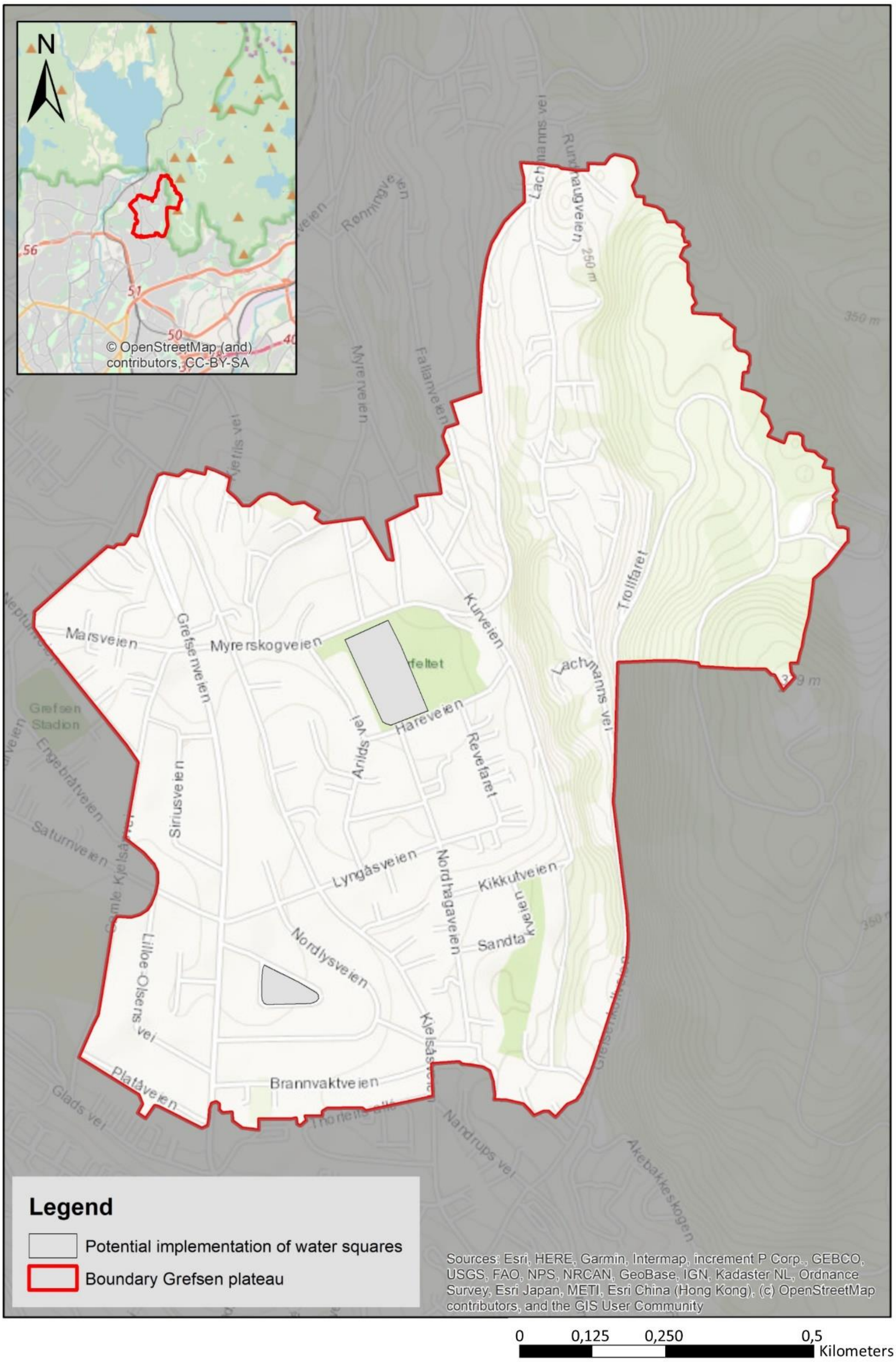


Figure 20. Proposed implementation locations for a water squares.

