Nature-based solutions for diluted wastewater management.

A series of actions for evaluating and selecting a cost-effective & high purification rate of NBS

Master thesis

Negin Hosseinzadeh Gharajehnarlou

AALBORG UNIVERSITET

Study program:

Aalborg University

Department of Sustainability and Planning

Urban, Energy, and Environmental Planning

Cities and Sustainability

Project:

Master thesis (MSc)

Project duration:

February 2024- June 2024

Author:

Negin Hosseinzadeh Gharajehnarlou

Supervisors:

Martin Lehmann

Simon Wyke

Total pages:

120

including references, appendix, and annex

End date:

June 7th, 2024

Abstact:

Heavy precipitation can lead to numerous challenges, including sewage overflows, mixture of rainwater and wastewater. Sewage overflows contain chemicals and viruses, damaging the environment, and human health and decrease the quality of water bodies. Therefore, this thesis employs the concept of nature-based solution (NBS) as an environmentally friendly and cost-effective solution to manage diluted wastewater and purify it in Nørre Nissum located in Lemvig municipality. To successfully implement an NBS an analytical framework has been made which contains guidelines from the International Union for Conservation of Nature (IUCN), a risk assessment framework, and a framework that is based on an adaptation pathway. To evaluate and select the best measurement a systematic approach based on adaptation pathways, namely multi-criteria analysis has been used to evaluate and select the best measures, ensuring alternative solutions if one fails. Furthermore, this thesis not only designs an NBS, but also provides a comprehensive formula for dimensioning it for wastewater retention. However, the solution can accommodate the short-term hazard, and Lemvig municipality should use another approach for the long-term solution.

Keywords: NBS, diluted wastewater, risk assessment

- *Preface*

This thesis has been conducted for the fourth semester of Cities and Sustainability at Aalborg University. The subject of this master's thesis is based on a problem that Lemvig municipality faces during heavy precipitation. This thesis focuses on nature-based solutions for diluted wastewater purification and retention. This master's thesis is the first step in pre-analysing different solutions and is in collaboration with Klimatorium.

Acknowledgment

While writing the thesis, I experienced several challenges that any student may experience. However, several people assist me in this way and here I have this opportunity to appreciate their help. I would like to extend my heartfelt thanks to Charlotte Rosenkilde Sørensen, and Per Kristiansen from Klimatorium. Their extensive knowledge of sewage systems, the capacity of the Nørre Nissum pump station, and data on sewage overflows, along with their support in the calculation aspects of my thesis, was instrumental in the completion of this work. Your endless help made my journey significantly smoother. Additionally, I want to thank Stephan Peter Hald Nielsen from Klimatorium who helped me in the initial part of my thesis. I also wish to express my sincere gratitude to my supervisors, Simon Wyke and Martin Lehmann, for their consistent feedback and guidance throughout the project. Your insights and encouragement were invaluable. Thank you all for your contributions and support. Finally, I want to express my major gratitude to my husband, Pooya Davari, who has been an immense supporter both financially and emotionally, throughout my education. Whenever I felt discouraged, you were there to motivate me and I feel incredibly privileged to have you by my side.

- *Summary*

In Denmark, climate change is causing warmer temperatures, sea level rise, and increased precipitation. However, heavy precipitation, a consequence of climate change poses significant challenges including flooding and sewage overflows in Danish cities. Increased volume of precipitation, coupled with urbanization, put new pressure on the sewage systems which leads to sewage overflows and contaminating the environment, water bodies, and human health. While traditional grey infrastructures struggle to cope with these challenges, nature-based solution (NBS) offers a sustainable alternative. Incorporating natural drainage systems including constructed wetlands, and willow treatment plants into wastewater management can help in the reduction/ prevention of sewage overflows while enhancing environmental and water body quality. Danish municipalities like Lemvig focus on implementing cost-effective, environmentally friendly solutions to address sewage overflows and at the same time have high purification rates aligned with Danish purification standards to increase water quality. Therefore, this thesis seeks to investigate: How can a cost-effective Nature-Based Solution be implemented for the purpose of capturing and purifying diluted wastewater?

Answering this research question is based on formulating two sub-research questions. The first step is to understand what is the concept of a nature-based solution and which criteria are required to be considered for the successful implementation of an NBS. Based on this the theoretical framework regarding the concept of nature-based solution and analytical framework based on the IUCN guideline has been made.

The second step is to analyze and map the risk of the case area by considering hazards, exposure, and vulnerability based on the IPCC's risk assessment framework. This process will help to understand the current and future hazards. The data for risk assessment was gathered through climate data, interviews, and SCALGO LIVE. The risk assessment mapping was conducted in QGIS.

The third step was to develop criteria based on adaptation pathways to acknowledge the fact that if one solution failed, there would be alternative solutions and increase the successful implementation since climate change has many uncertainties. Therefore, the solution needs to

be robust and flexible to deal with future hazards and has immediate benefits, since the aim of this project is to implement NBS that accommodates current hazards, does not negatively affect the groundwater level and the environment since the solution is for diluted wastewater, have a high purification rate and at the same time has environmental and cost co-benefits. The mentioned criteria are crucial in this thesis for the successful implementation. Therefore, a systematic approach based on the adaptation pathway was developed to score and weight the solutions based on the identified criteria. Moreover, this thesis provides a comprehensive methodology for dimensioning the solution based on the discharge rate of wastewater, evapotranspiration, precipitation, infiltration, and outflow rate.

Finally, the research found that willow treatment plants, as a cost-effective and high purification rate solution, can be implemented in the case area which can accommodate the current hazard, but the capacity/size of the selected area cannot accommodate further implementation. Therefore, the future precipitation still causes challenges for the Lemvig municipality.

Table of contents

List of abbreviations

CC: Climate change

CCA: Climate change adaptation

CW: Constructed wetlands

DMI: Danish Metrological Institute

EC: European Commission

EPA: Environmental Protection Act

FWSCW: free water surface constructed wetlands

GHG: Greenhouse gas emissions

IUCN: International Union for Conservation of Nature

NBS: Nature-based solution

NWRM: Natural Water Retention Measures

RCP: Representative Concentration Pathway

RQ: Research question

SDG: Sustainable Development goal

SSP: Shared Socioeconomic Pathways

List of Figures

List of tables

Chapter 1: Introduction

1 Introduction

It is estimated that more than half of the globe's population (Gómez-Baggethun & Barton, 2013) and approximately 75.19 % of the EU population live in urban areas (Statista, 2022). By 2050, this number is going to increase by roughly 5 billion (OECD, 2020). Changing in the concentration of population in both metropolitan and smallest cities puts new pressure on urban settlements including but not limited to higher use of impermeable surfaces, land use, and higher vulnerability to Climate Change (CC) effects (Chapman et al., 2017). Alterations in lifestyle and anthropogenic disturbances such as the utilization of fossil fuels along with net land use change, caused an increase in the atmospheric concentration of Greenhouse Gas emissions (GHG) (Calvin et al., 2023). This concentration will lead to earth warming and frequent and intense extreme events that will have negative impacts on natural dynamics and human health (Calvin et al., 2023). These extreme events can be varied depends on the geographical location some societies will experience frequent and intense heavy precipitation, and storm surges, while others will experience drought and heat waves (IPCC, 2022).

Climate change poses a huge threat to humanity, and its significance cannot be overstated, as the consequences are nothing short of disastrous. The increase in urbanization and high use of impervious services and other infrastructures have caused the establishment of new and critical systems to manage and handle stormwater and wastewater (Muttil et al., 2023). However, these systems are becoming more susceptible to failure and overflows as a direct consequence of global CC and urbanization. Frequent and high-intensity precipitation along with high use of impermeable surfaces, results in shorter response time in urban catchment areas and amplified stormwater runoff volumes that the capacity of the current sewage system cannot manage. As a result, pump station overflows contain not only surface water but a mixture of wastewater and surface water posing a significant threat to human health, groundwater quality, and the environment (Muttil et al., 2023).

1.1 *Climate Change in Denmark*

In the Danish context, the climate is manifesting through warmer temperatures, extreme sea level rise, and heavy and frequent precipitation, all directly linked to global CC (Danish board of technology, 2021). Denmark has already experienced significant impacts, including but not limited to heavy precipitation and storm surges as the average temperature has increased over the years (Klimatilpasning, 2023b). The average temperature in Denmark from the pre-industrial era until 2023 has increased from 7.2°C to 8.7°C, indicating an increase in the temperature (Klimatilpasning, 2023b). Additionally, extreme temperatures, defined in Denmark as three consecutive days with a maximum temperature above 28°C, are expected to occur more often and frequently in the future. The expected change in the temperature for the end of the century under a high emission scenario is 3.4°C (Klimatilpasning, 2023b). However, CC is uncertain and there is a particular risk that temperature will become more intense in the future.

The average increase in the temperature caused the sea level around Denmark to rise by 2mm per year (Danish board of technology, 2021). It is estimated that the water level will increase from 30 cm to 60 cm towards the end of this century (DMI, 2024c). However, there is uncertainty about how sea and ice will react to the high temperatures, it might become more intense.

In line with CC, Denmark has also witnessed a significant increase in annual precipitation which has risen by 100 mm over the last century (DMI, 2023b). This trend has led to several instances of severe and damaging precipitation, including the events in 2011, which caused pedestrian tunnels, roads, and houses to be flooded (Dark,T, 2016) and in 2016, more than 115 mm of rainwater hit Horsens municipality (Brandt, A, 2016). Lemvig municipality has not been immune to such hazards. In the autumn of 2019, Lemvig municipality experienced destructive precipitation that the sewage systems couldn't manage, resulting in flooded roads and pedestrian areas (Lundsgaard, J, 2019). This disaster occurred once again in 2023 which underscored the ongoing risk of flooding along lakes and streams in the central part of Jutland (Bodholdt, N, 2023). It is estimated that this development become more severe and frequent towards the end of this century. This is mainly due to the fact that winter floods including flash floods are going to increase in maritime regions (IPCC, 2022), and spring and autumn also tend to be wetter to some extent (DMI, 2023b) and summer will become wetter which can lead to flooding in most of the Danish cities (Klimatilpasning, 2023a).

The average precipitation events under a medium emission scenario are expected to increase by 2.15 mm/day and 2.17 mm/day under a high emission scenario until 2070 as illustrated in Figure 1, and a further increase in average precipitation is estimated to be more than 2.3 mm/day until 2100 (DMI, 2023a). One significant concern of heavy precipitation which will be elaborated upon in the next sections is sewage system overflows. The increased frequency and intensity of heavy precipitation have resulted in higher volumes of flow into sewage systems, consequently leading to overflows, thereby highlighting the necessity for Climate Change Adaptation (CCA) (Muttil et al., 2023).

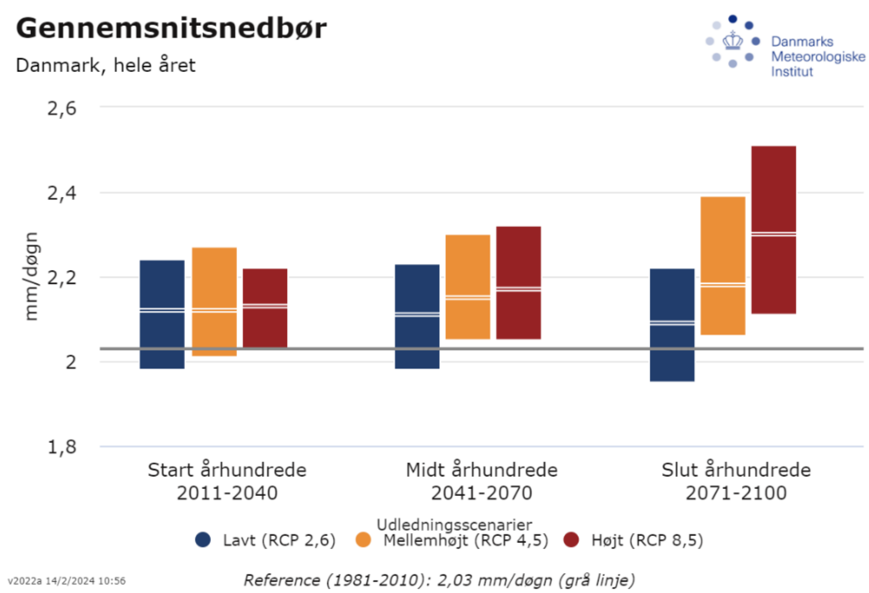

Figure 1. Changes in precipitation in Denmark. Figure adapted from (DMI, 2023a)

1.2 *Historical establishment of sewage systems and the problems of present CCA*

Historically water management systems have been designed and devised as centralized structures, ensuring the provision of dependable and efficient services for creating clean and healthy cities (Fratini & Jensen, 2014). In the Middle Ages, by developing cities, the demands for freshwater were increased and water management systems were constructed to provide citizens with a reliable freshwater supply (Brown et al., 2009), and drainage systems were implemented to carry out rainwater from roofs and pavements (Ambulkar, A & Nathanson, Jerry A, 2024). With the installation of toilets in the properties in the early nineteenth century, the demands for implementing swage systems were increased. This was mainly because the toilets were connected to cesspools where human wastes were collected. This action caused outbreaking Cholera (Ambulkar, A & Nathanson, Jerry A, 2024). Therefore, sewage systems were implemented to discharge unsanitary wastewater out of the city boundaries for the improvement of public health (Brown et al., 2009).

CC and frequent precipitation along with the rapid growth in population and the development of the cities, necessitated the establishment of combined sewage and stormwater drainage system to reduce surface runoff (Brown et al., 2009).

In the case of Lemvig municipality, the sewage systems which are dimensioned based on 5-year precipitation (Lemvig Kommune, 2023) need to cope with water from multiple sources including rainwater and groundwater. These sewage systems, some dating back to between 1970 and 2016 (Klimatorium, 2020) have been consistently maintained but their dimension and capacity have not been increased (Lemvig Kommune, 2023). Additionally, for managing wastewater and stormwater there are two sewerage systems one separate and one communal (WSP et al., 2021). Most of the properties have separate drainage systems for handling rainwater, however, in some places, this connection has been wrongly connected to the wastewater system (Lemvig kommune, 2013). There are also some properties that are not separated and have a connection through roof downpipes to the wastewater utility (WSP et al., 2021). This connection to the wastewater system has caused a problem. In case of increasing the annual precipitation because of CC and high groundwater level the sewage system cannot deal with this pressure and amount of water, and emergency overflows from some pumping stations will occur (WSP et al., 2021). Throughout both historical and contemporary periods, some pump stations of Lemvig municipality have been prone to water accumulation and diluted wastewater issues during intense precipitation events (Bodholdt, N, 2023; Lundsgaard, J, 2019) which highlights the insufficient capacity of the water management system to handle both present and future precipitation events.

1.2.1 Negative consequences of diluted wastewater on the environment and human health

The challenges for cities and communities have been the management of diluted wastewater, comprising a mixture of wastewater and surface water and contains organic matter, nitrogen, phosphorous, heavy metals, disease-causing bacteria, and viruses (Lemvig kommune, 2022). The municipality sewage and industrial wastewater contain chemicals and toxic materials that are harmful to the environment (Butala, S, 2023). The discharge of diluted wastewater into rivers and lakes poses a significant threat to the wildlife inhabiting the surrounding areas, rendering them highly vulnerable to the adverse effects of water pollution. This is not only a disruption to wildlife ecosystems but also contributes to a threat to aquatic ecosystems and a decline in water quality (Butala, S, 2023). Moreover, this discharge of wastewater into water bodies poses a significant hazard to recreational users and citizens exposed to contaminated sources. The presence of nitrogen and phosphorous in diluted wastewater leads to the production of algal blooms, thereby spreading human health issues. Health risks associated with untreated wastewater include but are not limited to skin disease, diarrhea, and dysentery (Kaushal & Singh, 2017)

Properties and agriculture areas situated downstream of sewage overflows are at superior risk of health hazards caused by bacteria and viruses in untreated wastewater. Discharging diluted wastewater into the environment causes groundwater and soil contamination. The infiltration of wastewater into the soil poses risks to plants, biodiversity, and human health. Crops cultivated in contaminated soil have the potential to absorb these pollutants, thereby posing a risk of food contamination and associated health risks and more irreversible damages (Butala, S, 2023).

1.3 *What is the thinking behind nature-based solutions for wastewater treatment*

The sustainable development goal (SDG) 6 "*Clean Water and Sanitation*" emphasizes the importance of water quality by reducing pollution and minimizing the release of wastewater into the environment (Cross et al., 2021) to prevent the upcoming consequences described in section 1.2.1. It is estimated that 80 % of the globe's wastewater is released into nature and merely 40 % of EU rivers and lakes adhere to the minimum ecological standards, signifying a concerning level of habitat degradation (Cross et al., 2021).

In recent years there has been a rapidly growing interest in the implementation of nature-based solutions (NBS) for the water and wastewater sector, to increase sustainability, and tackle problems related to the capacity of land area (Cross et al., 2021). However, this question may arise why should consider nature-based adaptation over grey infrastructures for wastewater treatment? To answer this, first, it is a requirement to look at the history of wastewater treatment and the benefits green solutions provide for the community compared to grey solutions.

Sanitation of wastewater has a long history in European countries (Ambulkar, A & Nathanson, Jerry A, 2024). The establishment of centralized sewage treatment plants which remove pollution of wastewater through a combination of physical and chemical processes began in the early twentieth century (Ambulkar, A & Nathanson, Jerry A, 2024). However, by increasing industrial wastewater, public concern regarding environmental quality was increased, and there was a higher requirement for a higher level of purification, hence it was necessitated to improve sewage treatment. The most common solution for treating diluted wastewater in EU countries is to utilize grey infrastructures that contain drainage networks by installing large-diameter pipes, creating storage facilities, and building pump stations (Chen et al., 2021). There are different options for grey infrastructures that help in the reduction of sewage overflows at the same time meet treatment classes, including seepage plants, arrow systems, and biological sand filters which are also commonly used in Denmark (Odense kommune, 2022). However, these gray infrastructures are mainly focused on removing pollution from grey water, lacking additional benefits like enhancing environmental co-benefits (Chen et al., 2021).

One major disadvantage of grey solutions is their low ability to adapt to the pressure of rapid urbanization and CC impacts including heavy precipitation. This necessitates that grey sewage treatment plants increase their capacity by occupying more land and utilizing more electricity for purifying and treating diluted wastewater before discharging it into the environment (Ambulkar, A & Nathanson, Jerry A, 2024; Oral et al., 2020).

In contrast, Denmark aims to increase the utilization of nature and enhance outdoor activities while at the same time improving water quality at water bodies by treating diluted wastewater, but faces "*a limitation in open spaces*" (Teknik og miljø, 2024). Grey solutions, which occupy significant space and offer limited aesthetic and environmental benefits, conflict with this goal. Therefore, there is a need for urban water management to incorporate holistic planning in the context of sustainable urban development by utilizing an alternative adaptation method namely NBS (Oral et al., 2020). NBSs not only reduce and sanitize diluted wastewater during intense precipitation but also provide co-benefits, including increasing green spaces for recreational purposes and aesthetic value (Oral et al., 2020).

NBSs are "*solutions to societal challenges that are inspired and supported by nature, which are cost-effective, and simultaneously provide environmental, social, and human well-being benefits. Such solutions bring more, and more diverse, nature and natural features and processes into landscapes and cities, through locally adapted, resource efficient and systematic interventions* " (European Commission, 2022; Veerkamp et al., 2021). NBS, due to its various advantages, is mostly used for CCA, including that they possess the potential to address sustainable water management strategies. They represent an integrated approach to urban planning, prioritizing short-term decisions that align with long-term objectives due to their inherent flexibility, and provide immediate benefits to the urban environment. Additionally, NBSs are environmentally friendly solutions that are cost-effective compared to traditional engineering systems (Oral et al., 2020). However, in most of the cities in Denmark, NBSs are primarily employed to capture stormwater runoff, aiming to reduce pressure on sewage systems during intense precipitation, rather than restoring diluted wastewater (DNNK et al., 2021; Lemvig kommune, 2022).