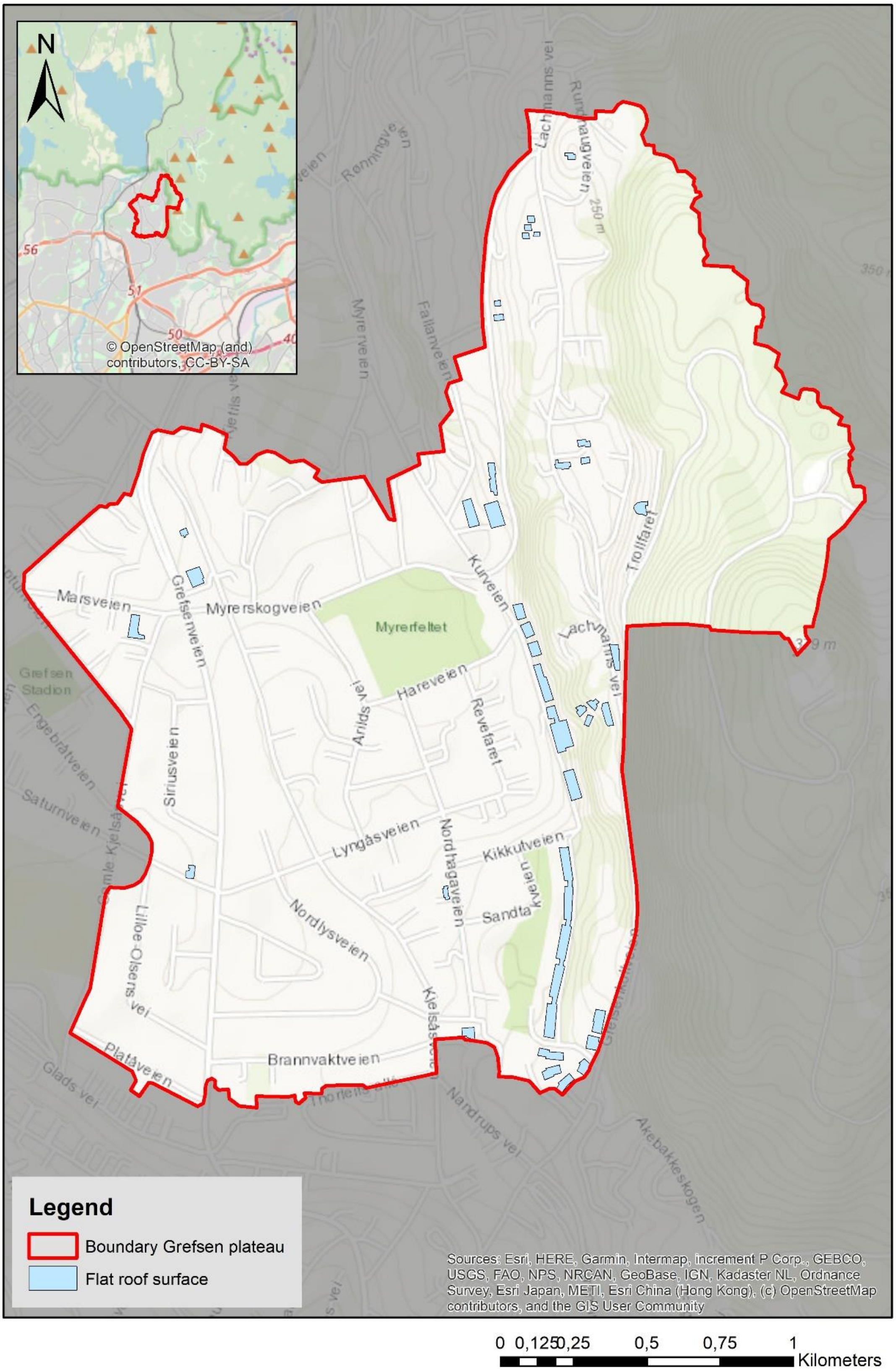


Figure 21. Flat and level roofs in Grefsen.

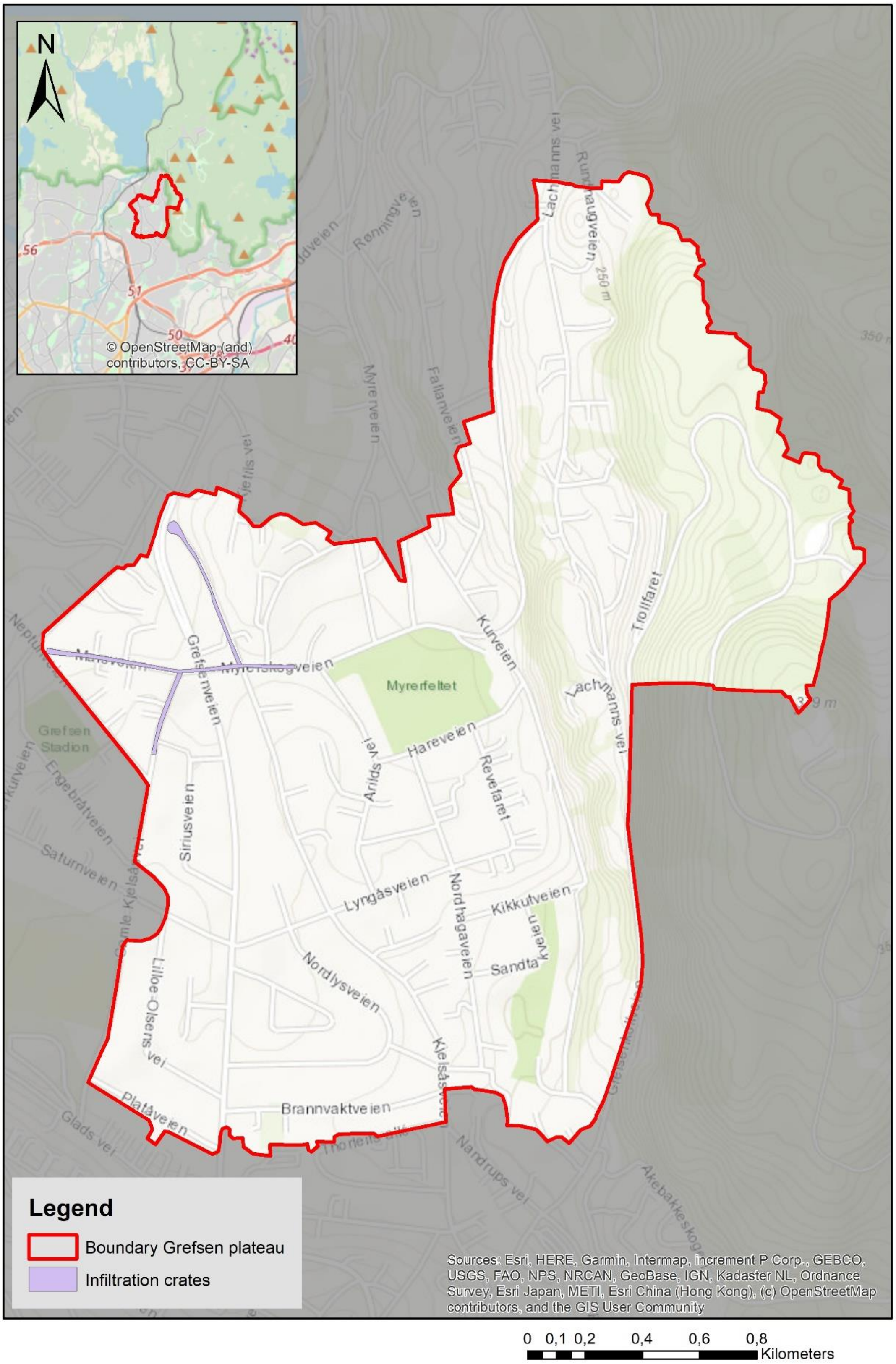


Figure 22. Proposed location for one infiltration crate unit in the lowest 15% of Grefsen.

APPENDIX B. LIST OF STORMWATER MEASURES

Table 5 and 6 provide an overview of all measures that have been found with the use of the Amsterdam rainproof toolbox and an additional literature scan.

Table 5. An overview of all nature-based stormwater measures considered within the research.

Nature based measures		
Retain	**Infiltrate**	**Discharge / guide**
Infiltration strip with above ground storage	Infiltration strip with above ground storage	Discharge trench
Ditch	Ditch	
Wadi	Wadi	
Replacing tiles with green	Replacing tiles with green	
Green roadsides	Green roadsides	
Green tram tracks	Green tram tracks	
Garden with height difference	Garden with height difference	
Rain garden	Rain garden	
Green garden separation	Green garden separation	
Facade garden	Facade garden	
Green roof		
New surface water		
Water retaining planter		
Rain water fence		
Rain barrel		

Table 6. An overview of all grey stormwater measures considered within the research.