1.3.1 NBS for Diluted Wastewater Retention in Denmark

In European countries constructing NBSs including but not limited to constructed wetlands, and willow treatment plants as decentralized treatment plants (Cross et al., 2021; World Bank, 2021) offers significant benefits for the area as they are reliable and sustainable (Darja Istenič, 2022). Such solutions are sustainable because they will reduce the need for mechanical elements for handling wastewater compared to conventional methods, thereby reducing costs (Cross et al., 2021). Moreover, such solutions will take advantage of ecosystem services to remove pollution including phosphorous, nitrogen, COD, and BOD from wastewater (Kjærgaard, Ch, 2013; Miljøstyrelsen, 2003; Oral et al., 2020).

In the Danish context, utilizing NBS as an environmentally friendly solution in the form of CCA is common to help in increasing human health. Therefore, based on this by increasing the effect of CC such as heavy precipitation the construction of ponds and wetlands as a tool for reducing surface runoff and capturing pollution has gained a lot of attention (Kjærgaard, Ch, 2013). However, nature as an integrated part of climate risk reduction for retaining and purifying diluted wastewater has not precisely developed in Denmark (Kjærgaard, Ch, 2013). The primary reason for the absence of NBS for wastewater management in Denmark is the overall lack of understanding regarding the functionality and potential benefits of such nature-based approaches (Fryd, O & Jørgensen, G, 2019) and the legislation regarding utilizing NBS for purifying diluted wastewater (Waly et al., 2022).

1.3.2 Danish legislation on NBS for diluted wastewater purification

Purification of diluted wastewater in a Danish context means that wastewater catchment areas should purify wastewater from certain chemicals including organic matter, phosphorus, nitrogen, COD, and BOD to not contaminate aquatic environments or natural ecosystems (Miljøstyrelsen, 2018). Therefore, NBS with the aim of capturing and purifying diluted wastewater should purify it from the mentioned chemicals.

The regulation of collection wastewater in Denmark is to prevent the direct connection of the population with wastewater such as discharges of sewage water into lakes, sea, and the fjord and indirect connection through drinking water (Miljøstyrelsen, 2001). The Environmental Union, Directive 91/271/EEC which aims to protect the environment from being adversely affected by the discharge of diluted wastewater, argues that the implementation of catchment areas for collecting diluted wastewater should follow certain criteria, including constructed NBS for wastewater collection should protect groundwater from being affected by diluted wastewater by implementing impervious and leakproof materials at the bottom of the system. Moreover, capturing systems should protect public health and be designed in a way to prevent the overflow of diluted wastewater into water or lands, unless the overflow is purified with local vegetation (Council of the European Union, 2023; EPA, 2019).

Therefore, according to this legislation, and the problems of diluted wastewater on the environment and human health, this thesis aims to investigate how NBS can be implemented and become a tool for collecting diluted wastewater to prevent sewage overflows during heavy precipitation and introduce the beneficial effect of such measurement on the environment.

1.4 *Delimination & Research Question*

The impact of CC such as frequent and intense precipitation coupled with the densification of cities including utilizing impermeable pavements caused surface flooding. To manage and reduce surface runoff sewage systems were established. In the case of Lemvig municipality, there are both communal and separate sewage networks. However, some property sewage systems are connected to the communal drainage network. During heavy precipitation, the water in the sewage systems will exceed the capacity of sewage and pump stations, and as a result, overflows and diluted wastewater which contains pollution and toxic chemicals flow into the environment and natural catchment areas. Sewage overflows have become an important issue for Lemvig municipality as the EU Water Framework Directive mentioned that all Danish municipalities including Lemvig municipality are mandated to ensure the release of cleaner water into coastal water, lakes, and groundwater (Lemvig kommune, 2022). Several strategies have been studied in different literature including but not limited to increasing the capacity of sewage networks or establishment of grey infrastructure for restoring wastewater. However, none of them do not mention a sustainable and cost-effective solution.

Lemvig municipality's future CCA plan aims to reduce the emergency overflows in sewage systems (Lemvig kommune, 2022) through the implementation of a cost-effective and environmentally friendly solution, NBS at rainfall-related outlets. This strategy aims to restore diluted wastewater caused by heavy precipitation, thereby preventing the release of untreated wastewater into lakes, and coastal areas and increasing the quality of water bodies (Lemvig kommune, 2022). (Cross et al., 2021) argues that it is necessary to mitigate or reduce the impact of discharges of diluted wastewater into the environment through the establishment of NBS. However, identifying a cost-effective solution capable of accommodating current hazards, with an additional 25-year lifespan is a critical consideration for the Lemvig municipality and local needs (IN 2). Therefore, the aim of this thesis is to investigate methods for retention of diluted wastewater using NBS, as well as assessment of the purification capacity of the different methods and therefore, investigate the following main research question:

Min RQ: How can a cost-effective Nature-Based Solution be implemented for the purpose of capturing and purifying diluted wastewater?

This thesis aims to design and propose an NBS that can be implemented in a rainfall-related outlet in a specific case area, Nørre Nissum, located in Lemvig municipality. This means that other types of solutions like hybrid and grey solutions that may reduce sewage overflows are not considered in this thesis due to the scope of the project. Therefore, to answer the main research question, the following sub-research questions have been developed. Including,

1. How can an NBS be implemented in the case area to accommodate current hazards and be sufficiently robust to deal with future hazards?

Identifying criteria based on NBS standards for suitable implementation is an important factor that helps to have a deep understanding of the situation of the case area. Moreover, as mentioned before the aim of the identified measurement is to be robust enough to capture diluted wastewater for current hazards and be flexible to accommodate future hazards. This means that the scope is limited to the risk of precipitation.

Therefore, it is important to first assess the current hazard, which, based on (DMI, 2023a) is for the period from 2011 to 2040, and then focuses on the future hazard that in this thesis is for the next 25 years, which, based on (DMI, 2023a) is considered from 2041 to 2070. Assessing the risk of the case area will directly help to answer the second sub-research question which is:

2. Which cost-effective NBS with a high purification rate can be implemented, and what design criteria are necessary for a successful implementation?

After assessing the risk and understanding the condition of the case area, it is important to choose the best cost-effective NBS with a high purification rate among other NBSs that reduce exposure related to hazards. Therefore, it is necessary to utilize a method that helps to evaluate solutions based on scoring and weighting against multiple criteria (Dean, 2020). However, these two criteria are not sufficient for a successful implementation. Consequently, additional complementary criteria for selecting the suitable NBS, have been chosen and described in the analytical framework, section 2.3.

Chapter 2: Theories

&

Methodology

2 Methodology

This section first describes the research design of this thesis which showcases the connection between different parts of the report. Moreover, section 2.2 describes the theoretical framework that provides a logical approach in this report. section 2.3 will elaborate upon an analytical framework that assists in shaping the use of methods and answering sub-research questions one and two by formulating guidelines for choosing the best NBS, and section 2.4 describes the theories of science. Finally, the methods used for data collection and analysis will be described in section 2.5.

2.1 *Research Design*

Research design provides a comprehensive overview of the entire research process and ensures that the conclusions drawn address the research question accurately. Figure 2 illustrates the research design of this thesis which outlines the process to reach the main research question, the theoretical and analytical framework, the methods used to answer sub-research questions, and how they are connected to each other to answer the main research question in the conclusion. The main sections in the research design are illustrated with red rectangular and the sub-sections are shown with green rectangular. The formulation of the methodology is based on (Farthing, S, 2016) which is a scientific article and describes clearly the formation of problem analysis by using published articles, papers, and literature which needs to be a strong foundation for the formation of the research question, and what justification (theoretical and analytical frameworks) need to be used to answer and support the main research question.

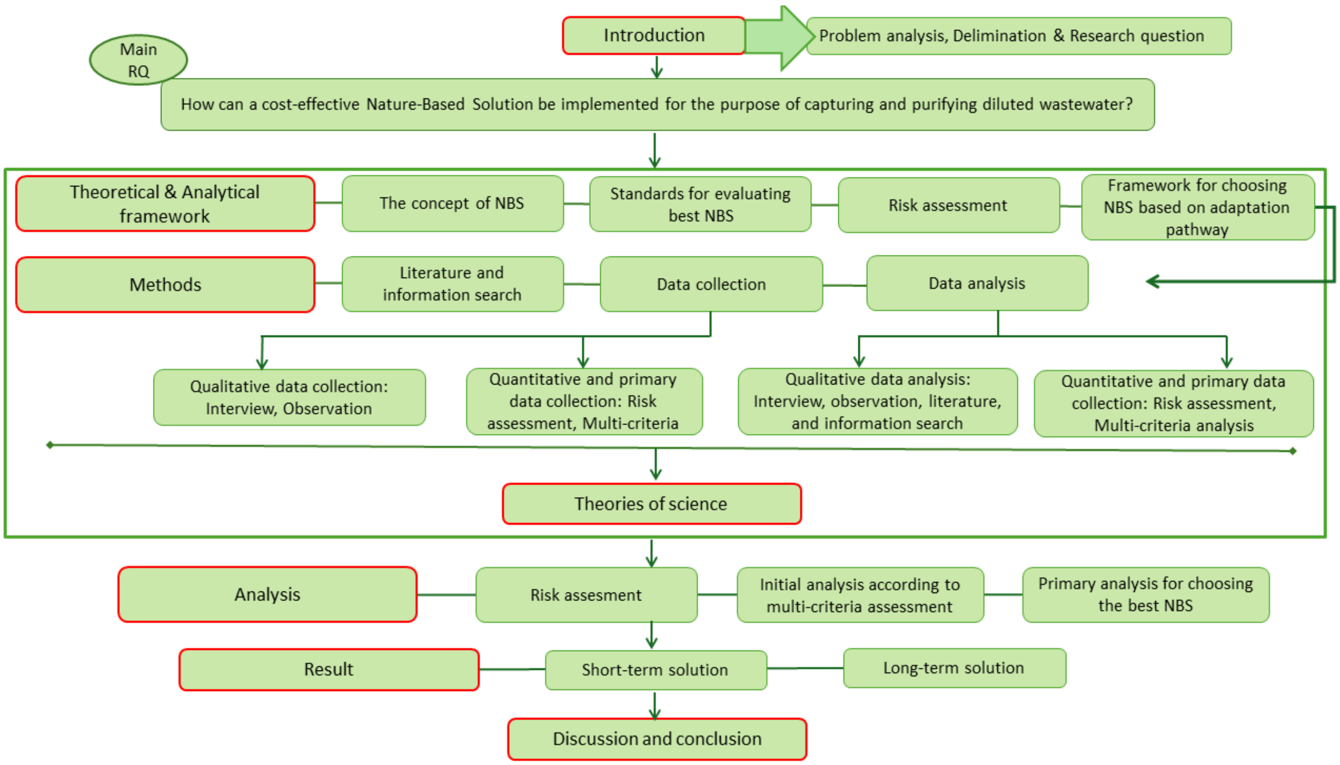

Figure 2. Research design

The theoretical framework is built upon the concept of NBS which is the main focus of this thesis, and the analytical framework represents complementary elements of the theoretical framework which makes a robust guideline for choosing the best NBS that can address social challenges and based on some criteria choose the most successful solution. The elements and criteria in the analytical framework will help to shape the use of methods including risk assessment and multi-criteria analysis.

The data collected in this thesis is guided by a mixed-method approach, combining both qualitative and quantitative methods, to enhance the research's validity (Farthing, S, 2016). A mixed-method approach was chosen for its ability to address a wider range of research questions, ensuring a more comprehensive exploration as the report is not restricted to a single research question (Cronholm & Hjalmarsson, 2011). The research design incorporates two different analyses to address the sub-research questions but interlinked to each other for comprehensive understanding including qualitative data analysis and quantitative and primary data analysis. Section 2.5.1, which is dedicated to data collection first elaborates on the literature and information search used to shape the initial part of the report and theoretical and analytical framework and then divides into qualitative, quantitative, and primary data collection.

In qualitative data collection, semi-structured and informal interviews are conducted to address both sub-research questions one and two, and observation helps to answer sub-research question two. In quantitative and primary data collection the mixture of methods including qualitative and quantitative data that will address sub-research questions one and two will be described.

Section 2.5.2, is dedicated to the analysis of qualitative, quantitative, and primary data for answering sub-research questions one and two. In quantitative and primary data analysis first, the data regarding the risk will be assessed, and second, a method named 'multi-criteria analysis' is employed to help in scoring and weighting measurements based on criteria described in the analytical framework. It should be noted that there are some criteria in section 2.3.1 that their definition is similar to the criteria in section 2.3.2, including 'adaptive management' which is similar to 'no regret/ successful solution' and 'balance trade-offs' which is similar to 'robustness', 'flexibility', and 'possible impacts on other risks' criteria. Therefore, to avoid repetition the mentioned criteria were merged with their similar criteria.

2.2 *Theoretical framework*

In this section, the theoretical framework has been developed which provides a justification for answering each sub-research question. The concept of NBS which this report centered around will be described.

2.2.1 The concept of NBS

Anthropogenic activities and the CC crisis accelerate the destruction of the natural world through intense weather including flooding, and drought cause minimizes the degree of resiliency in cities. Therefore, to the definition of " *as the crises are linked so are the solutions*" scientists gathered together to increase resiliency in cities by implementing NBS (European Commission. Directorate General for Environment. & University of the West of England (UWE). Science Communication Unit., 2021).

The concept of NBS was launched in 2013. This concept has emerged from research seeking innovative approaches to manage natural systems, aiming to balance benefits for both nature and society (Sowińska-Świerkosz & García, 2022). Based on the EC (European Commission), NBS is a "*Solution that is inspired and supported by nature*" (European Commission, 2022) and is an umbrella concept that covers Ecosystem-based Adaptation, Green Infrastructure, Ecosystem-based Disaster Risk Reduction, and Natural Water Retention Measures (NWRM) (European Commission. Directorate General for Environment. & University of the West of England (UWE). Science Communication Unit., 2021).

This concept argues that human communities can utilize and implement NBS towards more "*resilient, actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*" (IUCN, 2020). Therefore, based on this definition EC has developed some criteria for the evaluation and justification of the best practices for social challenges including protection, water management, human health, and a transformative adaptation that acknowledges the fact of flexibility and robustness (European Commission. Directorate General for Environment. & University of the West of England (UWE). Science Communication Unit., 2021).

2.3 *Creating an Analytical Framework for choosing the best NBS*

Achieving global sustainability necessitates the integration of NBS into city planning (European Commission. Directorate General for Environment. & University of the West of England (UWE). Science Communication Unit., 2021). To effectively select and implement the most suitable NBS for addressing urban challenges in a sustainable manner, it is important to employ a robust guideline for evaluating the quality and effectiveness of each solution. Moreover, as mentioned before, the main goal of Lemvig municipality is to implement NBS which restores diluted wastewater during heavy precipitation to prevent discharges of wastewater into the environment. Therefore, there is a requirement for building an analytical framework, complementary to the theoretical framework that helps in choosing and designing the best NBS in the specific area

2.3.1 Standards for evaluating the best NBS

The proposed standards for selecting optimal and effective NBS are drawn from recommendations by the International Union for Conservation of Nature (IUCN) (IUCN, 2020). This framework aims to establish a robust guideline for designing the most suitable and contextually relevant NBS in the designated area. Comprising eight criteria, the standard is illustrated in Figure 3.

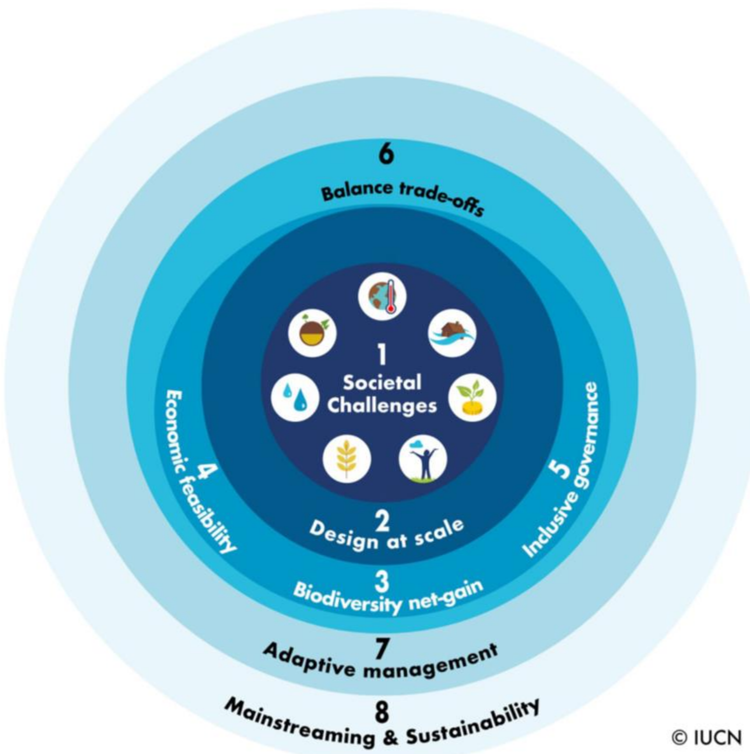

Figure 3. The 8 interdependent criteria for NBS. Figure adapted from (IUCN, IUCN, 2020)

Social challenges:

This criterion addresses "climate challenges", "*ecosystem degradation*", loss of biodiversity, and "*human health and water security".* The aim of this criterion is to deliver multiple benefits by implementing NBS (IUCN, 2020)

Design at scale:

This criterion aims to design, and plan solutions based on the geographic scale at which social challenges are being addressed. The aim of this criterion is to assess the soil condition to understand the infiltration and groundwater which is drinking water (IUCN, 2020).

Biodiversity net gain, economic feasibility, and inclusive governance:

These criteria underscore the importance of ensuring that NBS are environmentally sustainable means that support ecosystem and biodiversity (IUCN, 2020). Biodiversity net gain can be categorized into two sub-categories: environmental co-benefits and purification co-benefits (Cross et al., 2021). Economically viable argues about the cost-co benefits of the investigated measure, and inclusive governance means the solution is accepted by the public (IUCN, 2020)

Balance trade-offs:

This criterion refers to the robustness and flexibility of NBS in achieving both short and long-term objectives. This criterion necessitates a comprehensive understanding of the risks for the selected area, as well as the benefits and costs associated with an NBS. Moreover, this criterion argues that "*NBSs should have an associated set of costs and benefits, and it is necessary to safeguard that one adaptation does not negatively impact the other most disadvantaged elements of the society*" (IUCN, 2020).

Adaptive management:

This criterion refers to the adaptations that increase the chance of successful implementation and no-regret solution (IUCN, 2020)

Mainstreaming and sustainability**:**

This criterion argues that nature-based adaptations should be designed in a way to have long-term sustainability while simultaneously addressing human rights, human development, and other SDGs (IUCN, 2020)

2.3.1.1 Risk Assessment Framework

As described in the previous section, one of the NBS's criteria is to address social challenges. Social challenges encompass four critical elements. One of these elements is climate challenges which will be elaborated in this section.

Based on this, the concept of risk assessment will be described in this section which will help in the development of an evaluation for choosing the best solution and understanding the complexity of CC. Based on (CONCITO, 2023), all Danish municipalities for implementing CCA need to follow three steps:

- Assessing the local risk to understand the complexity of CC
- Assessing the impact of CC on vulnerable systems
- Assessing the uncertainty in CC which is an important factor in proposing a robust solution

The first step is to understand what defines the risk of CC impact; hence, the IPCC risk assessment framework is utilized. According to the IPCC, the risk of CC impacts arises from the active interplay among climate-related hazards with the exposure and the vulnerability of the affected people or the ecological system to these hazards (IPCC, 2020). Figure 4 illustrates this interaction.