Grey measures		
Retain	**Infiltrate**	**Discharge / guide**
Infiltration crates	Infiltration crates	Curbs and gutters
Water square	Infiltration well (Soakaway)	Separate sewer system with increased capacity
Water playground	Reversed drainage	Increase drainage to Akerselva
Water roof	Permeable pavement	Concave roads
Storage under buildings	Infiltration trenches	Storm drain
Underground storage unit		

Measures as presented in Table 5 and 6 will not all be taken up in the construction of pathways as this would lead to overlap and a too large number of pathways for effective accessibility. Therefore, seven measures have been chosen to represent the variety of stormwater measures as good as possible. For selecting representative green measures the following considerations have been made:

- Many measure variants can be described as vegetated plots of land without pavement that catch, retain and infiltrate water. Literature commonly refers to these kind of measures as 'swales' (Davis et al., 2012; Mobron et al., 2019). To best represent this measure type, one swale is chosen to be implemented in public space, and one swale is chosen to be stimulated to be implemented by private parties. Wadis are chosen to be the representative measure to be implemented in public space, because it is assumed to have a the largest storage capacity, see Appendix C. Because different types of swales differ relatively little among the types, a raingarden is – at random – chosen to be representative for measures to be stimulated for implementation on private property.
- At the moment a number of LID measures are being used and researched by both NIVA and the municipality of Oslo. Including these measures increases the relevance of the research within the NWW project. Rain barrels and green roofs are therefore also included in the construction of pathways.

In order to select representative technocratic solutions, the following considerations have been made:

- Up front two measures are excluded for pathway construction. Gutters and curbs used to guide water are likely to be needed to collect water for other measure types such as wadis and water squares, but because this is a small-scale measure, it is seen as part of another measure, and not as a stand-alone measure. Another measure, the water roof, is also not taken up in the final selection because only 20.900 m^2 of roof surface is completely flat and level in the study area, which makes that it is not in the storage domain as other large scale technical solutions.
- Two ways of storing water have been examined: underground and above ground storage. Above ground, the water square and the water play square are a possibility, both can be identical depending on how they are shaped. Therefore, – at random – the choice has been made to use a water square for pathway construction. Underground, a choice can be made between underground storage and infiltration crates. The choice has been made for infiltration crates because they can infiltrate freely under gravity, which reduces efforts for discharging the stored water.
- The current sewer system in Grefsen is mostly combined, which causes The largest risk for CSOs. Therefore the last technocratic measure that will be used in pathway construction will be a separate sewer system with increased capacity. This measure as a ‘traditional’ approach of dealing with stormwater is included to provide contrast to other measures.

APPENDIX C. ESTIMATIONS FOR STORAGE POTENTIAL OF MEASURES

Measure: Extensive green roofs

Storage potential: $Storage\ potential = roof\ surface * storage\ per\ unit\ of\ measurement * implementation\ rate$

$Storage\ potential = 183.163 * 0{,}0155 * 0{,}78 = 2.214\ m^3$

Assumptions:

- Assuming that roof slopes in the area are <35 degree, 183.163 m^2 of roof surface is available for implementation of green roofs. (see Appendix A)
- Estimates of storage capacities of green roofs vary substantially. According to Amsterdam rainproof (2020a) the storage capacity of an extensive green roof varies between 25 L / m^2 and 40 L / m^2. A study done to the hydrological capabilities of extensive green roofs in Nordic climates indicates storage capacities between 9 mm and 36 mm, depending on varieties in substrate, textile fabric and drainage layers (Johannessen et al., 2018). Johannessen et al. (2018) also observed actual precipitation in multiple Nordic cities. Their results show that the total available storage capacity was never fully used in during a single precipitation event, because the roofs are mostly partly saturated. Observations in Oslo show that roofs with a storage capacity up to 24 mm can store no more than 15,5 mm during a single event. The latter is used as reference storage per unit of measurement in this research.
- Furuseth et al. (2018) performed a survey among 462 households in Grefsen, 78 % of which indicated that they could imagine having an LID measure on their property. This percentage is used as the maximum adoption rate.

Measure: Rain garden

Storage potential: $Storage\ potential = residential\ buildings\ with\ a\ garden * storage\ per\ rain\ garden * implementation\ rate - initial\ storage$

$Storage\ potential = 873 * 0{,}3 * 0{,}78 - 48 = 224\ m^3$

Assumptions:

- GIS analysis revealed approximately 873 residential buildings with a garden within the study area, see Appendix A.
- The assumed properties of a rain garden are: a total top surface of 2 m^2, a bottom surface of 1 m^2, a slope of 1:3, this because of maintenance requirements (Amsterdam rainproof, 2020b) and an infiltration box of 1 m^3 filled with gravel that allows for 30% storage space.
- Given the assumed dimensions, the storage capacity per rain garden is 0,4 m^3, see Figure 24 for visualised dimensions.
- The assumed adoption rate is 78%, based on Furuseth et al. (2018).
- The initial storage of the area is estimated to be: $total\ volume\ of\ rain\ garden * storage\ coefficient * residential\ buildings\ with\ a\ garden$. According to Ingebrigtsen (2017) the K-value in Grefsen is relatively high. I therefore have chosen a reference storage coefficient of high infiltratable zavel (clay + sand) of 0,05 (Uijlenhoet et al., 2016). Initial storage is therefore: $1{,}1 * 0{,}05 * 873 = 48\ m^3$.

Measure: Wadi

Storage potential: $Storage\ potential = available\ space * storage\ per\ unit\ of\ measurement - initial\ storage$

$storage\ potential = 23.780 * 0{,}368 - 1.260 = 7.490\ m^3$

Assumptions:

- Available space for Wadis has been selected by a GIS analysis and satellite footage. Locations that were deemed suitable for wadi implementation are barren, unpaved, public area with no direct function and the plot had to be more or less level. The locations that have been selected are shown in Appendix A. The total surface is approximately 23.780 m^2.

- The assumed properties of a wadi are similar to that of a rain garden, but the slopes are excluded, leaving a storage of 0,368 m^3 / m^2 see Figure 23 below for a visualisation and calculations.
- The initial storage of the area is estimated to be: $depth\ of\ the\ wadi * available\ space * storage\ coefficient$. According to Ingebrigtsen (2017) the K-value in Grefsen is relatively high. I therefore have chosen a reference storage coefficient of high infiltratable zavel (clay + sand) of 0,05 (Uijlenhoet et al., 2016). Initial storage is therefore: $1{,}068 * 23.780 * 0{,}05 = 1.260\ m^3$.
- Approximately 15% of research area lies below the appointed locations for wadis, meaning wadis in itself cannot store all water. Appendix A shows the area with a lower elevation than the majority of proposed wadi locations.