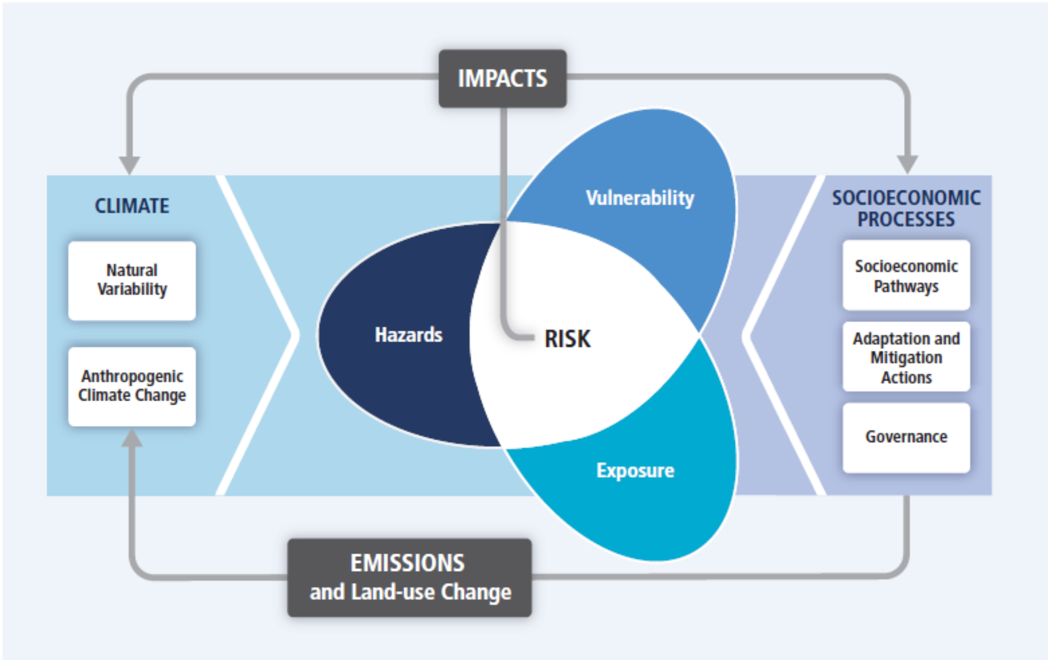

Figure 4. IPCC risk assessment framework. Figure adapted from (IPCC, 2014)

Therefore, according to this definition, it can be concluded that an increase in the frequency of precipitation level does not necessarily result in an increased risk of CC impacts, as risk needs to be connected to "*the potential adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain*" (IPCC, 2020). This means that the concept of risk should not only be used for describing the intensity of precipitation but also establish a connection to the consequences of such an event to human or ecological systems.

Moreover, the uncertainty in the concept of risk plays an important role as the changes in CC, socio-economic, and policies will influence future hazards, exposure, and vulnerability and thus change the future risk (IPCC, 2020). For assessing the local risk, first, it is important to define the characteristics of hazard, exposure, and vulnerability based on IPCC and Lehmann's definition (Lehmann et al., 2021).

Hazard: Hazards encompass the various physical potentials and types of climate events that are anticipated to affect current and future geographical areas (IPCC, 2014)

Exposure: Exposure means the individual (who) or entities (what) is likely to be affected by hazards (IPCC, 2014; Lehmann et al., 2021)

Vulnerability: Vulnerability quantifies the extent of impact and is influenced by a multitude of factors including institutional, socio-economic, cultural, historical, physical, and environmental considerations. Based on the IPCC definition, vulnerability is also considered as " *a lack of capacity to cope and adapt*"(IPCC, 2014).

2.3.2 Framework for developing NBS based on Adaptation Pathway

As described in the previous section one of the steps for implementing a robust CCA is to consider CC uncertainty. Moreover, as mentioned in the problem formulation the main goal of the Lemvig municipality is to a design solution that accommodates current hazard and future hazards. Planning for long-term CCA poses challenges due to uncertainties surrounding climate change, rapid urban development, and evolving socio-economic trends (Marchau et al., 2019). Therefore, there is a requirement to create a set of criteria based on the adaptation pathway. According to (Marchau et al., 2019) adaptive pathways consist of sequencing contiguous actions that need to cover initial action and long-term options. The reason for using the adaptive pathway in this project is to leave open different NBS options for a range of possible future (Marchau et al., 2019) and to evaluate the best adaptation that is flexible and robust for the uncertainties that will happen in the future. Moreover, the adaptation pathway assists in the decision-making process by providing alternative actions if one action in the evaluation part fails (Marchau et al., 2019). A set of criteria has been chosen from the literature (Baills et al., 2020), to evaluate and determine the most suitable solution. These parameters have been selected based on their relevance to the investigation conducted in this thesis. As mentioned before, the investigated solution needs to accommodate current hazards, therefore the criterion of immediate benefit needs to be taken into account. Secondly, as highlighted in the theoretical framework, NBS needs to be a transformative adaptation that acknowledges the fact of flexibility and robustness, hence the inclusion of these two parameters. Thirdly, as outlined in the legislation section 1.3.2, the investigated measure should not adversely affect the groundwater levels, hence possible impacts on other risks serve as another pertinent criterion for evaluating best adaptation. Finally, the criterion of the no-regret solution is another crucial factor that needs to be considered as CC has many uncertainties.

No regret solution/ highly successful solution:

No regret solution can be characterized as the capacity of NBS which produces benefits regardless of the level of future CC. Moreover, this criterion argues that measurement can have benefits even in the absence of CC (Baills et al., 2020). This criterion is relevant to the “adaptive management” described in section 2.3.1 As mentioned before, CC has many uncertainties, and measurements need to consider these uncertainties to be successful. When considering uncertainty the proposed measure can have “no regret” or in certain situations may have only a “low regret”. These measurements ensure no additional cost in the future. However, if uncertainty is not taken into account and the measure is not scored as “no regret”, such measurements are associated with notable additional costs if the future of CC turns differently than predicted (Baills et al., 2020).

Robustness:

This criterion is relevant to the “balance trade-offs” described in section 2.3.1. This criterion argues that if the measure has the capacity to be effective in the long term with different future climate conditions then can be characterized as a robust solution (Baills et al., 2020). Otherwise, the solution is not robust and is not effective. According to (The Rockefeller Foundation & ARUP, 2015), the robustness of adaptations does not rely solely on a specific type of measure but encompasses a variety of measures aimed at preventing damage from that hazard.

Flexibility:

This criterion is relevant to “ balance trade-offs” described in section 2.3.1. This criterion argues that it is highly important to consider solutions that can be highly flexible and can deal with climate uncertainties (Baills et al., 2020). Flexibility refers to climate uncertainty and acknowledges the fact that the measures can be retrofitted in the case that adaptation is left unused (Baills et al., 2020) or be a transformative adaptation that can deal with different future climate conditions (Tyler & Moench, 2012).

Short decision horizon:

There are a lot of uncertainties in the future of CC and its impacts. This uncertainty will be enhanced when adaptations with long-time horizons considered (Baills et al., 2020). Therefore, it is highly recommended to consider solutions with short-term horizons. Such solutions will provide the possibility of changing strategy over time and will not restrict other opportunities. Moreover, this strategy will reduce the corresponding cost of long-term uncertainty (Baills et al., 2020).

Immediate benefits:

The criterion of 'immediate benefits' is a complementary criterion (Baills et al., 2020) that addresses hazards and reduces vulnerability. Moreover, this criterion will assess whether the adaptation is effective as soon as it is implemented or if the effect is delayed (Baills et al., 2020)

Possible impact on other risks:

This criterion refers to the indirect effects of measurements both positive and negative on other risks (Baills et al., 2020) is similar to the 'balance trade-offs' criterion described in section 2.3.1. This criterion has been chosen because the implementation of NBS as a sustainable tool for restoring diluted wastewater should not adversely affect groundwater. Therefore, this criterion will ensure the impermeability of wastewater to the groundwater.

2.4 *Theories of science*

This thesis seeks to design an NBS to capture diluted wastewater to reduce the risk of sewage overflows at the same time have a high capacity in gray water purification. When investigating the concept of NBS and risk assessment, it is crucial to consider ontology and epistemology presumptions and reflections (Farthing, S, 2016). According to (Farthing, S, 2016), the main criticism of the research before starting the research is to recognize the assumptions and presumptions about ontology, which is about understanding the social world, the nature of knowledge, and epistemology, meaning to know about the world and gain knowledge of social reality. This can be described as an iceberg. Ontological assumption lies deep beneath understanding. Epistemology builds on the ontological assumption, concerning how one can acquire knowledge about this reality, and on top of the iceberg are the methods used for the research. These assumptions will help to find the cause and effects of the nature of the research topic (Farthing, S, 2016).

The planning and designing of the research field rely on the CC effects and wastewater management by NBS. This means that the research touches upon the effects of climate change. Based on (Farthing, S, 2016) the knowledge and assessment of CC should be based on scientific data and the researcher's opinions and imagination should not interfere. Therefore, this scientific research is characterized by a positivistic understanding of the world which is regarded as value-free and objective that the reality of this research is based on scientific evidence. However, when dealing with planning for wastewater management and purification, the complexity of planning in reality by characterizing legislation and stakeholders will appear. Therefore, the result of the research cannot continue to be based on value-free and scientific evidence, since the stakeholders, and decision-making ideas will interfere with the process of the research.

According to (Farthing, S, 2016), since research is based on both scientific evidence and the decision-making context, the nature of knowledge highly depends on the background of the research. The background of the research is dedicated to understanding the problem of the social world in diluted wastewater wastewater and sanitation of wastewater. The assumption of this thesis underlies that the municipality can utilize the climate science data gathered through sources like Climate Atlas, and HIP, alongside the technical tools introduced in this thesis including SCALGO LIVE and QGIS for modeling the risk of the case area. However, planning for wastewater management in the context of CC cannot rely solely on scientific data, but also requires a comprehensive guideline for the municipality and stakeholders to choose a valid and suitable solution that can be robust to accommodate current hazards, and be flexible to deal with future hazards. Additionally, the NBS should not only focus on mitigating the risk of overflows, but also need to be cost-effective and provide additional benefits, including environmental benefits, and meet the legislation requirement for purification rate. Moreover, this research also focuses on providing a comprehensive methodology for the municipality to calculate the dimension of NBS to have an immediate benefit by accommodating current hazards.

Therefore, this research advocates for the concept of NBS, as the theory, which is the main point of this research. Given the numerous uncertainties regarding the future, this research develops criteria based on adaptive pathways to choose the best and most suitable NBS.

2.5 *Methods*

This section is dedicated to data collection and data analysis used to answer each sub-research question.

2.5.1 Data collection

In this sub-section, first, literature and information search used to formulate the introduction, theoretical, and analytical framework and help in answering sub-research questions one and two will be described. Second, qualitative data collection including interviews used to answer both sub-research questions and observation used to answer sub-research question two will be elaborated. Finally, quantitative and primary data collection which is a mixture of qualitative and quantitative data collection used to answer both sub-research questions will be introduced.

Literature and Information search

The gray literature including reports, and scientific literature including academic and scientific articles were utilized to form the problems that this thesis aims to address. The documents including the Lemvig climate adaptation plan and Lemvig wastewater plan have been reviewed to gain valuable data regarding the dimensions of sewage systems and the problems they face during heavy precipitation. Moreover, scientific reports and scientific articles were used to formulate the basis of a theoretical and analytical framework to build a robust foundation for developing a comprehensive understanding of the concept of NBS. The analytical framework in this thesis made a comprehensive foundation of how NBS can be evaluated and chosen.

Additionally, documents including the Environmental Protection Act, European Union, miljøstyrelsen, and Lemvig municipality wastewater plan have been reviewed to establish comprehensive and logical legislation. Understanding regulations for implementing and utilizing NBS as a sustainable tool for collecting and purifying diluted wastewater was an important factor.

Initially, the research was carried out using databases of scientific and academic articles, journals, and books. The amount of literature focusing on NBS and sewage overflows was a lot. Therefore, to find the most appropriate literature among numerous references some steps were followed, including:

- The literature was limited to the period from 2020 to 2024 to ensure the most recent information that aligns with current weather conditions.
- The literature for finding the most appropriate NBS was limited to Danish documents and cold regions to ensure that the solution aligns with the Danish weather conditions.
- Their abstract and keywords were reviewed to find the most relevant paper.

The information was collected from different platforms including ResearchGate, Google Scholar, Google, and ScienceDirect. The research was performed by searching keywords in the research engines to identify the most relevant documents and make the research process easier. The keywords include:

"*Climate Change", "Nature-Based Solution", "Wastewater Management in Lemvig Municipality", "History of Handling Water", "Consequences of Wastewater", "Extreme Rainfall", "Sewage Overflows", "Urban Water", "Wetlands", "Artificial wetlands", "Multi-criteria analysis", "Constructed wetlands", "Adaptive Pathway", "Willow treatment plants", and "NBS for wastewater restoration*" were utilized in search engines to facilitate targeted exploration of relevant literature.

- *Qualitative data collection*

In this section, the qualitative data collection including interviews and observation used to answer each sub-research question will be described.

Interview

For this thesis, a combination of semi-structured and informal interviews was utilized as part of a qualitative method to gain specific and general information about the case project. The semi-structured interview was conducted to gain more in-depth information by pre-planning specific questions. According to (Mashuri, S et al., 2022) a semi-structured interview needs to follow a framework that is prepared in advance and has a balance between main questions, and follow-ups which can be read in Appendix A. The biggest advantage of a semi-structured interview is that it lets the interview remain flexible (Mashuri, S et al., 2022). A semi-structured interview for analyzing a specific location will be beneficial if it includes a wide range of stakeholders (Adeoye-Olatunde & Olenik, 2021). Therefore, based on stakeholder analysis focusing on expertise and familiarity with the case project, their insights were utilized to facilitate preliminary and targeted data collection during the research design phase of this thesis, as outlined in Table 1.

Table 1. Interviews utilized as part of the project

Number of Interviewees	Region-Year	Role/ Title	Contribution to the report
IN 1	West Coast of Denmark, 2024	Project manager	Contribute to the understanding of the pump station problem. Through face-to-face interview
IN 2	West Coast of Denmark, 2024	Project manager	Contribute with the knowledge and reflection on the case project. Through both face-to-face and Teams meeting interviews.
IN 3	West Coast of Denmark, 2024	Project manager	Contribute with the knowledge on locations of sewage overflows. Through face-to-face and Teams meeting interviews.
IN 4	North Jutland of Denmark, 2024	Nature-based and Landscape designer	Contribution with the knowledge of biodiversity and environmental benefits of investigated solutions. Through Teams meeting interviews

Observation

In this thesis, observation was used as a complementary qualitative method during a workshop in Lemvig municipality, held at Klimatorium. According to (Ahmed, S & Mohd Asraf, R, 2018) workshops involving various stakeholders enable the researcher to collect data through a collaborative and shared experience. Additionally, the key aspect of using a workshop as a qualitative observation is to identify the field or subject of the observation beforehand (Ahmed, S & Mohd Asraf, R, 2018). Therefore, the subject was to understand stakeholders' perspectives regarding the importance of each criterion described in the analytical framework. The observation data was collected through attempts in three groups of stakeholders who came from different municipalities, private companies, and utilities. The steps for collecting data during the workshop were based on recommendations from (Raudaskoski, P. L, 2020) which are described in Appendix A. The data collected during the workshop is shown in Table 2.

Table 2. Data collection through being in a workshop

Stakeholders in the workshop	Region-year	Contribution to the report
NBRACER workshop for nature-based adaptation	West Coast of Denmark, 2024	The NBRACER workshop highlighted the visions and criteria that are important for stakeholders to choose a suitable solution.

- ### *Quantitative and primary data collection*

In this sub-section, both qualitative and quantitative data collected from different sources will be described. The aim of utilizing both qualitative and quantitative methods is to collect data regarding the risk of the case area which helped to answer sub-research question one and then data regarding multi-criteria analysis which was used to answer sub-research question two. The reason for considering multi-criteria analysis data collection in this section is that both qualitative and quantitative data collection have been used for the evaluation of measurements.

Risk assessment data collection

To comprehend the future climatic conditions for planning purposes, climate models are essential. They aim to describe the physical, chemical, and biological processes of the climate system, providing projections of future climatic conditions under various potential scenarios (IPCC, 2022). The data collected to assess the risk is collected from various platforms. First, the hazard assessment is based on IPCC emission scenarios. The IPCC relies on emission scenarios, with its fifth assessment report, known as Representative Concentration Pathways (RCP), and the sixth assessment report utilizing a new scenario called Shared Socioeconomic Pathways (SSP). In this thesis data utilized to assess the daily precipitation which is considered as a hazard of the case area is collected from regional climate models, Klimaatlas. Klimaatlas (Climate Atlas) is a Danish online platform that provides data on temperature, precipitation, water level, and storm surges for the future. In klimaatlas the atmospheric indicators are shown by RCP and ocean indicators rely on SSPs (DMI, 2023a). Therefore, given that precipitation is the primary focus of this thesis, the RCP scenario has been selected. The RCP contains four scenarios which are shown in Table 3.

Table 3. Description of RCP Scenarios

Scenarios	**Description**
RCP 2.6	Reducing global temperature to 2°C. Low emission scenario
RCP 4.5 and RCP 6.9	Both scenarios argue that global emissions need to be reduced and the effect on climate is maintained at the end of the century. Medium emission scenario
RCP 8.5	High emission scenario

Source adapted from (DMI, 2018)

Exposure data collection is based on the IPCC's definition described in the analytical framework and is through two-step processes. Firstly, data regarding mapping and understanding which location will be affected by heavy precipitation has been collected from SCALGO LIVE which is described in Table 4. Moreover, data regarding sewage systems and their connection has been collected from an online website which is for Lemvig Vand, and provides data about the connection of sewage systems, pump stations, the age of sewage systems, and rainwater basins. Finally, to complete the first step of data collection an interview was conducted with a professional to collect data regarding pump station overflows.

Second, data regarding who or what will be affected or exposed by sewage overflows is collected which is described in Table 5. Data regarding the historical condition of groundwater level in the selected area and the changes in the future condition of groundwater level has been collected from an online platform, HIP which is an open web-based platform that offers free public access to hydrological information, facilitates modeling calculations, and forecasts future climate adaptation, water management, and planning (HIP, 2023), and data regarding the current situation of groundwater level for the case area has been collected from a Danish online platform, Klimatipasning (KAMP), which provides data about buildings, nature, low-lying areas, sea level rise, and groundwater level (KAMP, 2023)

The reason for collecting exposure data through a two-step process is to first, determine if the sewage overflows happen before the Nørre Nissum pump station. This approach helps to identify areas that experiencing water accumulation due to heavy precipitation and at the same time exposed to sewage overflows. Therefore, implementation solutions in those locations to reduce the associated risk in the Nørre Nissum pump station.

Table 4. The first step of exposure data collection

Collected data	Source
Land depression. Water accumulation on the surface	SCALGO LIVE
Connection of sewage systems	(Lemvig Water, 2024)
The pump station that will experience sewage overflows	Interview

Table 5. The second step of exposure data collection

Collected data	Source	Link to IPCC definition
The lake near the catchment area	(Miljøministeriet, 2023)	Environment
Soil type	(HIP, 2023)	Environment. Will cause groundwater contamination by diluted wastewater
Groundwater level	(HIP, 2023; KAMP, 2023)	Environmental
Species that will be affected by diluted sewage overflows	Interview	Environment

It should be noted that there may be other exposed elements including agricultural areas and crops. However, due to the timing of the project and the given solution which will reduce the risk of exposure areas, they have not been considered.

Vulnerability data collection is also based on the IPCC's definition described in the analytical framework. However, the first definition "*socio-economic, cultural, physical and environmental consideration that will be affected by hazard*" is considered to be related to exposure. Therefore, the first definition is utilized in exposure data collection. The second definition "*lack of capacity to cope and adapt*" is the main interest of this data collection. The lack of capacity in this thesis is the capacity of the sewage systems and the pump station. For collecting data about the soil type, HIP has been used. The capacity of sewage systems has been collected from the Lemvig wastewater plan and data about the pump station capacity was by having a semi-structured interview with person no 3. The collected data is shown in Table 6.

Table 6. Vulnerability data collection

Collected data	Source	Link to IPCC definition
Soil type	(HIP, 2023)	Influence infiltration opportunity
Capacity of sewage systems	Literature review	Useful to analyze pressure on the pump station
Pump station	Interview	Useful to understand at which level of water the system will overflow.

Multi-criteria analysis data collection

A multi-criteria analysis for evaluating a successful measure based on identified criteria in the analytical framework was developed. Various types of data including qualitative and quantitative were used to assess the measure's performance in relation to these criteria. The qualitative data was collected through literature research which helped to collect data about the co-benefits including environmental co-benefits, purification rate, cost co-benefit of different measures, flexibility, and the quantitative data regarding scoring and weighting of the identified criteria was also collected from literature research and the observation. Moreover, for the immediate benefit criterion, a formula to calculate the dimension of the selected measure was formulated from the literature search.

2.5.2 Data Analysis

This section will analyze the data collected in the previous section. In qualitative data analysis, the data gathered by literature and information research, interviews, and observation will be analyzed. Finally, the data regarding risk assessment and multicriteria analysis will be analyzed in quantitative and primary data collection.

- *Qualitative data analysis*

The data collected from the information search was used to form the problem analysis and theoretical and analytical frameworks. Moreover, they were used to answer sub-research question one and sub-research question two.

The interviewees were interviewed both face to face by visiting the case area that has a problem with sewage overflows and through online meetings. The questions for the interview were based on principles described in the analytical framework, section 2.3 to understand which principles are the most important ones for the Lemvig municipality in the evaluation part of the solutions. Moreover, the interview helped to understand the problem of sewage overflows. All interviewees were interviewed in English some of them were through the semi-structured interview guideline as shown in Appendix A, while others were through informal interviews. The interview analysis was used to answer one part of the sub-research one by providing data regarding the exposure, and sub-research question two by collecting data regarding the discharge rate of wastewater into the case area and have an insight into which criteria outlined in the analytical framework hold greater importance for Lemvig municipality in weighting measures for the multi-criteria analysis. The collected data for the discharge rate of wastewater into the Nørre Nissum pump station is shown in Appendix B.

During the two-day workshop, physical observation was conducted to assess stakeholders' reactions to different topics. The subject of the workshop was about understanding the connection between natural and social systems, with a theme centered around NBS. Stakeholders were divided into three groups of seven. The first group collaborated in Danish, frequently using the phrase " *Det er dyrt at implementere grå løsninger*", which means implementing grey solutions is expensive. Two other groups of stakeholders mainly spoke in English, expressing concerns about increasing "*cost-effective, environmentally friendly solutions*". Finally, at the end of the second day, a vision was made by stakeholders which was written in English, and the relevant parts of this vision are included in this thesis. The picture of the vision is shown in Appendix A.

- ### *Quantitative and primary data analysis*

In this section, data collected for answering sub-research question one and sub-research question two has been analyzed. First, data regarding risk assessment which will answer sub-research question one will be described, and then multi-criteria analysis which helps to answer sub-research question two will be described.

Risk Assessment

According to the analytical framework, the risk assessment will be conducted by analyzing the hazards, mapping exposure, and vulnerability of the selected area. Therefore, the following section will describe the methods used for assessing the risk.

Hazard assessment

In order to analyze the hazardous two different scenarios including RCP 4.5 and RCP 8.5 have been used. According to the Danish Metrological Institute (DMI) scenario RCP 4.5 has been used for planning horizons until 2050 and scenario RCP 8.5 for periods beyond 2050 (DMI, 2018). Based on the criterion 'immediate benefit' described in the analytical framework, the current precipitation (hazard) under scenario RCP 4.5 for three different daily precipitation events including 10-, 20-, and 50-year events have been assessed. This aims to understand the short-term challenges and short-term CCA objectives. Moreover, as mentioned in the problem formulation the goal of the Lemvig municipality is to implement NBS that has a 25-years lifespan. Therefore, future precipitation events will be investigated for the same return periods under scenario RCP 8.5. It should be noted that the selection of future precipitation events is not outlined in Lemvig municipality's goal. The precipitation events are chosen based on different criteria, including the dimensions of the pipes. They can handle and manage 5-year precipitation. Therefore, precipitation after the 5-year event will be elaborated. The second criterion is to analyze the robustness and flexibility of CCA. Therefore 10, 20, and 50-year events have been chosen as the probabilities of these events to happen each year are 10%, 5%, and 2% (Lemvig Kommune, 2014), and the result is shown in SCALGO LIVE.

It should be mentioned that the dimensions of pipes that can accommodate 5-year precipitation events and can handle 51 mm/day precipitation were subtracted from the SCALGO simulation. This adjustment was crucial as SCALGO LIVE cannot consider the infiltration capacity of rainwater into the sewage systems

Exposure and Vulnerability assessment

To effectively assess the area exposed to heavy precipitation and sewage overflows, two-part exposure analyses were employed. First, the accumulation of current precipitation on land was assessed in SCALGO LIVE. SCALGO is an online digital tool for simulating and visualizing the future condition of precipitation on the surface (SCALGO LIVE, 2023). To visualize and analyze the exposure a workspace that contains three pump stations including, Godum, and Febjerg which are connected to the Nørre Nissum pump station was made.

Second, have a semi-structured interview with person number 3 who is a professional in sewage systems to determine the location that is exposed to heavy precipitation and sewage overflows. The aim of this methodology is to determine whether areas experiencing water accumulation also face sewage overflow issues. The questions that have been asked are described in Appendix A

To assess and analyze the groundwater level the available QGIS map layers from HIP and KAMP were used. For future changes, a special resolution of 100 m grid under medium and high emission scenarios for the seasonal variation of summer and winter for the period of 2041-2070 was assessed.

To map the soil type of the selected area in QGIS, available GIS map layers from HIP were used. This data shows the soil type for the plow layer between 0-25 cm for the selected area which is known as topsoil, and the soil type with the depth of 1 meter under the plow and culture layer with a scale of 1:25000 to understand the infiltration capacity of the soil.

Limitation:

SCALGO LIVE has some limitations including that this online platform does not consider the infiltration capacity of rainwater to the soil. Therefore, there is uncertainty regarding the accumulation of rainwater on the surface and the rainwater runoff flow. Therefore, it is important to note that the simulation and visualization in SCALGO LIVE may not be the same as the actual event. Therefore, these analyses should not be taken as the actual magnitude of the event, but rather as an estimation.

Argumentation:

The qualitative data analysis section covers the data collected through interviews, including data for vulnerability assessment and one part of exposure. This means that all interview data is discussed within the qualitative data analysis and is not separately detailed in each sub-section.

- *Assessment of Successful Implementation of NBS*

As mentioned in the analytical framework, effectively designing, and implementing NBS in a case area necessitates following specific standards. Therefore, in this section which will answer sub-research question two, the method for evaluating the best adaptation will be described.

Assessing suitable measure

As mentioned in section 2.3.1.1 climate change has many uncertainties, therefore, to ensure the flexibility and robustness of the solution for the future, a systematic approach based on the adaptation pathway described in section 2.3.2 is required. To determine the most appropriate and effective measure for implementation in the case area, additional criteria outlined in the analytical framework will undergo assessment and evaluation via multi-criteria analysis. Multi-criteria assessment involves a systematic approach to evaluating various NBS options based on a diverse set of criteria. This method will increase the strength of the selected measure due to the specific characteristics of the selected criterion within the analytical framework. This method enables the identification of optimal solutions, or the ranking of alternatives based on their performance across multiple criteria (Dean, 2020). This approach will help in the decision-making process of the research that if one action fails, alternative actions are available. Therefore, some steps based on (USAID, 2013) have been established for multicriteria analysis including:

- Identifying NBS options
- To establish assessment criteria along with their respective assessment scale

- Identifying the outcome and performance of each NBS against identified criteria.
- Assess the weight of each criterion
- Finally calculating the final weight rates

Risk assessment to identify hazards and vulnerability is an important factor in the first step of identifying NBS options (USAID, 2013). After analyzing the risk of the selected area, the best NBS that aligns with the legislation described in section 1.3.2, meets purification standards and fits in the context of the case area for collecting diluted wastewater will be investigated.

The second step, which is establishing the assessment criteria along with their respective assessment scale, is based on the remaining seven criteria mentioned in the analytical framework. To assess the scale of each criterion there is a requirement for developing a score range. Therefore, based on this Table 7 will describe the score of each criterion. According to (Dean, 2022), performance scores range from 0 to 100. A score of 1 indicates a low-performance option, while 100 signifies high performance. Therefore, a score of 0 represents very low and strongly negative performance effects, 1 indicates low and negative performance effects, 2 signifies medium performance effects, 3 denotes high or positive performance, and finally, 4 represents very high or strongly positive effects (Dean, 2022). Due to the scope and timing constraints of the project, this report utilized a 3-point scoring system, ranging from 1 to 3, to evaluate measurements based on their performance levels, from low to high.

Table 7. Description of the score range

Criteria	Score 1	Score 2	Score 3	Weighting
Environmental co-benefits	NBS provides a low level of environmental co-benefits	NBS provides a medium level of environmental co-benefits	NBS provides a high level of environmental co-benefits	10 %
Purification co-benefits	NBS provides a low-level purification rate	NBS provides a medium-level purification rate	NBS provides a high-level purification rate	22 %
Cost co-benefits	NBS is associated with a low-cost co-benefit	NBS is associated with a medium-cost co-benefit	NBS is associated with a high-cost co-benefit	22 %

Flexibility	NBS has low flexibility	NBS has medium flexibility	NBS has high flexibility	10 %
Robustness	NBS is characterized by low robustness	NBS is characterized by a medium robustness	NBS is characterized by high robustness	10 %
No-regret solution/ highly successful solution	NBS is characterized by a high level of regret or low success	NBS is characterized by a medium level of success	NBS is characterized by a low level of regret or high success	10 %
Possible impacts on other risks	NBS is characterized by a high level of impact on other risks	NBS is characterized by a medium level of impact on other risks	NBS is characterized by a low level of impact on other risks	16 %

In order to analyze and assess the 'no-regret or successfulness' of adaptive management, the criteria 'flexibility, and robustness' will be used. This is because the data about the no-regret solution has not been found in the literature. As a result, the assessment of the 'no regret/ successfulness' will be evaluated based on these two mentioned criteria. For evaluating the 'cost co-benefit' criterion of the selected NBSs three factors that are important for Lemvig municipality, including the implementation and maintenance cost, the biomass production, and the reuse of water for irrigation will be evaluated. Based on this, if the measure has a high implementation cost will be scored as 1, while those with a low implementation cost will be scored as 3. This process is the opposite of those two elements. If the measure has a high capacity in biomass production or water irrigation will be scored as 3. It should be noted that the maintenance cost of investigated measures is overall and does not specify any specific events since the data was gathered through literature research. Additionally, the 'no regret or successful implementation' criterion has been assessed through two criteria, including robustness, and flexibility since the literature regarding this criterion has not been found.

According to the criteria described in the analytical framework, the criterion of a short decision horizon has been left out. According to (Baills et al., 2020) the short decision is a measure that its implementation demands a financial commitment of less than 10 years. Therefore, this thesis which is a pilot project for Lemvig municipality will be implemented in the next "one-two years" (IN 2). Hence, this criterion is not considered.

The third step will entail the actual assessment of each adaptation's performance against each criterion. According to 'possible impacts on other risks' and 'balance-trade offs' criteria described in section 2.3.1 "*NBSs should not negatively impact the other most disadvantaged elements of the society*" (IUCN, 2020). For instance, an NBS may have environmental co-benefits, but it does not have a high level of purification and may adversely affect the environment and groundwater level.

The fourth step is assessing the weight of each criterion. The weighting of each criterion is based on the goal Lemvig municipality climate adaptation plan, workshop observation, and the Environmental Protection Act (EPA) for wastewater. Cost is considered one of the most essential criteria for the stakeholders present in the workshop and Lemvig municipality as the budget for implementing NBS for collecting diluted wastewater is 1 million DKK (IN 2). Therefore, a certain NBS cannot be chosen if the alternative measure is cheaper. Moreover, according to the EPA, the purification rate of the selected measurement for purifying diluted wastewater has a high priority since the wastewater should not negatively impact the natural environment (Miljøstyrelsen, 2018). Therefore, measurements that have a higher purification rate will be prioritized. Moreover, based on legislation described in section 1.3.2, the investigated measure should not negatively affect the groundwater. Thereby, the 'possible impacts on other risk' is another criterion that needs to be prioritized. However, the cost-benefit and purification rate are the most important and focal factors in this thesis since the municipality, legislation, and stakeholders mentioned them. Therefore, each of these two criteria will receive a weight of 22%, and the possible impact on other risks will receive a weight of 16%. The other four remaining criteria are important but they are the complementary criteria for a successful implementation. Therefore, each of them will be allocated a weight of 10%.

Besides, this simple weighting method (Dean, 2022) argues that some decision-making faces some challenges during the weighting of solutions in the multi-criteria analysis. This is because, during the weighting process, some solutions can obtain the same weight. In that case, it will be difficult for decision-makers to choose a solution. To tackle this problem it is important to establish a degree of dominance that one option has over another. This means using a "*pairwise*" method like A 1>A 2 (Dean, 2022). To make it more understandable an example based on two important criteria in this thesis is made. In both legislation and Lemvig municipality's goal the purification rate of investigated measure has been mentioned. However, cost-co benefit is the criterion that is important for Lemvig municipality. Therefore, the purification rate will be over the cost-co benefit.

$$Purification\, rate > Cost\ co - benefit$$

Limitation:

The criterion of inclusive governance has not been assessed in this project because of the timing of the project for involving various stakeholders in the decision-making process. This criterion can be considered as a secondary step process after analyzing the risk and proposing NBS (IUCN, 2020). The concept of mainstream and sustainability has not been evaluated in this analysis, and the reason behind this is this criterion primarily addresses human rights and human development, objectives which are not the focus of this thesis.

Immediate benefit

The criterion of immediate benefit has not been added to the evaluation table since the aim of this project is to design an NBS to capture diluted wastewater. Therefore, the capacity of the investigated measure should be designed in this thesis. And then assess the immediate benefit of the selected measure.

Based on the definition of immediate benefit described in the analytical framework the investigated measure should reduce the risk as soon as it is implemented. Therefore, for assessing the immediate benefit the current precipitation has been assessed in section 3.1.1. Then, the capacity of the investigated measure for retaining diluted wastewater will be assessed based on recommendations from (Rhys Gustafsson, 2014). The formula determines the water balance in the catchment area to highlight the required capacity for retaining diluted wastewater. The formula is:

$$\boldsymbol{Qo = Qi + Ai(P - ET - I)} \qquad (1)$$

A_i = Wetlan area m^2

Q_i = Inflow (influent) m^3/ day

Q_o = Outflow (effluent) m^3/ day

P= Precipitation m/ day

ET= Evapotranspiration m/day

I= Infiltration m/ day

Data analysis regarding the inflow rate of wastewater into the Nørre Nissum pump station is based on the two pump stations connected to the Nørre Nissum pump station. Therefore, for calculating the discharge rate of wastewater in this pump station the sum of the total discharge from the Gudum pump station and Febjerg pump station for the period of 2023 was done, then divided the obtained number by the number of days which is 31 days.

The document analysis for collecting data regarding the evapotranspiration rate was based on some criteria including being a Danish document since the evapotranspiration rate depends on the climate conditions and geographical location. Second, considering the evapotranspiration rate in central or western Julland since according to (Miljøministeriet, 2003) wind, air temperature, and coastal areas will affect the evapotranspiration.

Chapter 3: Analysis & Result

3 Analysis & Result

Section 3.1 will provide a throughout risk assessment of the case area for both current and future situations. Moving forward, section 3.3 presents an initial analysis and scoring potential measures based on multi-criteria analysis. Section 3.4 is built upon the evaluation conducted in the previous section, and focuses on the primary analysis for weighting the measures and choosing the appropriate NBS. Finally, section 3.5 delves into the detailed design and capacity calculation for the investigated measure, ensuring they are robust for the short term and some recommendations for the long term.

3.1 *Risk Assessment*

This thesis aims to answer the main research question by assessing the specific case area which is located in Lemvig municipality. Lemvig is a small municipality on the west coast, in the Midtjylland region of Denmark. Lemvig municipality has approximately 19 722 inhabitants (Lemvig kommune, 2020) and has been always at risk of water accumulation due to heavy precipitation and sewage overflows. The specific case area is Nørre Nissum pump station which is located in northern West Jylland and the eastern part of Lemvig municipality (Lemvig kommune, 2022). Nørre Nissum pump station from the past until now has experienced sewage overflows numerous times due to its capacity (IN 3). The capacity of this pump station is 352 cm and during heavy precipitation when the water exceeds the pump station capacity, it will be overflowed (IN 3). The capacity of the Nørre Nissum pump station is shown in Appendix F. Therefore, this section will contribute to assessing the risk of the case area. The following sections will examine the hazards, exposure, and vulnerability of the Nørre Nissum pump station.

3.1.1 Hazard

This section will describe the hazard of the case area. As mentioned in the analytical framework one of the standards of evaluating the best adaptation is that NBS address social challenges including CC (IUCN, 2020). Therefore, this section will describe and visualize heavy precipitation events in SCALGO LIVE which will cause sewage overflows.

3.1.1.1 Current and Future Hazard

It is expected that in the future Denmark will experience heavier and more frequent precipitation. Therefore, the following tables will describe the current and future precipitation events under scenario RCP 4.5 (Table 8) and scenario RCP 8.5 (Table 9).

Table 8. The current precipitation events under scenario RCP 4.5

Precipitation events	Reference period (1981-2010)	Current Century (2011-2040)
10-year event	58.2 mm/day	51 mm/day (uncertainty: 50-72 mm/day)
20-year event	67 mm/day	68 mm/day (uncertainty: 56- 84 mm/day)
50-year event	80 mm/day	81 mm/day (uncertainty: 64-103 mm/day)

Reference: adapted from (DMI, 2024a)

Table 9. The future precipitation events under scenario RCP 8.5

Precipitation events	Reference period (1981-2010)	Future Century (2041-2070)
10-year event	58.2 mm/day	63 mm/day (uncertainty: 53-77 mm/day)
20-year event	67 mm/day	72 mm/day (uncertainty: 59-90 mm/day)
50-year event	80 mm/day	86 mm/day (uncertainty: 69-109 mm/day)

Reference: adapted from (DMI, 2024a)

The 20 and 50-year events of the current precipitation along with flow accumulation are estimated in SCALGO LIVE and visualized in Figure 5. Since sewage systems can handle 51 mm of precipitation per day, hence the current 10-year precipitation does not pose a significant threat. As can be seen in the Figure below the case area is defined as the main depression with a volume of 158 648.53 m^3 (SCALGO LIVE, 2023).