Measure: Rain barrel

Storage potential: $Storage\ potential = residential\ buildings\ with\ a\ garden * storage\ per\ rainbarrel * implementation\ rate$

$Storage\ potential = 873 * 0{,}2 * 0{,}78 = 136\ m^3$

Assumptions:

- Assumed is that residential buildings with a garden can potentially adopt a rain barrel. GIS analysis revealed approximately 873 residential buildings within the study area, see Appendix A.
- The storage capacity of a single rain barrel is set on 0,2 m^3 (Amsterdam rainproof, 2020c)
- Furuseth et al. (2018) performed a survey among 462 households in Grefsen, 78 % of which indicated that they could imagine having an LID measure on their property. This percentage is used as the maximum adoption rate.

Measure: Water square

Storage potential: $Storage\ potential = maximum\ required\ storage\ space - storage\ capacity\ of\ one\ infiltration\ crate\ unit$

$storage\ potential = 18.461 - 2.769 = 15.694\ m^3$

Assumptions:

- The main assumption for this measure that the measure can be dimensioned to meet the total water surplus. Dimensions are therefore based on what is required.
- Available space for water squares has been selected by a GIS analysis and satellite footage and are similar to those of Wadis. Water squares can per m^2 store more water then wadis because there are fewer limitations to depth. Hence, only two possible locations for water squares have been proposed, see Appendix A. The total surface of these locations is 18.636 m^2. Assumed is that this surface is sufficient to store the highest calculated water surplus.
- The maximum required storage space is 18.461 m^3. However, approximately 15% of research area lies below the appointed locations for water squares, meaning water squares are not able to store all water. Therefore there is only a need to store 85% of the maximum required storage potential. Appendix A shows the area with a lower elevation than the proposed water square locations.
- The small location has a surface 4.414 m^2, the large location is divided in 2 for pathway purposes leaving two 7.111 m^2 storage possibilities. This leaves two water square variants:
    - Variant 1→ normal water square consisting of the small location and half of the large location. The accumulated storage here is 9.706 m^3
    - Variant 2 → in this variant the water square is expanded up to 15.694 m^3.

Measure: Infiltration crates

Storage potential:

- $Storage\ capacity\ for\ one\ infiltration\ crate\ unit = maximum\ water\ surplus * fraction\ of\ area\ that\ is\ below\ potential\ locations\ for\ water\ squares$

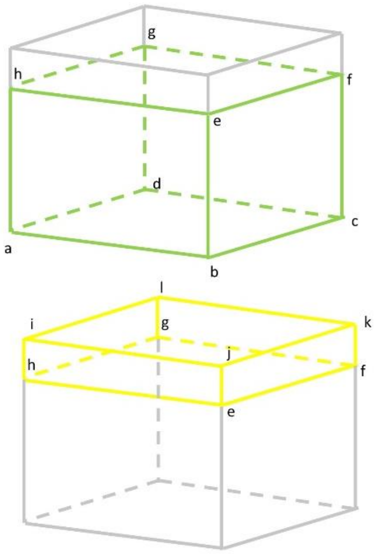
  $Storage\ capacity = 18.461 * 0{,}15 = 2.769 m^3$

Assumptions:

- Infiltration crates can be implemented under roads, pavement or fields (Amsterdam Rainproof, 2020e). Therefore, the main assumption here is that infiltration crates can be dimensioned in such a way that all of the water surplus is stored. For the construction of pathways, the measure is divided in smaller ‘units’. Firstly because a small technical measure is required to be implemented alongside wadis or water squares. This is because 15% of the area is out of reach of these measures due to elevation properties of the land. Secondly, because a pathway consisting entirely of infiltration crates is likely to be implemented in different stages rather than completely at once.

Measure: Implement separate sewer system with increased capacity.

Discharge potential: $discharge\ potential = maximum\ required\ discharge = 7\ m^3/s$



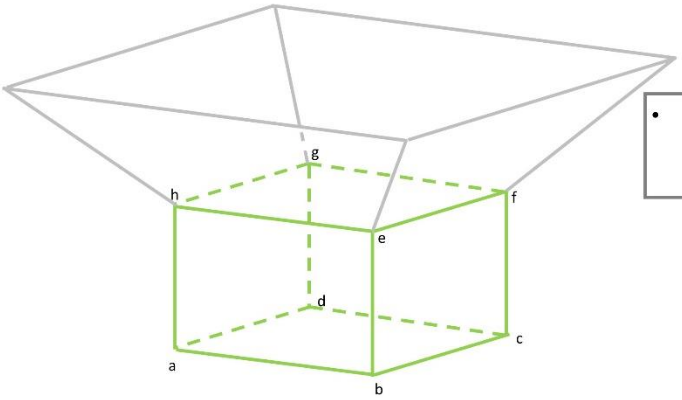
- Given that ab=1m, bc=1m and be=1m, the total volume of the green cube is 1m3. as it will be filled with gravel which allows 30% storage, the total capacity is 0,3m3 of water storage.

- Given that he=1m, ef=1m and hi=0,068m, the total volume of the yellow cube is 0,068 m3. This space is completely used for storage.

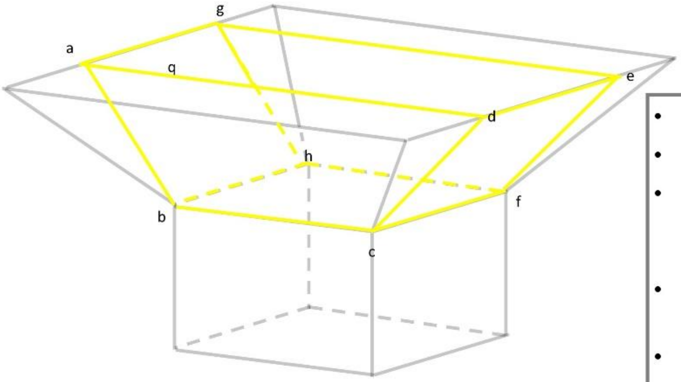
Conclusion

The total storage capacity per square meter of wadi = 0,3 + 0,068 = 0,368 m3 / m2.

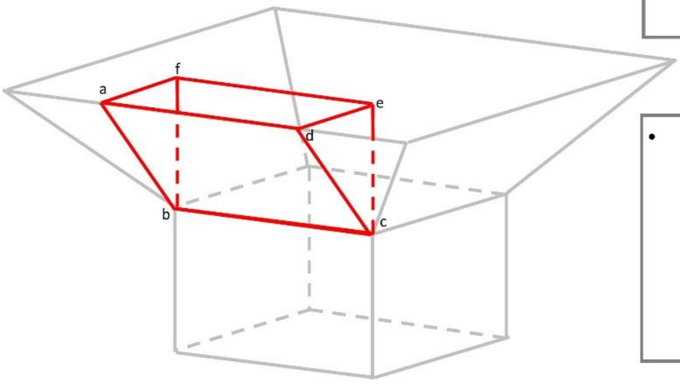
Figure 23. Dimensions of a square meter wadi.



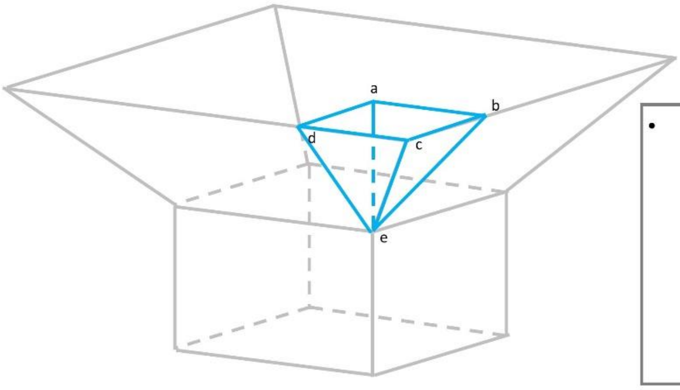
- Given that ab=1, bc=1 and be=1, the total volume of the green cube is 1m3.



- ad =1,41 m
- bc = 1 m
- ab = has a slope of 1:3 which corresponds with hight bq of 0,068 m
- Surface of abcd = 0,068*1,205 = 0,082 m2
- Given that cf = 1 m, the volume of the yellow figure = 0,082 m2



- Because the red figure is mirrored at the other side, the figure can also be seen as a cube with dimentions de=0,205, ec=0,068 and fe=1. The volume of two red figures is therefore 0,205*0,068*1= 0,014m2



- Because the blue figure is mirrored in the three empty corners, four blue figures can form a piramide with a hight of 0,068m and a base of 0,41* 0,41 m, meaning the total volume of 4 blue figures = 1/3*(0,41*0,41)*0,068 = 0,004 m3

Conclusion

The total volume of the wadi = 0,082+0,014+0,004 = 0,1m3. Additionally storage of a 1m3 gravel box is added.

Figure 24. Dimensions of a rain garden

APPENDIX D. MEASURE COST ESTIMATES

In the sections below the cost for stormwater measures are estimated. When using labour costs in estimations an amount of 500 NOK / hour is used (Intermediair, 2019). The costs are summarized in Table 7.

Table 7. Overview of the estimated stormwater measure costs.

Measure	Initial costs [NOK]	Maintenance
LIDs	127.465.690	2.025.485 /year 510.000 / 20 years 126.392.690 /50 years
Wadi	11.969.000	16.000 / year 3.719.000 / 50 years
Water square	28.440.000	48.000 / year
Water square expantion	17.545.000	48.000 / year
Infiltration crates	39.634.500	4.000 / year 35.584500 / 50 years
Separate sewer system	285.000.000	8.000 / year

Measure: Extensive green roof

Lifespan: The expected life span of green roofs varies in literature. Carter & keeler (2008) indicate a maximum life span as low as 40 years, whereas Porsche & Köhler (2013) report existing green roofs of 90 years old. Other authors generally settle on a lifespan between 40 and 55 years (Shafique et al., 2018; Bianchini & Hewage, 2012). In this research a reference expected lifespan of 50 years is used.

Initial cost: Initial cost vary as well. Ascione (2013) indicates implementation costs of 80 euro / m^2 for short and tall green sedum roofs. Carter & Keeler (2008) indicate a price difference of approximately 75 USD per m^2 between conventional roofs and green roofs, where the latter one is the most expensive. Porche & Köhler (2013) recon this additional cost for a green roof to be 50 USD / m^2. Numri et al., (2013) described a total cost of 62 euro / m^2 to install a green roof, including taxes. Because Numri et al., (2013) focussed their research on Finland, another Nordic country where green roofs are not yet regularly implemented, this research will be used for cost reference. Given the total roof surface available for green roofs, the total cost is 115.392.690 NOK

Project management cost: A literature scan to the costs of stakeholder management in case of large scale green roof implementation has not been found. A basic assumption of 1 hr / green roof has been made against mean hour labour cost for Norway. Costs for project management are therefore estimated on 225.000 NOK

Recurrent cost: Porsche & Kohler (2013) describe annual optical inspection and removal of tree seedlings to be the maintenance cost of green roofs. This is estimated to be 1 USD / m^2 / year, which comes down to 1.685.000 NOK / year in case of full scale green roof implementation.

Measure: Rain barrel

Lifespan: The lifespan cost for rain barrel has – to my knowledge – not been reflected upon in scientific research. The municipality of Portland indicated a lifespan of around 20 years for a wooden rain barrel (Portland Oregon, 2006), but plastic barrels are likely to be far more durable. However, because rain barrels will be owned privately, there is a reasonable possibility that barrels will be replaced before the maximum lifespan is reached. Therefore a lifespan of 20 years is considered representative.

Initial cost: Costs for a rain barrel vary widely. A 200 L barrel is available for 500 NOK, but 1000 NOK barrels are common as well. This research settles on 750 NOK a barrel, which translates to 510.000 NOK for full scale implementation of rain barrels.

Project management: A literature scan to the costs of stakeholder management in case of large scale rain barrel implementation has not been found. A basic assumption of 30 min / rain barrel has been made against mean hour cost for Norway. This translates to 113.000 NOK.

Recurrent cost: A literature scan did not result in the identification of recurrent costs. It is however likely that annual cleaning and preparing the barrel for sub-zero temperatures result in labour. The estimation is 30 minutes per barrel per year, which corresponds with 170.235 NOK / year

Measure: Rain garden

Lifespan: Literature reports on the lifespan of raingardens / wadis have not been found. Rain gardens and wadis do however make use of filter fabric that is also used for infiltration crates. Therefore the same lifespan of 50 years is assumed.

Initial cost: Approximately 6 m^2 filter fabric and 1 m^3 gravel is required per rain garden. Combined total material costs are in this case are 126.000 NOK (Buma, 2020; Grindwebshop, n.d.). Labour is estimated on 32 hours per raingarden (Brian Kuiper, personal communication, 18-12-2019) the total implementation cost per rain garden are approximately 16.185 NOK the total implementation costs for 681 raingardens are 11.000.000 NOK

Project management: A literature scan to the costs of stakeholder management in case of large scale rain barrel implementation has not been found. A basic assumption of 1 hr / rain barrel has been made against mean hour cost for Norway. This translates to 225.000 NOK.