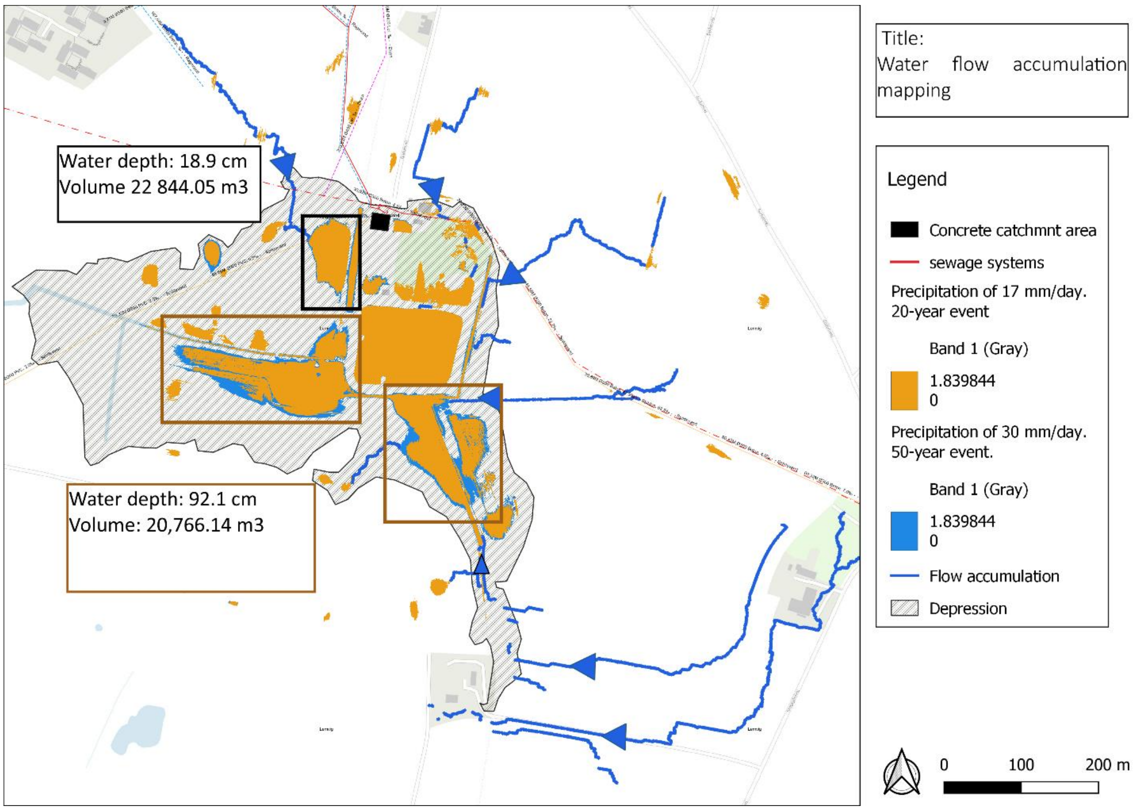

Figure 5. Current hazard mapping. Data source: (SCALGO LIVE, 2023)

As illustrated in the figure above, the case area is a low elevated area where rainwater from uphill will flow into this location. There are three main depressions within the case area which have a high volume in the 50-year event. Two of the depressions which are highlighted with brown rectangular are not located near the concrete catchment. Therefore, for the current precipitation event, they may not have significant pressure on the pump station. However, the catchment area which is shown with black rectangular has a higher volume compared to two other depressions and is located near the concrete catchment area and will cause pressure on the pump station.

In the future when there is more rainfall these three depressions will be connected as illustrated in Figure 6, and put more pressure on the pump station, as a result, the diluted wastewater will be overloaded.

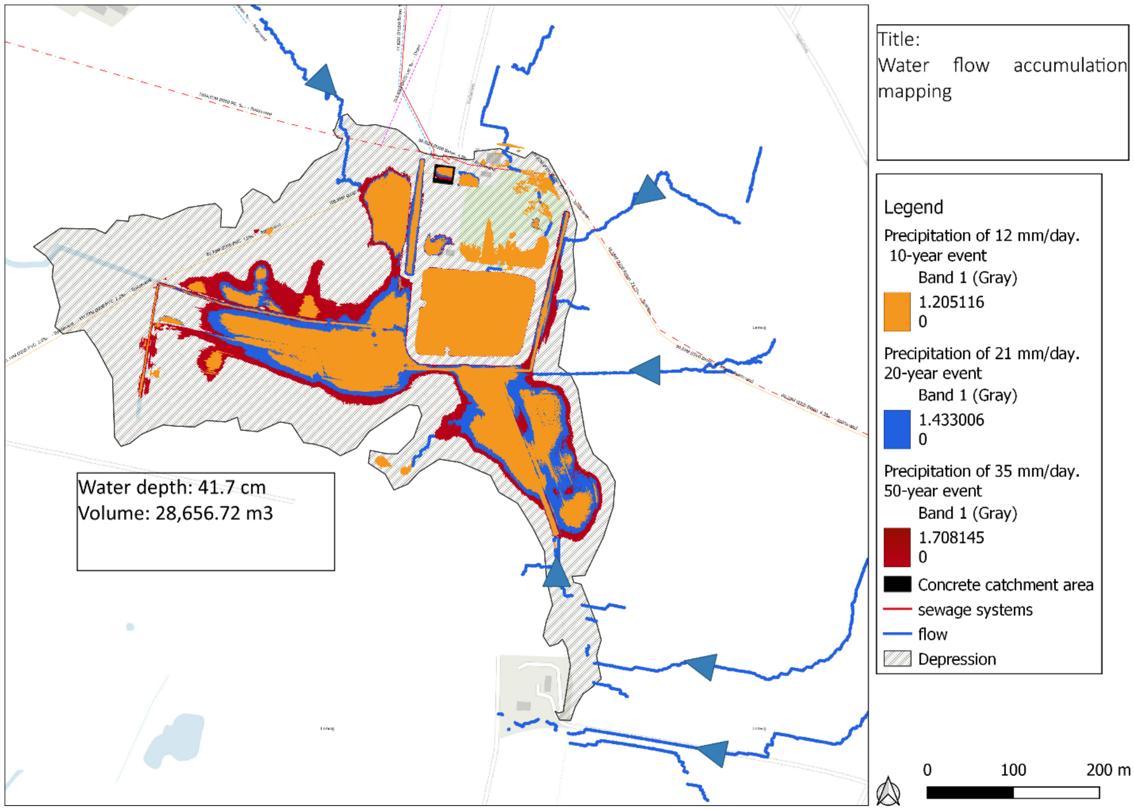

Figure 6. Future hazard mapping. Data source: (SCALGO LIVE, 2023)

3.1.2 Exposure

Exposure assessment is based on the IPCC definition described in the analytical framework 'who or 'what' will be affected by exposure. This assessment comprises two interconnected steps. First, the assessment will zoom out to assess the water accumulation on the surface to determine whether areas experiencing water accumulation also face sewage overflow issues. And then zoom in, to assess the exposure in the selected case area. As mentioned before, the aim of this assessment is to propose solutions in areas exposed to sewage overflows to reduce the pressure on the Nørre Nissum pump station. Therefore, for the first assessment, the current precipitation will be analyzed since the solution should have an immediate benefit and the result is shown in Figure 7.

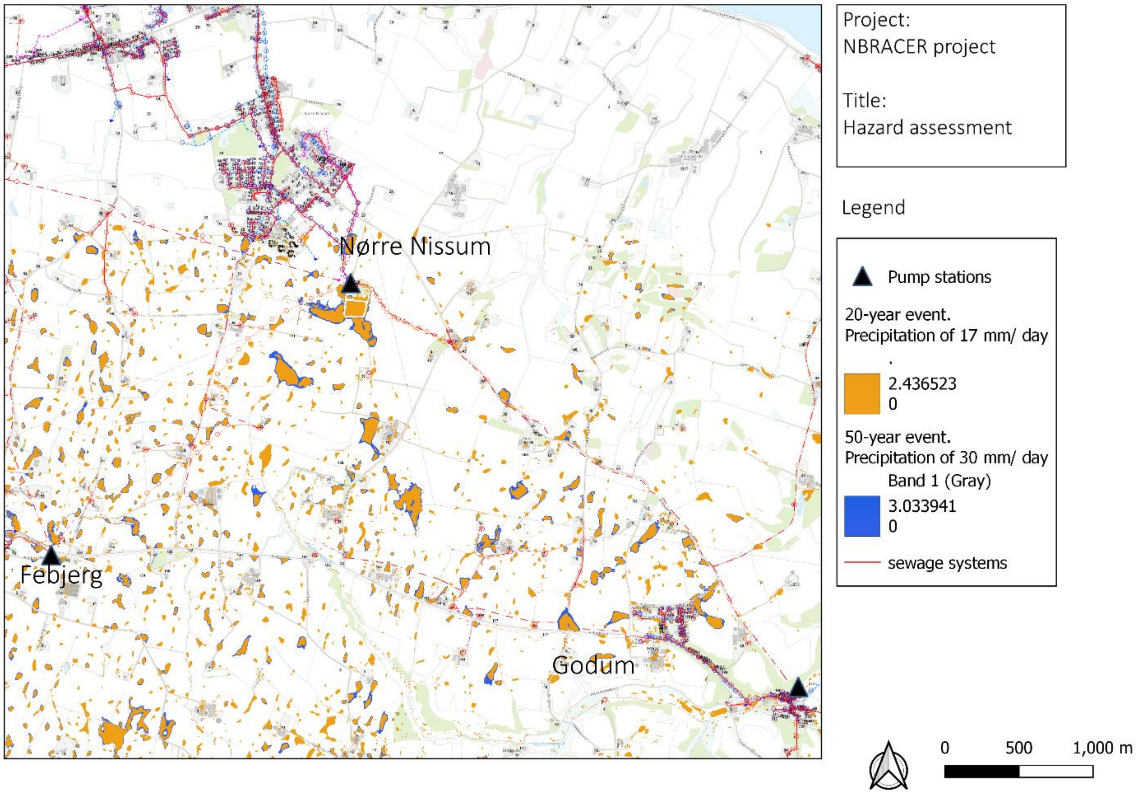

Figure 7. Accumulation of water on the train based on RCP 4.5. (Source for sewage system adapted form (Lemvig Water, 2024)

Based on the figure above there are three main water accumulations on the surface. However, as shown in Figure 8 "*the two water accumulated areas that are shown with black rectangular are not considered as sewage overflows since they are not near the pump stations*" and "neither of these two pump stations, Godum and Febjerg, have experienced overflows, this is because of their capacity" (IN 3,). Conversely, the rectangular which is shown with the green line "the Nørre Nissum pump station, has experienced overflows numerous times including February 2022-March 2022, December 2022- January 2023, and February 2023-March 2023" (IN 3). Therefore, the area exposed to sewage overflows is the Nørre Nissum pump station, and the other highlighted locations are not exposed to sewage overflows.

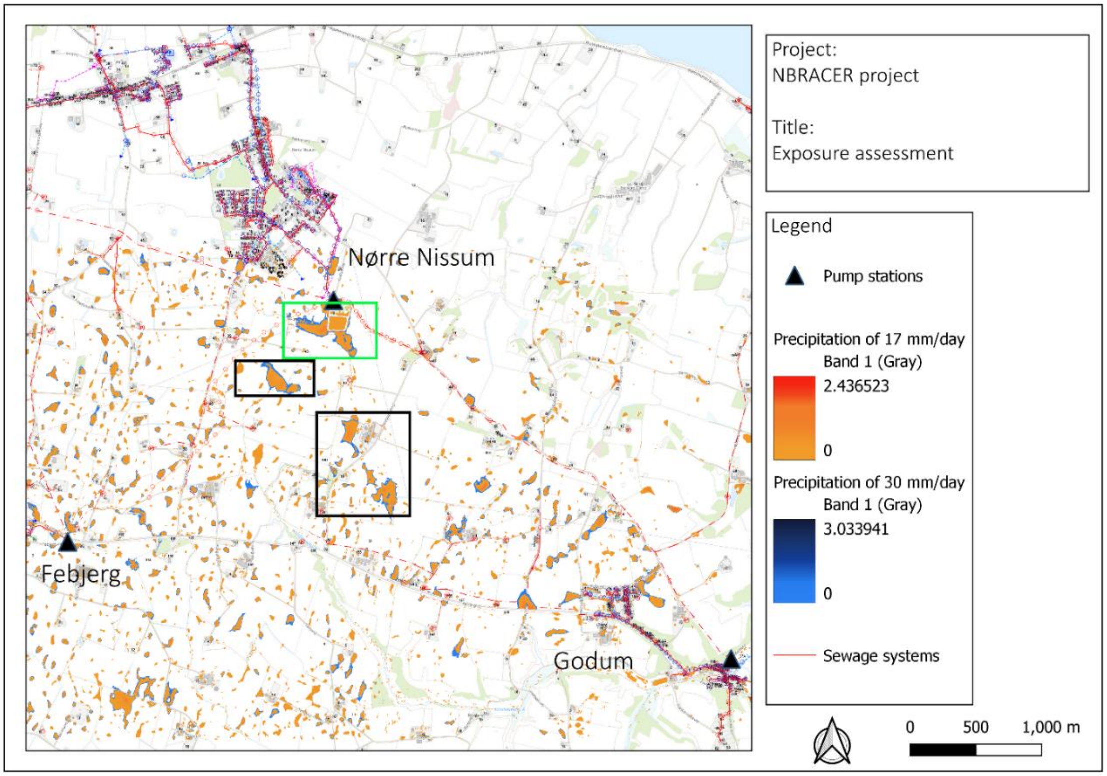

Figure 8. Rainwater accumulation and sewage system connection to the case area. Source for swage systems adapted from (Lemvig Water, 2024)

The designated area, Nørre Nissum, that experiences sewage overflows is under the ownership of the municipality (KAMP, 2023) and covers an area of approximately 28 186.3 m^2. This location consists of a concrete catchment area for wastewater, a recreational space for citizens, a green space, and a lake which is a habitat for different species (IN 2) and the total area for the lake is 12 035.94 m^2 (IN 3) which is shown in Appendix G. The figure of the lake and the concrete catchment area are shown in Figure 9.

Concrete catchment area The lake

Figure 9. Illustration of the lake and the concrete catchment area. Own observation

The current situation of groundwater level based on the reference period 1990-2019, in summer, is approximately 3 m below the surface and in winter the case area will experience a slightly higher groundwater level compared to summer with relatively 2 m near the surface (KAMP, 2023). Therefore, it can be concluded that the current situation of groundwater level is not a big challenge. Moreover, the future projected groundwater in the selected area is mapped and illustrated in Figure 10, to have a deep understanding regarding the distance of groundwater level to the surface.

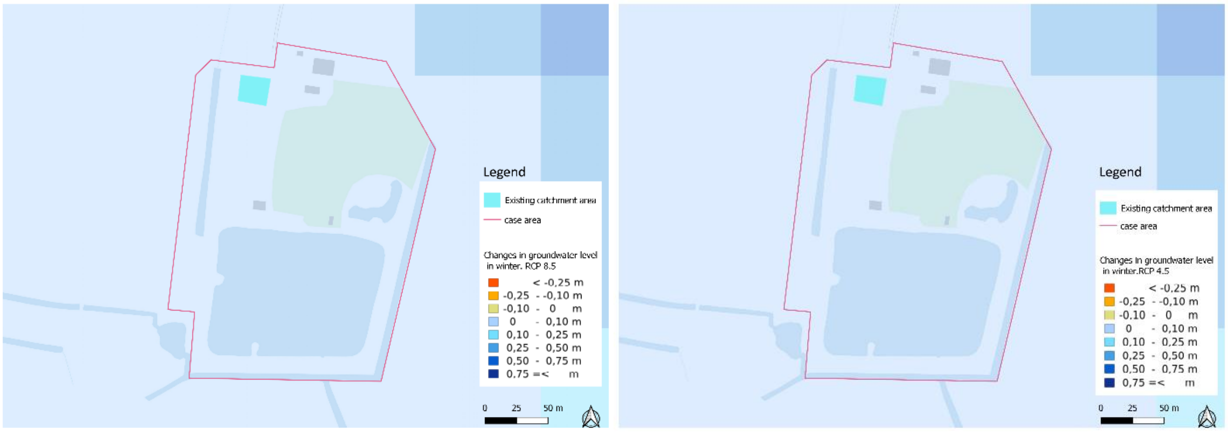

Figure 10. Changes in groundwater level in the period of 2041-2070. The top two figures represent summer under medium and high emission scenarios, and the bottom two figures represent winter. Source adapted from (HIP, 2023)

The future change of groundwater based on the figure above illustrates that the case area for both summer and winter under high and medium emission scenarios experiences the same change with approximately 0-0.10 m increase in groundwater level (HIP, 2023). Based on this assessment and legislation described in section 1.3.2 the the diluted wastewater poses minimal threat to the groundwater as groundwater is situated two meters below the surface. however, it highly depends on the soil type of the selected area which along with recreational space, lake, and concrete catchment area has been mapped and illustrated in Figure 11 and Figure 12.

Figure 11. Exposure mapping along with soil type in the case area. Soil data adapted from (HIP, 2023)

As can be seen in the figure above, the topsoil in this area is mostly humus, characterized by its high infiltration capacity and water absorbency (Jensen. Trine S & Hjotnæs Daniel, 2022). Additionally, as illustrated in the figure below, the soil type at the depth of 1 m is freshwater peat which lets the water flow quickly into streams and groundwater level (Labadz, J et al., 2010). Consequently, will cause the groundwater to be negatively affected by diluted wastewater.

Figure 12. The soil type of the selected area. Soil data adapted from (HIP, 2023)

Additionally, considering this location serves as a recreational space for citizens and a habitat for various species, the potential exposure to diluted wastewater poses concerns for both human and ecological health.

3.1.3 Vulnerability

Based on the vulnerability definition described in the analytical framework, in this section, the vulnerability of the case area will be assessed. An interview revealed that most sewage systems, including those in Nørre Nissum, are connected to the pump station located in Rønbjerghage, which purifies diluted wastewater from chemical pollution before discharge into the Limfjord (IN 1). However, during heavy precipitation, this pump station, which is working mechanically to purify the wastewater struggles to handle the increased water volume. Therefore, there is a necessity to push water back which comes to the Nørre Nissum pump station (IN 1). Moreover, some properties have incorrectly connected rainwater drainage systems to the communal sewage systems(Lemvig kommune, 2013). Additionally, the Godum and Febjerg pump stations are connected to the Nørre Nissum pump station via a sewage network dating back to between 1970 and 2016 (Klimatorium, 2020) which are dimensioned based on a 5-year event (Lemvig Kommune, 2023). Consequently, during heavy precipitation, the amount of water that flows into the Nørre Nissum pump station will be more than its capacity.

Another factor in increasing vulnerability is the soil type, which consists of humus and freshwater peat. As described in the previous section, the infiltration capacity of humus soil is high and freshwater peat spreads the water quickly. Additionally, as mentioned in the hazard assessment, the volume of collected rainwater near the pump station is significant. Therefore, the high infiltration capacity of soil will increase the water pressure on the sewage systems especially if they are aged and have some cracks on their body.

All these factors will cause the capacity of the Nørre Nissum pump station to be insufficient to handle diluted wastewater, which is a mixture of rainwater and wastewater and will overflow into nature potentially causing health and environmental problems. Therefore, the Nørre Nissum pump station due to its capacity is vulnerable to hazards. The capacity of the Nørre Nissum pump station is shown in Appendix F.

3.1.4 Future climate change and uncertainty

There are uncertainties regarding the future of CC and the groundwater level near the surface. More precipitation and high groundwater levels lead to increased water in the sewage systems and in the pump station. Moreover, there are a lot of uncertainties regarding urban development in Nørre Nissum. More houses, means more wastewater into the pump station, as a result, the pressure on the pump station will increase and experience a severe and higher volume of sewage overflows.

3.2 *Risk of the case area*

Based on the definition of risk, described in the analytical framework, risk will arise by the interaction of hazard with exposure and vulnerability of the affected system. Table 10 summarizes the hazard, exposure, and vulnerability and it shows how they are affected by hazard.

Table 10. Risk of the case area

Hazard	Exposure	Vulnerability
The case area will experience flooding for both current and future events	Groundwater will be exposed	The capacity of the pump station
There are 3 depressions that put pressure on the pump station	There is a recreational space for citizens and visitors	
The volume of water in the depressions is high	A natural lake which is a place for flora and fauna services as a vibrant ecosystem	

According to this analysis, it is evident that the Nørre Nissum pump station is at risk of sewage overflows. The case area during the current century and the future (mid-century) will experience significant water accumulation with volumes of more than 22 000m^3 and 28 000m^3. These volumes along with the soil type of the selected area will have significant pressure on the Nørre Nissum pump station, leading to potential overflows. Additionally, the case area is designated as a recreational space for citizens, green space, and a lake that serves as a vibrant ecosystem for flora and fauna species, pump station overflows will cause significant health and environmental issues. Furthermore, the soil of the case area is humus soil and is characterized by a high infiltration capacity, hence, increasing the risk of groundwater contamination in the event of pump station overflows. Figure 13 illustrates the risk of the selected area.