Recurrent cost: A literature scan did not result in the identification of recurrent costs. Assumed is 30 minutes of annual plant maintenance per rain garden. This comes down to 170.250 Kr / year

Measure: Wadi

Lifespan: 50 years, see description raingarden and infiltration crate.

Initial cost: Literature or reference projects of large scale wadis that indicate costs have not been found. The estimated costs for initialisation have been estimated based on labour and material cost:

- An approximate amount of 25.000 m^3 of soil needs to be moved. When this is done by one crane and three transportation units the estimated labour and machine rent costs are 25 NOK / m^3, thus 625.000 NOK in total (Jaco Lekkerkerk, personal communication, 5-2-2020; Brian Kuiper, personal communication, 4-2-2020) an approximate amount of 23.800 m^3 of gravel needs to be delivered and distributed at wadi locations. Using the same reference costs as for soil removal the total costs are 595.000 NOK.
- Two basic materials are needed: infiltration fabric on top and bottom of the gravel boxes, and gravel. Infiltration 47.600 m^2 of filter fabric has an approximate cost of 952.000 NOK while 23.800 cubic meters of gravel costs 1.547.000 NOK (Buma, 2020; Grindwebshop, n.d.)
- The cost for realization of infrastructure changes to get water to the wadi is estimated by using a 1 m wide sidewalk as a reference. This is approximately 700 NOK / m^1 (Urban Reality, 2013). To estimate the length of required gutters, a rough raster has been drawn in GIS. An approximate 6.000 m of gutter installation is used as a reference, meaning the total cost is 4.200.000 NOK.

Project management: Literature did not provide an indication of design costs. If 5 engineers work 45 weeks on a design and project management (225 FTE) the costs are 4.050.000 NOK

Recurrent cost: Assumed is 4 time annual cleaning and grass cutting. 8 hours are estimated per cleaning session. This comes down to 32 hours / year = 16.000 NOK / year

Measure: Water square

Lifespan: Because a water square is a solid structure implemented in the build environment, the life expectancy used in this research is estimated on >70 years.

Initial cost and project management: The Enghaven climate park in Copenhagen is used as a reference for cost. A municipal note indicated planned costs of 2.170 DDK / m^3 storage, which is roughly 2.930 NOK / m^3 (Københavns Kommune, 2016). The total implementation costs are therefore approximately 28.440.000 NOK. The additional cost for water square expansion are approximately 17.545.000 NOK

Recurrent cost: The Benthemsquare in Rotterdam, a water square in the Netherlands, requires regular cleaning. (Knudsen, 2016)) Regular cleaning safeguards the hydrological function of the square. Therefore it is assumed that the square is cleaned each month in an 8-hour session. This comes down to 48.000 NOK / year.

Measure: Infiltration crates

Lifespan: A literature research to the observed lifespan of infiltration facilities revealed that infiltration facilities are seldomly monitored. The expected failure of a facility is pointed out to be the clogging of the filter fabric. Besides clogging, Boogaard & Wentink (2007) describe, blocking, compression, iron oxidation, bio particles, liming, biological growth as processes that cause malfunctioning of filter fabric, and thus the infiltration facility. Because observed data is lacking Boogaard & Wentink (2007) made their best estimates of a hydrological lifespan for underground infiltration facilities between 40 and 60 years. In this research the lifespan is set on 50 years.

Initial cost and project management: No cost could be found for a reference case study. Because opening up the road is a major expense, the unit price of installing a sewer system is used as a reference. Additionally the material cost for infiltration crates are added. Assuming a storage capacity of 0,5 m^3 per m^2, one infiltration crate unit covers 5.538 m^2. A number of roads were selected in GIS to be an example. When installed here, a length of 855 m is covered. When using 40.000 NOK / m the costs of installation are 34.200.000 NOK / unit. Assuming material cost of 500 NOK / m^3 the total cost of one infiltration crate unit comes down to 35.584.500 NOK (BP Plastics, 2020).

Project management: Literature did not provide an indication of design costs. If 5 engineers work 45 weeks on a design and project management (225 FTE) the costs are 4.050.000 NOK

Recurrent cost: The inlet needs to be regularly freed of sand and leaves. For each infiltration crate unit 4 hours of cleaning per six months are estimated, meaning 4000 NOK / year.

Measure: separate sewer system

Lifespan: Sewage systems on solid ground can potentially function for decades (Laakso et al., 2019). The lifespan is therefore estimated to be >70 years.

Initial cost and project management: The costs for designing and constructing a new sewage system is estimated to cost 50.000 NOK / m (Isabel Seifert Dähnn, personal communication, 27-1-2020) GIS analysis revealed that there is approximately 5.700 m of sewer in the study area, meaning a total cost of 285.000.000 NOK.

Recurrent cost: Costs are expected to be low. Annual inspection of 16 hours in total. The total cost therefore is 8000 NOK / year.

APPENDIX E. SWMM MODEL OUTCOMES

Table 8. Overview of the expected water surplus in different scenarios in time steps of 10 years.

	RCP 4.5 M5		**RCP 4.5 M20**		**RCP 8.5 M5**		**RCP 8.5 M20**
Year	Water surplus	Year	Water surplus	Year	Water surplus	Year	Water surplus
2000	9011	2000	13118	2000	9011	2000	13118
2010	9161	2010	13350	2010	9398	2010	13661
2020	9336	2020	13524	2020	9801	2020	14219
2030	9461	2030	13815	2030	10170	2030	14749
2040	9686	2040	13871	2040	10609	2040	15334
2050	9889	2050	14288	2050	10969	2050	15874
2060	10091	2060	14490	2060	11385	2060	16403
2070	10283	2070	14738	2070	11790	2070	16886
2080	10474	2080	14906	2080	12139	2080	17325
2090	10654	2090	15176	2090	12611	2090	17910
2100	10823	2100	15401	2100	13005	2100	18461

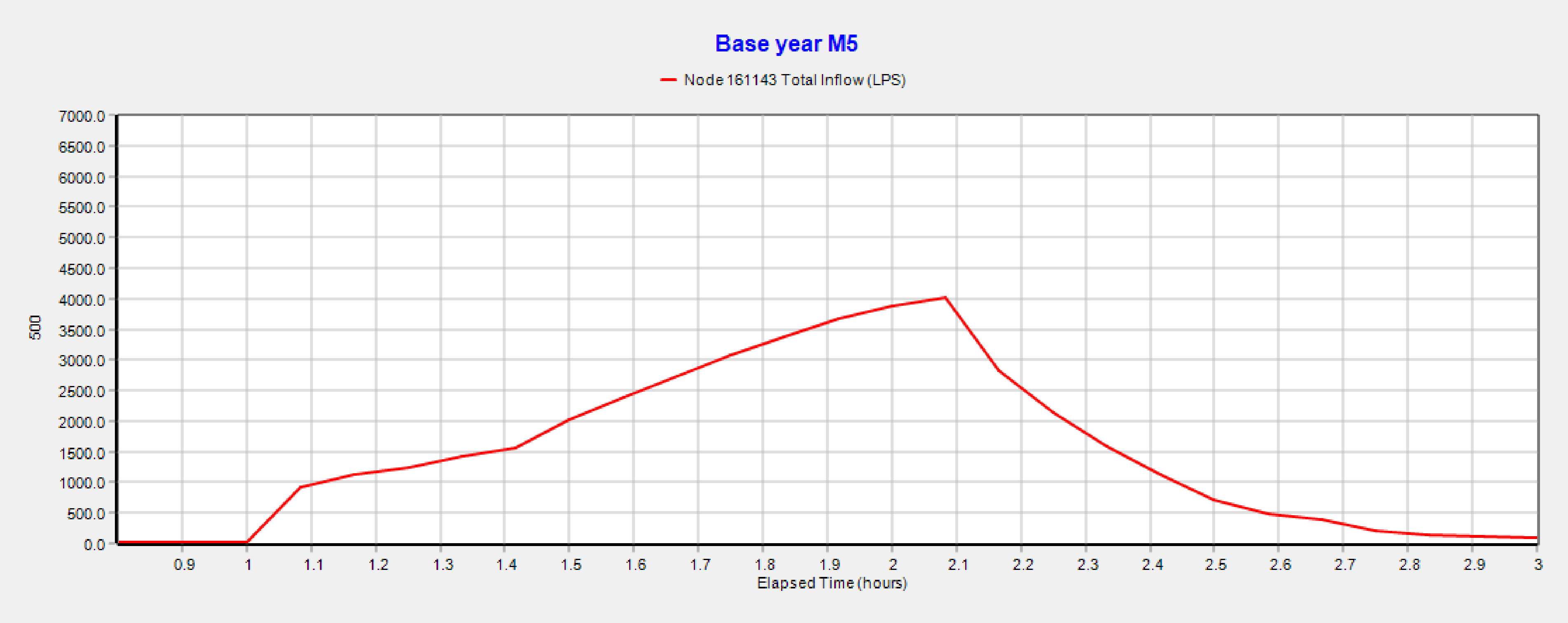


Figure 25. The model output for the water surplus caused by a 60-minute precipitation event with a return interval of 5 years in the year 2000. Values on the vertical axis are given in l / s. Note that the lowest 600 l / s is not a part of the water surplus, as that is the current sewer capacity without overflowing.

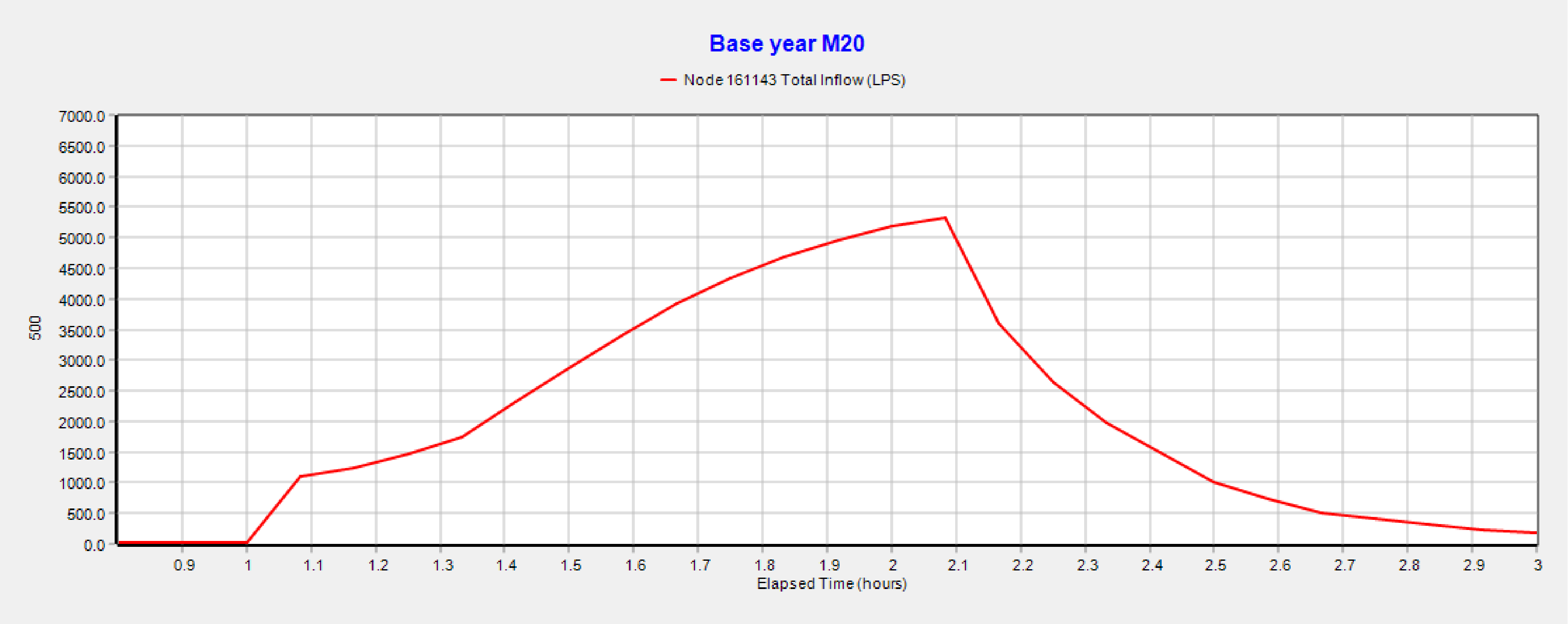


Figure 26. The model output for the water surplus caused by a 60-minute precipitation event with a return interval of 20 years in the year 2000. Values on the vertical axis are given in l / s. Note that the lowest 600 l / s is not a part of the water surplus, as that is the current sewer capacity without overflowing.