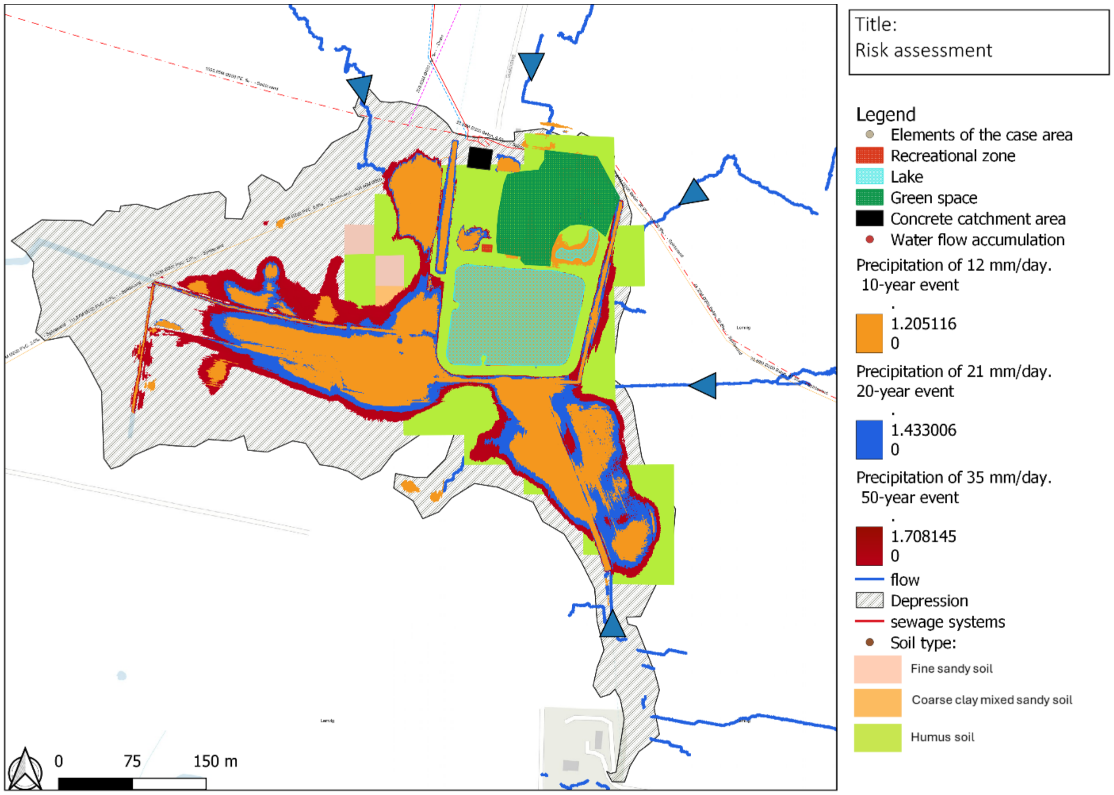

Figure 13. Mapping the risk of the selected area

3.3 *Initial Analysis According to multicriteria analysis for the implementation of suitable NBS*

In this section, the investigated measure will be evaluated and scored based on Table 7, described in the methodology. First, an introduction about the investigated measures will be described to have an overview of their function, and then in section 3.3.3, the measures based on the multicriteria analysis will be evaluated and scored.

3.3.2 Investigated measure

Constructed wetlands

Constructed wetlands (CW) are the most common and accepted NBS among other natural solutions for controlling and collecting wastewater and greywater in European countries (Oral et al., 2020). Such solutions due to the interaction of plants, substrates, soils, microbes, and water will remove multiple pollutions from wastewater and enhance water coolness (Rahman et al., 2020). CWs generally manifest in two forms distinguished by two types: free water surface constructed wetlands (FWSCW) and subsurface flow constructed wetlands. FWSCW are more similar to natural wetlands where wastewater or sewage water flows shallowly above the substrate through shallow vegetation zones. While subsurface flow structures, allow wastewater to flow horizontally or vertically below the soil surface through a porous medium stream route made of sand or gravel which is used as a growth medium and a place for rooted vegetation of the wetland (Kjærgaard, Ch, 2013). Moreover, subsurface CW can also be designed to have both horizontal and vertical flow over substrates which is called hybrid CW and is efficient in the recycling of wastewater and re-use it for irrigation (Rahman et al., 2020). However, due to the scope and the timing of the project, the hybrid CWs will not be investigated.

In the horizontal subsurface CW, the wastewater will flow in a horizontal path until the purification happens and exit from the opposite side of the wetland. In a vertical subsurface flow strategy, the wastewater flows on the bed surface, percolates, and drains downward vertically by gravity through the media in the batch mode (Justino et al., 2023). Figure 14 illustrates both FWSCW and subsurface constructed wetlands.

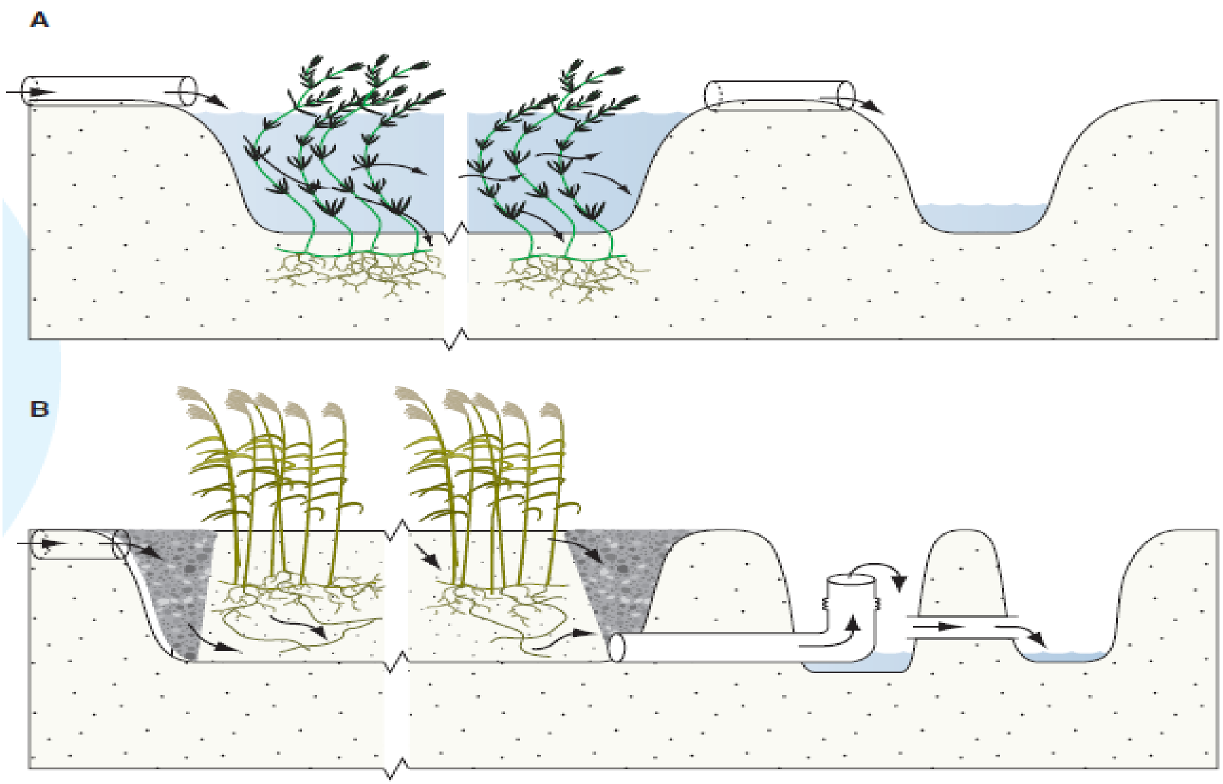

Figure 14. Illustration of two types of constructed wetlands. A: FWSCW. B: subsurface CW. Source adapted from (Kjærgaard, Ch, 2013)

Willow treatment plants

Willow treatment plants compared to CW are the most usable tool for collecting and treating wastewater in Denmark (Hans Brix & Carlos A Arias, 2011). According to (Istenič & Božič, 2021) willow treatment plants are systems with no discharge of wastewater into the environment and these systems will be established in locations where the infiltration of water is not possible due to high groundwater. These systems first time were developed in Scandinavian countries to produce woody biomass for energy production (Hans Brix & Carlos A Arias, 2011). The soil of willow treatment pants will absorb wastewater materials during winter which will be cleaned by the willows during the growing season. The dense branch roots of the willows convert and evaporate the absorbed water. When the willows are harvested and the wood pulp is removed, the nutrients will also be extracted. (Istenič & Božič, 2021). Figure 15 illustrates the willow treatment plant.

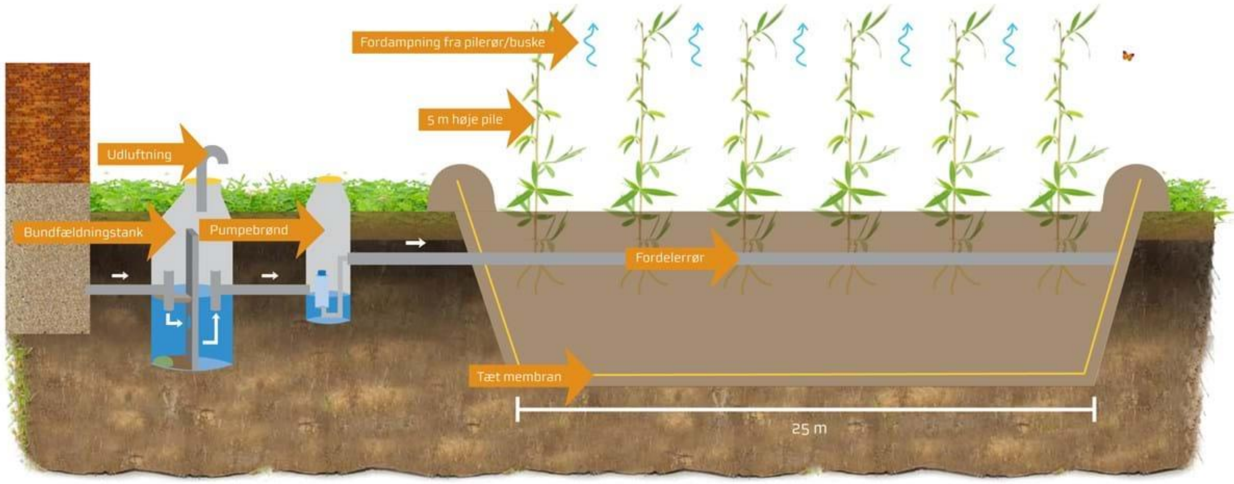

Figure 15. Illustration of the willow treatment plant. Figure adapted from (Holbæk kommune, 2023)

3.3.3 Evaluating the investigated measures based on multicriteria analysis

In this sub-section, the investigated measures will be evaluated and scored.

Co-benefits

In this sub-section, the co-benefits including environmental co-benefits, purification co-benefits, and cost co-benefits of selected measures will be evaluated and scored based on Table 7. It should be noted that, first an overall description of CWs and their environmental and purification rate will be described in Table 11 to understand whether they are used for wastewater purification or not. Then, two kinds of constructed wetlands including subsurface constructed wetlands and FWSCW will be evaluated. Finally, the willow treatment plants will be evaluated and scored.

Constructed wetlands (CW):

Table 11. Co-benefits of constructed wetlands

Co-benefits	Description	Source
Environmental co-benefits	The positive effect of implementing CWs is that they will help to reduce sewage overflows during heavy precipitation by collecting wastewater and greywater	(Oral et al., 2020)
	The green part of CW will provide ecosystem services by reducing GHG emissions and urban heat islands.	(Oral et al., 2020)
	CW by employing vegetation will increase biodiversity.	(Masi et al., 2018)
Purification rate	CW due to employing local vegetation, substrates, and soil will remove multiple pollutants from the wastewater.	(Rahman et al., 2020)
	CW will purify TTS up to 88 %, BOD up to 92 %, COD up to 83%.	(Oral et al., 2020)
	CW can purify total phosphorous between 46-90 % and nitrogen between 16-84 %.	(Kjærgaard, Ch, 2013)
Cost co-benefits	CW requires low cost for establishment and low requirement for maintenance.	(S.E. Jørgensen et al., 2004)

	The total cost of constructed wetlands is approximately between 200.000 – 650.000 DKK/ ha.	(Kjærgaard, Ch, 2013)

Based on the table above it can be concluded that the CWs are sustainable measurements for collecting diluted wastewater. Therefore, the following tables, Table 12 and Table 13 will evaluate two different CWs including subsurface CW and FWSCW based on their environmental, and purification co-benefits and they will be scored based on scoring from Table 7. It should be noted that since the area is a recreational space for citizens and the selected measure will be established near the recreational zone, therefore increasing mosquitos has been considered to be a negative aspect. Therefore, low capacity to increase mosquitos will be scored as 3 and high capacity will be scored as 1.

Subsurface CW:

Table 12. Potential co-benefits of sub-surface constructed wetlands

Co-benefits	Description	Score	Source
Environmental co-benefits	Has a medium capacity to reduce GHG emissions	2	(Oral et al., 2020)
	Has a medium capacity to increase biodiversity	2	
	Has a low capacity to increase mosquitos	3	(Cross et al., 2021)
Purification rate	Sub-surface CW is suitable for cold regions and the purification rate of nitrogen, Phosphorus, BOD, and COD is high.	3	(Kjærgaard, Ch, 2013; Liang et al., 2020)

	Purification of total nitrogen is approximately 40 % mg/l		(Kjærgaard, Ch, 2013; Thisted kommune, 2022)
	The purification rate of total phosphorus is 70% mg/ l		
	Purification of COD and BOD is 45% mg/ l and 30 % mg/l		

FWSCW:

Table 13. Potential co-benefits of free water surface constructed wetlands

Co-benefits	Description	Score	Source
Environmental co-benefits	Has a high capacity to increase mosquitos	1	(Cross et al., 2021; World Bank, 2021)
	Has a high capacity to increase biodiversity	3	
	Has a medium capacity for reducing GHG emissions	2	
Purification rate	FWSCWs are susceptible to cold regions, and this will negatively impact the purification rate of nitrogen.	1	(Kjærgaard, Ch, 2013; Liang et al., 2020)
	The purification rate of phosphorus is low		

	The purification rate of total nitrogen is approximately 0.02-11.8 $mg/m^2/h$ (low)		
	The purification rate of total phosphorus is approximately 46 % mg/l		

Willow treatment plants

Another investigated measure which is shown in Table 14 is willow treatment plants which are the most conventional tools for collecting diluted wastewater in Denmark (Hans Brix & Carlos A Arias, 2011). The scoring of criteria is based on Table 7, described in Section 2.5.2.

Table 14. The potential co-benefits of willow treatment plants

Co-benefits	Description	Score	Source
Environmental co-benefits	Has a low capacity for increasing mosquitos	3	(Istenič & Božič, 2021)
	Willow treatment plants have a high capacity to reduce CO2 emissions.	3	(Istenič & Božič, 2021)
	Has a medium capacity to increase biodiversity.	2	(Hans Brix & Carlos A Arias, 2011; Istenič & Božič, 2021)

Purification rate	Willow treatment plants due to two different processes including evaporation and transpiration through soil and plants have a high capacity for purification.	3	(Hans Brix & Carlos A Arias, 2011)
	This system can purify diluted wastewater from BOD up to 67-74 % mg/l, total nitrogen up to 52-75 % mg/l, total phosphorus up to 90-98% mg/l, and COD approximately 92-100 % mg/l.		(Cross et al., 2021; Miljøstyrelsen, 2003)
	Willow treatment plants have a high capacity to adapt to nutrients and salinity		(Isteničč & Božič, 2021)

Cost co-benefit

To analyze the cost co-benefits of each measure, initially, an assessment of the implementation and maintenance costs of each measure will be conducted. Secondly, the cost-benefit including biomass production, and reuse of water for irrigation of different measurements will be evaluated and scored, since these two elements will provide the municipality with additional benefits. Finally, based on these two-step assessments the cost-benefit of each measurement will be evaluated through summing the scores.

Implementation and maintenance cost

The implementation and maintenance cost of each measure is described in Table 15. Since there is uncertainty regarding the accuracy of the implementation and maintenance costs of the selected measurements, the implementation and maintenance costs are shown by plus (+). More stars indicate that the solution is expensive. The source and the costs of the selected measurements are available in Appendix H.

Table 15. The implementation and maintenance cost of each investigated measure

Measures	**Implementation cost DKK/ m3**	**Maintenance cost DKK/ m3/ year**	**Source**
Subsurface CW	++++	++++	(Cross et al., 2021; Slagelse kommune, 2017)
FWSCW	++	++	(Slagelse kommune, 2017)
Willow treatment plants	+++	+	(Slagelse kommune, 2017)

Cost co-benefit

As illustrated in Table 15, the implementation and maintenance costs of each measurement are estimated. Table 16 describes the cost co-benefit of each measure. Based on the scoring range in Table 7 measurements associated with high costs are scored 1 and measures with low costs are scored 3. As subsurface-constructed wetland is costly, therefore, it will be assigned a score of one, and FWSCW which entails a moderate cost will be scored as 2. Finally, for the willow treatment plants, the implementation cost is higher than FWSCW, but the maintenance is lower, therefore, this solution will also be scored as 2. As mentioned before, biomass production and water reuse have been considered as one of the elements of cost co-benefits due to substantial advantages for municipality utilization.

Table 16. Cost co-benefits of investigated measurements

NBS type	Description	Score	Source
Subsurface CW	Implementation and maintenance costs compared to other measurements are expensive	1	(Slagelse kommune, 2017)
	Have a high capacity to purify wastewater and reuse it for irrigation.	3	(Cross et al., 2021)
	Have a medium capacity in using vegetation as biomass	2	
FWSCW	Implementation and maintenance costs are less than subsurface CW	2	(Slagelse kommune, 2017)
	Have a high capacity in biomass production	3	(Slagelse kommune, 2017)
	High capacity in water reuse	3	
Willow treatment plants	Implementation and maintenance costs are less than Subsurface CW	2	(Slagelse kommune, 2017)
	High capacity in biomass production due to willows	3	(Cross et al., 2021)

	Since this measurement is with zero discharge, therefore, it doesn't have any capacity for water reuse	1	(Cross et al., 2021)

Summarizing environmental, purification, and cost co-benefits

For evaluating and finalizing the co-benefits of the mentioned measures Table 17, illustrates the sum of the co-benefits of each measurement.

Table 17. Total potential co-benefits of investigated measures

NBS measures	co-benefits	Total co-benefits
Sub-surface CW	Environmental co-benefits	7
	Purification rate	3
	Cost co-benefits	6
Total score		16
FWSCW	Environmental co-benefits	6
	Purification rate	1
	Cost co-benefit	8
Total score		15
Willow treatment plants	Environmental co-benefits	8
	Purification rate	3

	Cost co-benefit	6
Total score		17

Robustness

Based on the robustness definition described in the analytical framework the investigated measures should have the capacity to be effective in the long-term. In this thesis, since the capacity of investigated measures should accommodate the diluted wastewater in order to reduce or mitigate sewage overflows, their robustness is assumed to be high. However, additional elements, including their ability in flood mitigation from the precipitation have been added to this process to strengthen the validity of the result. The result is shown in Table 18.

Table 18. The robustness of investigated measures

NBS type	Description	Score	Source
Subsurface CW	has a high capacity for controlling sewage overflows	3	
	Has a low capacity in flood mitigation.	1	(Cross et al., 2021)
Total		4	
FWSCW	Has a high capacity for controlling sewage overflows	3	
	Has a medium capacity for flood mitigation	2	(Cross et al., 2021)
Total		5	
	Has a high capacity for controlling sewage overflows	3	

Willow treatment plants	Has a medium capacity for Flood mitigation	2	(Cross et al., 2021)
		5	

Flexibility

According to the flexibility definition described in the analytical framework, a flexible solution should be a transformative adaptation that deals with future uncertainty. Therefore, due to the timing of the project, the flexibility of the identified measurements based on their ability to combine with other investigated measures in this thesis will be assessed. The result is illustrated in Table 19. However, the definition of retrofitted will not be assessed and evaluated in this thesis as the literature regarding this data has not been found. Based on the scoring range in Table 7, the solution that has low flexibility will be scored as 1, the medium will be scored as 2, and the measurement that has high flexibility will be scored as 3.

Table 19. Flexibility of investigated measurements

NBS type	**Flexibility description**	**Score**	**Source**
Subsurface CW	It can be combined with FWSCW and willow treatment plants.	3	(Cross et al., 2021)
FWSCW	It can be combined with subsurface-constructed wetlands and willow treatment plants	3	(Cross et al., 2021; Davis & USA, 2015)
Willow treatment plants	It can be combined with FWSCW and subsurface-constructed wetlands (established in the outflow of CWs)	3	(Cross et al., 2021)

No regret/ successful solution

In this thesis, the no regret or successful measurement will be evaluated based on two criteria, flexibility and robustness. According to the no-regret definition in the analytical framework, the CC has many uncertainties, and if the solution considers these uncertainties can be successful. Based on this, if the investigated solutions have high flexibility and robustness to deal with future uncertainties, can be characterized as successful solutions. Then high successful measure will be assigned a score of 3, if it has a medium capacity to be a success will be scored as 2, and if its success is low then will be scored as 1. The assessment of this criterion is shown in Table 20.

Table 20. Assessment of successful measures

NBS type	Scoring
Subsurface CW	2
FWSCW	3
Willow treatment plants	3

The total score of the robustness of subsurface CW is 4 and its flexibility is 3. However, the sum of flexibility and robustness is slightly less than the two other measurements, therefore it will be assigned a score of 2.

Possible impact on other risks

This section will evaluate the potential adverse effects of the investigated measures on other risks. It is crucial to clarify that the positive impacts of the mentioned measurements are evaluated in the environmental co-benefits. This section will focus on the negative impacts that may arise by implementing the selected solutions. It should be noted that the possible impact on other risks will be evaluated based on the discharge opportunity of investigated measures into the environment and their capacity to purify diluted wastewater. Based on this, subsurface CW due to its high capacity to reduce chemicals does not have any/ minimal impact on the groundwater.

On the other hand, the FWSCWs due to their low capacity to purify diluted wastewater may have a possible impact on the groundwater. Finally, Willow treatment plants due to their zero discharge characteristic, do not have any/ minimal impacts on other risks. The results are shown in Table 21, Table 22, and Table 23.

Table 21. Possible impacts of subsurface CW on other risks

Issue type	Description	Possible impacts on other risks	Source
Groundwater	In the subsurface CW, wastewater flows horizontally or vertically below the soil surface through a porous medium stream route made of sand or gravel which is used as a growth medium and a place for rooted vegetation of the wetland. This kind of CW, due to the interaction between roots and biofilms will treat the wastewater from households, and industries and then release it into the environment.	X	(Kjærgaard, Ch, 2013)
Environment		X	

X: the measurement does not have any potential impacts on other risks

Table 22. Possible impacts of FWSCW on other risks

Issue type	Description	Possible impacts on other risks	Source
Groundwater	FWSCWs are considered as the secondary treatment plant due to the low rate of purification rate. Wastewater or sewage water flows shallowly above the substrate through shallow vegetation zones and after the treatment is completed will be discharged into the environment.	~	(Kjærgaard, Ch, 2013; Rahman et al., 2020)
Environment		~	

~: Measurement may have possible impacts on other risks

Table 23. Possible impacts of willow treatment plants on other risks

Issue type	Description	Possible impacts on other risks	Source
Groundwater	Willow treatment plants are systems with no discharge of wastewater into the environment and potentially will be established in locations	X	(Istenič & Božič, 2021; Slagelse kommune, 2017)
Environment		X	

	where the infiltration of water is not possible due to groundwater.		

Summary of potential impacts of different measurements on other risks

Table 24 has summarized and scored the potential impact of investigated measures on other risks. The solutions that have no impact on other risks will be scored as 3 and solutions that have a medium capacity to affect other risks will be scored as 2.

Table 24. Summary of potential impacts of investigated measurements on other risks

NBS type	Score
Subsurface CW	3
FWSCW	2
Willow treatment plants	3

3.4 *Primary analysis*

In the previous section, the evaluation of different measures has been done. Table 25, illustrates this evaluation or assessment of each investigated measure's performance against these criteria.

Table 25. Scoring assessment of suitable measure

Criteria	Subsurface CW	FWSCW	Willow treatment plants
Environmental co-benefits	7	6	8
Purification co-benefits	3	1	3
Cost co-benefits	6	8	6
Flexibility	3	3	3
Robustness	4	5	5
No regret solution/ highly successful solution	2	3	3
Possible impacts on other risks	3	2	3
Total score	28	28	31

As mentioned in the assessing suitable measure in section 2.5.2, the criteria of purification co-benefits and cost co-benefits are assigned 22%, and the possible impacts on other risk criterion is assigned 16%, and each of the remained criteria are assigned 10%. Therefore, the scores from the table above are weighted and the results are shown in Table 26.

Table 26. Weighting assessment of suitable measure

Criteria	Weight	Subsurface CW	FWSCW	Willow treatment plants
Environmental co-benefits	10 %	0.7	0.6	0.8
Purification co-benefits	22 %	0.66	0.22	0.66
Cost co-benefits	22 %	1.32	1.76	1.32
Flexibility	10 %	0.3	0.3	0.3
Robustness	10 %	0.4	0.5	0.5
No regret solution/ highly successful solution	10 %	0.2	0.3	0.3
Possible impacts on other risks	16 %	0.48	0.32	0.48
Total weight	100 %	4.06	4.15	4.36

According to the scoring and weighting analysis of the selected measures, it can be concluded that the willow treatment plants compared to two other measurements is the more conventional solution.

3.5 *Results*

The selected measure based on weighting that has been done in the previous section is willow treatment plants. For a comprehensive solution that can manage diluted wastewater on a daily basis, it is important to address the wastewater discharge effectively. In Appendix B, the daily discharge rate of wastewater from two pump stations, Gudum and Febjerg are shown. This thesis proposes a two-fold approach to address the issues, delineated into short-term and long-term strategies.

One of the primary reasons behind this division is that CC has many uncertainties regarding precipitation which is one of the main factors in wastewater management. It should be taken into account that the capacity of the implemented system may not be enough to handle a large amount of diluted wastewater in the future. On the other hand, if the willow treatment plant is implemented on a large scale certain risks may arise including the system being underutilized during drier periods. Based on the no-regret solution definition described in the analytical framework, a solution can be characterized as a no-regret solution if the selected NBS has benefits even in the absence of CC (Baills et al., 2020). Therefore, it should be considered that a large capacity of the facility to control and reduce sewage overflows may have some drawbacks during rain-free periods potentially remaining underutilized.

Another reason for dividing the solution in the short and long term is the productivity of willow treatment plants. The productivity of willow treatment plants in capturing and purifying diluted wastewater is high in the first two or three years of growth due to the most vigorous root development (Istenič & Božič, 2021; Miljøstyrelsen, 2003). Once the willows are cut down the time for their development and growth may decrease the nitrogen removal (Hans Brix & Carlos A Arias, 2011). Therefore, it is crucial to extend the system to have a better result in the future.

3.5.1 Short-term solutions

According to (Hans Brix & Carlos A Arias, 2011; Istenič & Božič, 2021; Miljøministeriet, 2003) the standard installation of the willow treatment plants always has a width of 8 m and a depth of 1.5 m. The length of the willow treatment plant depends on the discharge rate of wastewater to the system (Miljøministeriet, 2003). As mentioned before, there are two pump stations including Gulum and Febjerg which are connected to the Nørre Nissum pump station. Therefore, the inflow rate of wastewater is the sum of the total discharge from the Gudum pump station and Febjerg pump station which are shown in Appendix B, and divided the obtained number by the number of days which is 31 days.

$$\frac{27255\ m3 + 9592.5\ m3}{31} = 1188.6\ m3/day$$

Furthermore, based on the interview with person number 3, it is concluded that several buildings in Nørre Nissum are connected to the Nørre Nissum pump station via gravitational sewage systems, a total of approximately 160 properties. It is assumed that the properties are flat houses. It should be noted that since the buildings were counted by the author, there may be some uncertainty. It is essential to consider those houses in the dimensioning process of the willow treatment plant. Based on this, it is recommended to consider the volume of 2 m^3 for 1-5 individuals (Lemvig kommune, 2022). Hence the final discharge rate of wastewater to the Nørre Nissum pump station will be:

$$1188.6\ m3/day + 320\ m3/day = 1508.6\ m3/\ day$$

However, there is a concrete basin that has a volume of 635. 07 m^3 (SCALGO LIVE, 2023)(shown in Appendix C), hence, the discharge rate of wastewater to the willow treatment plan will be:

$$1\ 508.6\ m3/day - 635.07\ m3/day = 873.53\ m3/day$$

According to (DANVA, 2007)the average annual evapotranspiration rate in the western part of Denmark is approximately 570 mm/year which will be 1.6 mm/day, and in the willow treatment plants, this rate is 2.5 times greater (Miljøministeriet, 2003). Evapotranspiration encompasses two simultaneous processes, evaporation and transpiration, and "*there is no easy way to distinguish between these two processes"* (Hans Brix & Carlos A Arias, 2011). The reason for the high evapotranspiration rate in the willow treatment plants is that the water from the topsoil of this system when the vegetation/ plants are small will be evaporated and once the plants mature and fully cover the soil, transpiration becomes the focal process (Hans Brix & Carlos A Arias, 2011)

According to (Miljøministeriet, 2003), the maximum evapotranspiration rate in willow treatment plants is 1 470 mm/year, the minimum is 1 343 mm/year and the middle is 1 399 mm/year. Converting them to the daily evapotranspiration will be 4.08 mm/day, 3.73 mm/day, and 3.88 mm/day (0.00408 m/ year, 0.00373 m/ year, 0.00388 m/ year). The middle evapotranspiration rate will be considered for the dimensioning of willow treatment plants which covers both summer and winter evapotranspiration (Miljøministeriet, 2003).

According to (Miljøministeriet, 2003) for calculating the dimension of willow treatment plants in an area it is important to consider low and high precipitation since in summer there is lower precipitation than in winter. Moreover, based on (Miljøministeriet, 2003) recommendation, it is recommended to incorporate the 30-year event precipitation for dimensioning willow treatment plants. However, since this event is not encompassed in klimaatlas (climate atlas), the alternative event which is close to a 30-year event will be considered in this calculation. Therefore, the 10^{th} percentile and 90^{th} percentile for the current 20-year event which has a 5% chance probability of happening each year will be considered and is illustrated in Table 27.

Table 27. The 20-year event precipitation under scenario RCP 4.5.

20-year event for the period of 2011-2040		
Reference (1981-2010)	**10^{th} percentile**	**90^{th} percentile**
67.04 mm/ day	56.20 mm/ day	84.28 mm/day

Source adapted from (KAMP, 2023)

Based on formula number 1, described in section 2.5.2, the calculation will proceed. Willow treatment plants are considered as no discharge of water into the environment, therefore, the Q_o will be 0. Furthermore, "*the chosen solution should not have any seepage into the ground*" (IN2). Hence the infiltration rate will be 0.

As mentioned before the lowest precipitation and highest precipitation will be calculated individually.

10th percentile: $0 = 873.53\ m3 + Ai(0.0562\ m - 0.00388\ m - 0)$

$$Ai = \frac{873.53\ m3}{0.05232\ m}$$

$$Ai = 16\ 695.9\ m2$$

90th percentile: $0 = 873.53\ m3 + Ai(0.08428\ m - 0.00388\ m - 0)$

$$Ai = \frac{873.53\ m3}{0.08428\ m}$$

$$Ai = 10\ 364.61\ m2$$

According to (Miljøministeriet, 2003), it is recommended to calculate the difference between the highest and lowest dimensions to calculate the required retention capacity. Therefore, the obtained area for the 10th percentile will be subtracted from the obtained area for the 90th percentile. The dimension of the required willow treatment plant for the period of 2011-2040 will be 6 331.2 m^2.

As mentioned before, there are some standards regarding the width and depth of the willow treatment plants. The width is 8 m the depth is 1.5 meters and according to the calculation, the area is 6 331.2 m^2. Therefore, The volume of the willow treatment plant will be:

$$6\ 331.2\ m2 \times 1.5\ m = 9\ 496.8\ m3/\ day$$

Lemvig municipality has a desire to accommodate 9 000 m^3 of wastewater per day in the selected measure (IN 3). According to this accurate dimension that has been done in this section, it can be concluded that the obtained volume, 9 496.8 m^3 is correct.

3.5.2 Long-term solution

There are a lot of uncertainties regarding the development of sewage systems and their dimension in the future and the discharge rate of wastewater in the Nørre Nissum pump station.

If the dimension of sewage systems increases in the future, they may be big enough to accommodate the future precipitation and prevent sewage overflows. Otherwise, the next step in sequence with the previous action should be implemented.

An increase in precipitation will lead to a higher volume of wastewater discharging into the selected measure. Therefore, the obtained measure described in section 3.5.1 will not be sufficient in the future. According to (DMI, 2024b), the precipitation pattern in 2024 compared to 2023 has increased, as illustrated in Appendix D. This trend suggests a likelihood of heightened precipitation in the future of Lemvig municipality. Consequently, there is a high demand for the implementation or extension of willow treatment plants to accommodate future hazards.

Since the 20-year event precipitation has been considered for the dimension of the willow treatment plant in the previous section, the same event with the scenario RCP 8.5 for the period of 2041-2070 will be considered for the long-term solution. Table 28, illustrates the 10th and 90th percentile for 20-year event precipitation for the period of 2041-2070.

Table 28. 10th and 90th percentile of 20- year event under scenario RCP 8.5

Events	**Reference (1981-2010)**	**10th percentile**	**90th percentile**
20-year event	67.04 mm/day	59.48 mm/day	89.91 mm/day

Source adapted from (KAMP, 2023)

The calculated dimension in the previous section can accommodate the 10th percentile of the 20-year event. However, the 90th percentile is approximately 7% more than the capacity of the dimensioned solution. the 90th percentile of the 20-year event for the period of 2041-2070 requires 1 866 m^3 more than the dimensioned capacity described in the previous section. Since willow treatment plants have a high capacity for scaling up or combining with other solutions, another Willow treatment plant with this capacity needs to be implemented in sequence with previous action to prevent sewage overflows in the future. The calculation of the required capacity for the 20-year event is shown in Appendix E.

3.5.3 Criteria for Designing Willow Treatment Plants

Since the chosen solution for the short and long term is willow treatment plants, it is important to describe the designing criteria of the willow systems and some suggestions for the vegetation.

According to (Hans Brix & Carlos A Arias, 2011) willow treatment plants need to be implemented with 45-degree slopes on the side, and a 0.3 m earth embankment around the entire facility to prevent the penetration of surface water into the facility as well as insurance for the facility itself to prevent overflows during heavy precipitation as illustrated in Figure 16 (Miljøministeriet, 2003). Moreover, a sedimentation tank needs to be implemented to pre-treated wastewater before discharging into the willow treatment plant (Hans Brix & Carlos A Arias, 2011).

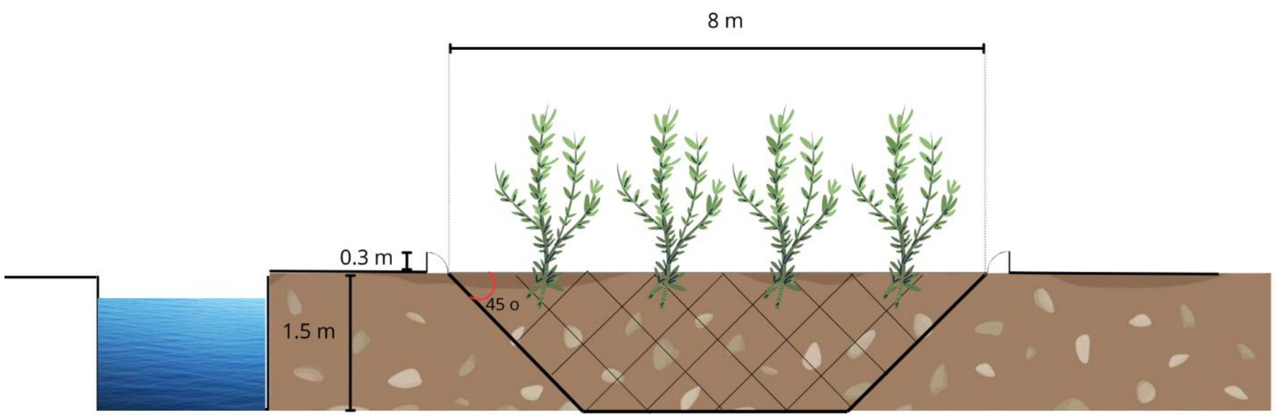

Figure 16. Illustration of willow treatment systems with standard dimensions(Miljøministeriet, 2003)

As mentioned before the soil type in the selected area is mostly freshwater peat and humus and the infiltration capacity is high. Therefore, the entire bottom of the system should be sealed with an impermeable material such as a tight membrane to prevent infiltration. According to the (Miljøministeriet, 2003) recommendation, an impermeable material with a minimum 50 mm thick layer needs to be implemented at the bottom of the system.

To ensure a high evapotranspiration rate in the willow system they should be planted with fast-growing woody species. There are two focal evapotranspiration processes in willow systems including the 'Clothesline effect', and 'Oasis effect' (Cross et al., 2021; Miljøministeriet, 2003).

For the clothesline effect, willows need to be planted from a single row of trees surrounded by short vegetation. This action will cause the trees to sense the heat from the air and radiant energy which will increase evaporation, and wind which will transport water vapor away from the soil and plant, as a result, increase the evapotranspiration (Hans Brix & Carlos A Arias, 2011) as shown in Figure 17.

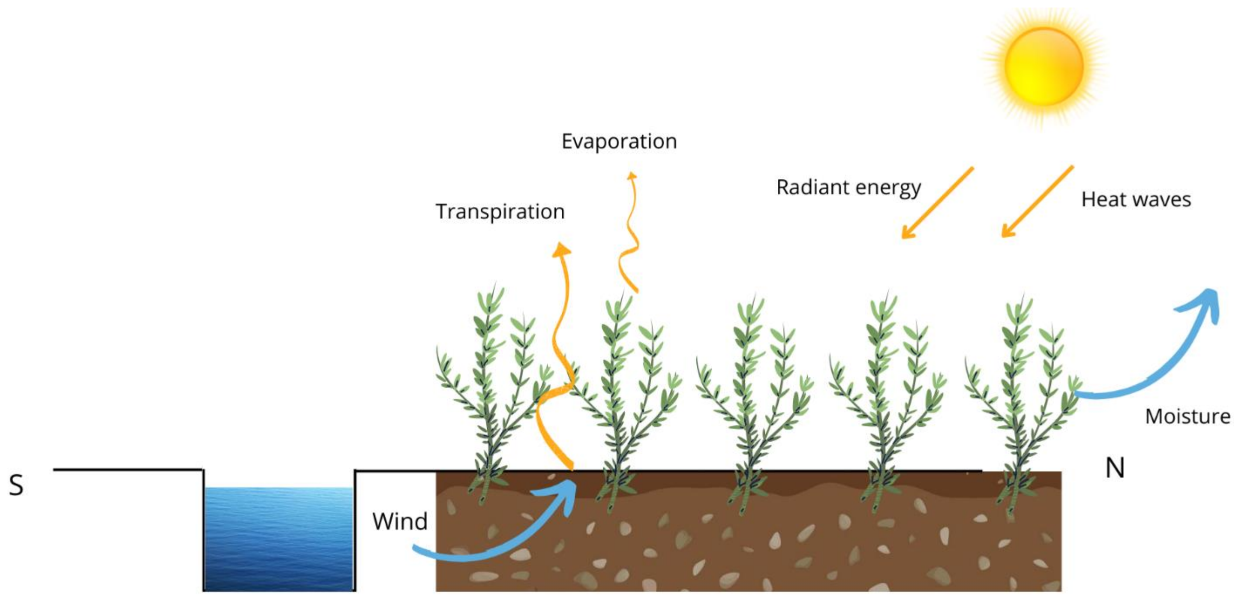

Figure 17. Illustration of the effect of wind, radiant energy, and heat waves on willow treatment plants. Source adapted from (Cross et al., 2021)

The oasis effect occurs when winds flow from a smooth surface to a rough surface, which enhances the evaporation rate. In the Danish condition, the willow plants must be planted in a north-south direction to maximize wind energy supply (Miljøministeriet, 2003). Moreover, to keep the evaporation high, it is crucial to have 5 m space between each willow system (Cross et al., 2021).