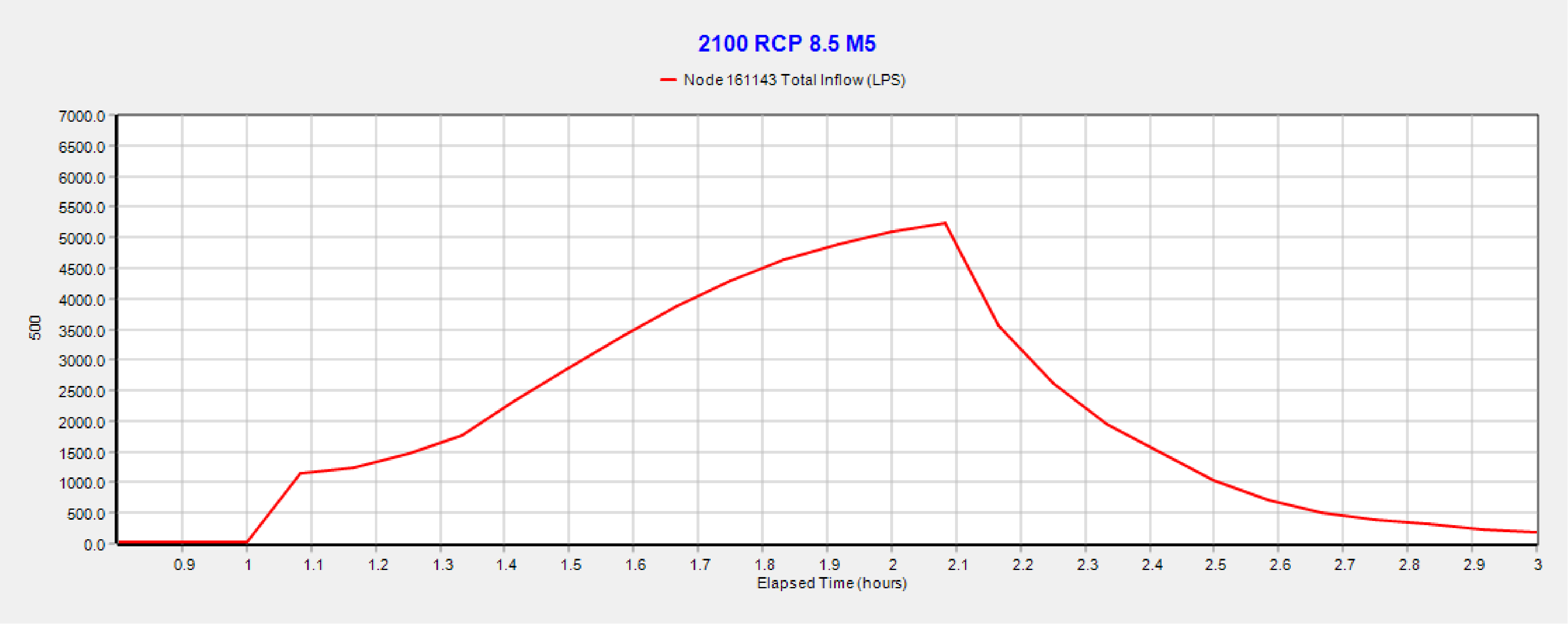


Figure 27. The model output for the water surplus caused by a 60-minute precipitation event with a return interval of 5 years in the year 2100. Values on the vertical axis are given in l / s. Note that the lowest 600 l / s is not a part of the water surplus, as that is the current sewer capacity without overflowing.

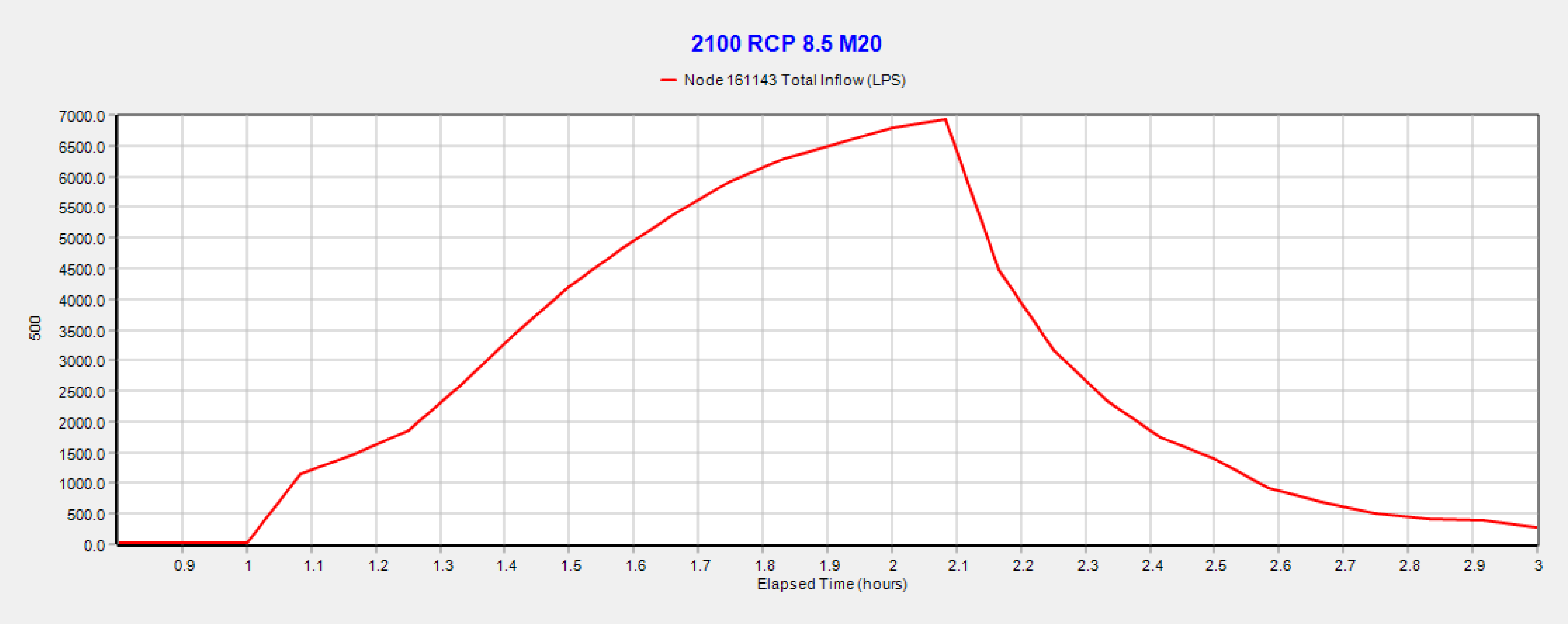


Figure 28. The model output for the water surplus caused by a 60-minute precipitation event with a return interval of 20 years in the year 2100. Values on the vertical axis are given in l / s. Note that the lowest 600 l / s is not a part of the water surplus, as that is the current sewer capacity without overflowing.