The plants selected for willow treatment systems should exhibit robust adaptability to high nutrient and salinity levels (Istenič & Božič, 2021). Willows and poplars demonstrate exceptional resilience to these conditions and have a high transpiration rate. They will grow fast and will provide biomass production. However, there are some notable differences, including willows exhibiting superior tolerance to permanent flooding and anaerobic conditions compared to poplars. Moreover, willows require more water than other crops, hence the reduction of water in willows is greater. Due to these factors, willow has been chosen as the best plant (Istenič & Božič, 2021). In Denmark, the most common crop or plant used for willow treatment systems is *Salix viminalis* (Istenič & Božič, 2021).

3.5.4 Designing of willow treatment plants based on the obtained area

In this subsection first, the goal and objective of Lemvig Municipality for the implementation of NBS to capture diluted wastewater will be described and then, the selected measure will be mapped on the site with the obtained dimension.

According to the Lemvig Municipality plan the goal is to limit the discharges of diluted wastewater into the environment to ensure they do not hinder the achievement of the ecological status of the receiving waters (Lemvig kommune, 2022). To achieve this objective, there are some stages that need to be taken into account:

- Wastewater should be purified before discharging it into the environment (Miljøministeriet, 2004). Therefore, NBSs need to be implemented before draining into a receiving water body (Lemvig kommune, 2013, 2022).
- In regions designated as areas of high groundwater, the sitting of NBS for wastewater collection should be at least 1.5-2 meters above the highest groundwater level.

(Lemvig kommune, 2013, 2022)

Therefore, based on the above argument, and calculating the required area for the establishment of willow treatment plants in section 3.5.1, it is time to design them on the selected site. As illustrated in section 3.1.2 the groundwater level in most parts of the selected area is 3 m below the surface and some parts experience 2 m groundwater near the surface. Therefore, the establishment of willow treatment plants with tight membranes at the bottom of them does not negatively affect the groundwater. Moreover, as illustrated in Figure 18, the willow systems will be established before the lake, and as mentioned they are characterized by their zero discharge. Therefore, there is no threat to the lake.

As illustrated in the figure below, the selected area can accommodate six willow treatment plants. The distance between each willow system as mentioned before is 5 m and the width of them is 8 m. The length of the willow systems is varied between 130.56 m, 88.63 m, and 68.5 m.

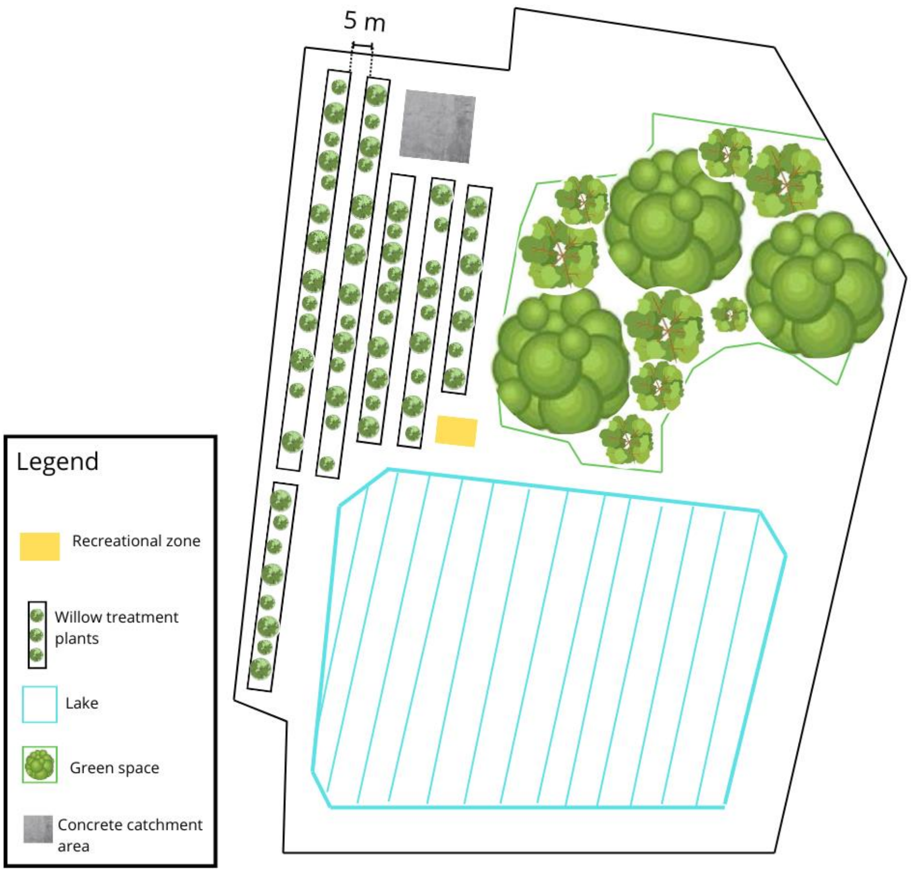

Figure 18. Mapping of willow treatment plants in the selected area

According to the figure above, the willow systems which are dimensioned based on the 20-year event for the period of 2011-2040 can be implemented without adversely affecting the green space and recreational zone. However, there is not enough space in the surrounding area for the implementation/ extension of willow systems to accommodate future hazards. Therefore, the selected area can accommodate the current hazard.

Chapter 4:

Discussion &

Conclusion

4 Discussion

This chapter discusses the findings and results of the thesis. First, discuss the findings and results and evaluate the selected solution based on five questions proposed by IUCN. Second, discuss the barriers of the willow treatment plants and the limitations of the project. Finally, propose some future research ideas.

4.1 *Discuss findings and result*

This thesis's framework is centered around using NBS as a sustainable and cost-effective tool to accommodate current hazards to prevent sewage overflows and be sufficiently robust to deal with future hazards. Therefore, for the first step, the concept of NBS has been employed in this research. For the next step, an analytical framework based on standards from the IUCN was developed to choose the best NBS that addresses social challenges namely climate risks, human health, and the risk of water security. Moreover, helps in the effective implementation of NBS by considering the soil type and the level of groundwater in the area. Considering the mentioned criteria was crucial since the NBS should capture diluted wastewater.

Additionally, the aim of the project was to develop a solution that can purify diluted wastewater and accommodate current hazards and future hazards while being cost-effective. Therefore, criteria including 'biodiversity net gain' for purification and environmental benefit, 'economic feasibility' for implementation, and maintenance cost from the IUCN along with economic benefits that the measurement provides for the municipality were selected. Moreover, considering the fact that CC has many uncertainties in the future, additional criteria besides previous criteria for choosing the best NBS based on the adaptation pathway were developed to evaluate measurements based on their flexibility, robustness, successfulness, and possible impacts on other risks namely groundwater level through the multi-criteria analysis tool. Multi-criteria assessment usually presupposes a wide range of stakeholders to rank the measurements. In this project, the stakeholder engagement was through considering their idea regarding which identified criteria are most important for them which helped in the weighting of the utilized criteria. Multi-criteria analysis tool was used to ensure if one solution failed in the assessment process there were other alternative solutions to be implemented.

On this basis, it can be concluded that the development of the multi-criteria assessment to rank and weight investigated solutions is a focal key to building a sequence of actions to cover the initial plan and long-term objectives. By utilizing ranking and weighting, an overview in regard to which solution should be implemented to manage diluted wastewater was developed.

For assessing the immediate benefit of the selected measure to accommodate the current hazard, it was crucial to calculate the dimension of the selected measure based on daily precipitation, daily discharge of wastewater, and daily evapotranspiration. In this regard, the data regarding the inflow rate of wastewater through two pump stations into the Nørre Nissum pump station plus the inflow rate of wastewater through properties that are connected to this pump station via gravity were important to be considered. The 10^{th} and 90^{th} percentile of daily precipitation were considered to propose a solution that can be sufficient in both rainy and dry weather. For assessing the evapotranspiration rate of the selected measurement the literature review was used due to the timing of the project. Therefore, the proposed dimension will accommodate the current hazard and prevent sewage overflows.

To evaluate the balance benefit for both nature and society which is part of the concept of NBS described in the theoretical framework the (IUCN, 2020) has provided five questions. These questions are used to reflect on the benefits of the willow treatment plants.

- Does the NBS use natural processes?

  Yes, it does. The soil of the willow treatment plants will absorb the waste materials in the diluted wastewater during winter, and the diluted wastewater will be cleaned by willows during the growing season. The dense branch roots of the willows convert and evaporate the absorbed water. When the willows are harvested and the wood pulp is removed, the nutrients will also be extracted.

- Does the NBS provide or improve social benefits?

No, it does not. Since the willow systems are used for purifying diluted wastewater, they should not be accessible to citizens since the soil absorbs the wastewater materials. However, they will improve aesthetic value since willow systems have green elements.

- Does it provide or improve economic benefits?

Yes, it does. Willow treatment plants due to their high capacity in producing biomass production which is an alternative energy to fossil fuels will provide economic benefits for the municipality. However, it is crucial to acknowledge that their productivity hinges on large-scale implementation; otherwise, biomass production may not reach its full potential.

- Does it provide or improve environmental and human benefits?

Yes, it does. Willow treatment plants due to purifying diluted wastewater and their characteristic of zero discharge to the environment, will secure the water bodies of being negatively affected by diluted wastewater, and secure the groundwater level by utilizing a tight membrane at the bottom of the system to prevent the penetration of wastewater into the groundwater, consequently secure human health.

- Does it have a net benefit for biodiversity?

Yes, it does. This question has been answered in the evaluation process of the measurements by evaluating environmental co-benefits and purification rates. Willow treatment plants due to utilizing vegetation and green elements will have positive impacts on fungal diversity. However, some scientists believe that since they are planted and are not permanent like forests, and will be cut down, their capacity to increase biodiversity is low (IN 4). Besides this fact, the argumentation for this question can be willow treatment plants due to their green elements will increase biodiversity compared to gray solutions.

Besides the fact that willow treatment plants will not provide social benefits, however, they have other valuable benefits that were not considered in the IUCN questions including willow systems have a high capacity to reduce CO_2 emissions which is one of the main goals of most of the municipalities including Lemvig municipality (Lemvig Kommune, 2023). By answering these questions it can be concluded that Willow systems will provide balance between nature and society by utilizing green elements to purify diluted wastewater.

4.2 *Limitations of the project and barriers of willow systems*

As with other projects, this thesis also has some limitations that need to be discussed in this section. First, describe the difficulties regarding evaluating the purification rate of measurements

There were limitations to assessing the purification capacity of the investigated measure since the purification rate is highly dependent on the size of the facility. Different literature was used to find the overall description regarding the purification rate of the identified measurement. It was highly considered not to use the comparing or assessing literature since their methodology for assessment were different. However, there may be some uncertainty regarding them.

In the analytical framework, the criterion of inclusive governance was one of the parameters for choosing the best NBS. This criterion has not been considered in this report for three reasons. First and foremost, the focus of this thesis was on the pre-analysis of the investigated solutions based on literature search and rating. Therefore, having an interview with the public wasn't the focal point of this thesis. Second, the selected area is managed by the municipality and the selected measure does not affect the landowners. Third, the selected measure does not disrupt the recreational zone and lake used by citizens. Therefore, having an interview with citizens and locals wasn't considered in the thesis.

In the design process of willow treatment plants, it was mentioned to design a sedimentation tank to pre-treat the wastewater before discharging it into the willow systems. The pre-treated wastewater is important since the system is connected to a level-control pump to distribute the water equally in the willow systems (Miljøministeriet, 2004). This equal distribution will help in growing the willows and pollution removal (Miljøministeriet, 2003). However, this process is considered to be the third step in designing willow treatment plans (Carlos Arias et al., 2023). The first step is assessing the risk of the case area, the infiltration capacity of the soil, and the level of the groundwater. The second step is calculating the dimension of willow systems based on the discharge rate of wastewater, precipitation, and evapotranspiration. Therefore, these two steps have been analyzed in this thesis, however, due to the timing of the project the third step was not considered in the design process.

Finally, the interviews with designers and professionals who have worked on large-scale willow treatment plants in Denmark were planned for this research but could not be conducted due to their unavailability. This limitation affected the understanding of the potential functionality of willow systems for wastewater purification and flood mitigation on a large scale, especially during drier periods. The emails sent to request these interviews are attached in the Annex.

Barriers

There are some barriers to utilizing willow treatment plants as a sustainable tool for capturing and purifying diluted wastewater including, the time of willow plantation. According to (Miljøministeriet, 2003), willow plants should be implemented in early spring otherwise the willows will not have productivity in purification and evapotranspiration.

4.3 *Future research*

According to (Miljøministeriet, 2003), there are two types of willow treatment plants, one with infiltration to the ground, and one without infiltration. In this thesis, due to the request from the Lemvig municipality and the interview with person number 2, the infiltration of diluted wastewater into the willow systems is considered to be zero. It will be beneficial for the Lemvig municipality or future research to consider the filtration capacity based on the required legislation for the long-term solution. This approach will help to reduce the size of the investigated measure and require less space for implementation. Another alternative approach for the long-term solution to reduce sewage overflows is the implementation of NBS before the Nørre Nissum pump station. As described in section 3.5.4, the selected area cannot accommodate the long-term solution due to its capacity and size. Therefore, based on the exposure assessment described in section 3.1.2, there are two main water accumulations on the surface before the Nørre Nissum pump station, due to the intense precipitation. Therefore, it will be valuable research to analyze if the implementation of NBS like delay basins in those areas can help in reducing surface runoff as a result, solving sewage overflows in the future.

Moreover, as mentioned in section 3.5.1 for the willow treatment plants, there are two factors that will increase the evapotranspiration rate including, heat and wind. In this thesis, due to time limitations, there wasn't an opportunity to analyze the direction of the wind in the selected area. However, it will be effective research for the future to consider the wind direction for implementing willow systems since it will increase the evapotranspiration rate.

5 Conclusion

The aim of this thesis was to design and propose an NBS for capturing diluted wastewater that can address current hazards and remain robust for future hazards. Denmark, an European country concerned about water quality due to the discharge of diluted wastewater, has well-developed NBSs in the form of CCA to reduce surface runoff. However, due to strict purification standards, large-scale NBSs for capturing and purifying diluted wastewater are not as advanced. Consequently, the main research question developed is:

How can a cost-effective Nature-Based Solution be implemented for the purpose of capturing and purifying diluted wastewater?

To answer the main research question two sub-research questions were developed. The first is: How can an NBS be implemented in the case area to accommodate current hazards and be sufficiently robust to deal with future hazards? Since the focal point in this thesis is NBS, a guideline based on IUCN criteria in the analytical framework has been developed which introduces important factors that an NBS should address, including social challenges that refer to climate change, water security, and human health.

The risk of CC in the case area has been assessed by analyzing the interaction of hazard with exposure and vulnerability. Since precipitation is considered a hazard in this thesis, this assessment will help to understand the current risk and the future risk of heavy precipitation. Moreover, this assessment will help to answer the second sub-research question as the measurement needs to be robust and flexible to accommodate future hazards. Additionally, understanding the soil type and the groundwater level in the selected area will help with the first step to understanding how an NBS can be implemented. This is important because legislation specifically mentioned that the investigated measurement should not negatively affect groundwater level.

The second sub-research question is: Which cost-effective NBS with a high purification rate can be implemented, and what design criteria are necessary for a successful implementation? When planning a solution with the aim of long-term objectives it is important to consider future uncertainties, as neglecting them can lead to the solution's failure. It is important to acknowledge the fact that in the process of selecting a solution, some of them may fail. Hence, an adaptation pathway should be considered to provide alternative solutions if one fails. Based on this, six criteria based on the adaptation pathway have been established to ensure the successful implementation of the solution. Since the solution needs to be cost-effective and has a high purification rate two additional criteria, including biodiversity net gain, and economic feasibility from the IUCN guideline were also used. To choose the best NBS, a systematic approach based on the adaptation pathway, named multi-criteria assessment was employed to evaluate solutions based on rating and weighting. Based on this evaluation, an NBS named willow treatment plant was selected to capture and purify the diluted wastewater. To answer the second part of the question, it is crucial to design a dimension for the willow systems that can accommodate current hazards and seal the bottom of the system with a tight membrane to prevent the groundwater from being negatively affected by diluted wastewater. These processes will help for a successful implementation.

By answering these questions, a comprehensive answer can be formulated for the main research question. The willow treatment plants as an NBS not only have the flexibility to scale up, and mix with both gray and green solutions to accommodate diluted wastewater, but also utilize two processes including evaporation and transpiration to efficiently purify diluted wastewater from BOD, COD, and nitrogen, and phosphorous at a high rate, meeting legislative requirements.

Moreover, willow treatment plants will increase environmental, and ecological benefits for water bodies, and human health. However, the current capacity of the case area can only accommodate the willows for the present hazard. This means that the future hazard that can cause severe sewage overflow, remains a challenge for the Lemvig municipality. Moreover, there is uncertainty regarding how future CC will affect weather patterns. As mentioned in the introduction of this thesis, the precipitation in summer is likely to become heavier and more frequent (Klimatilpasning, 2023a), but it is unclear whether the future will become wetter or dryer.

Finally, while NBS have demonstrated significant potential for wastewater purification, they may not be entirely foolproof compared to grey solutions. NBS will provide substantial benefits, including cost-effectiveness, environmental enhancements, and compliance with legislative requirements for purification rates. However, they alone may not achieve 100 percent purification efficiency. To optimize the efficiency, it is recommended to combine NBS with traditional grey solutions like sedimentation tanks. This combination leverages the strengths of the robustness approach.

- *Bibliography*

Adeoye-Olatunde, O. A., & Olenik, N. L. (2021). Research and scholarly methods: Semi-structured interviews. *JACCP: JOURNAL OF THE AMERICAN COLLEGE OF CLINICAL PHARMACY*, *4*(10), 1358–1367. https://doi.org/10.1002/jac5.1441

Ahmed, S & Mohd Asraf, R. (2018). *The Workshop as a Qualitative Research Approach: Lessons Learnt from a "critical Thinking Through Writing' Workshop*. https://www.researchgate.net/publication/330526938_The_Workshop_as_a_Qualitative_Research_Approach_Lessons_Learnt_from_a_critical_Thinking_Through_Writing'_Workshop/citations

Ambulkar, A & Nathanson, Jerry A. (2024). *Wastewater treatment*. https://www.britannica.com/technology/wastewater-treatment#ref72337

Baills, A., Garcin, M., & Bulteau, T. (2020). Assessment of selected climate change adaptation measures for coastal areas. *Ocean & Coastal Management*, *185*, 105059. https://doi.org/10.1016/j.ocecoaman.2019.105059

Bodholdt, N. (2023). *Heavy rain creates a risk of new floods in Jutland*. https://www.dr.dk/nyheder/seneste/kraftig-regn-giver-risiko-nye-oversvoemmelser-i-jylland

Brandt, A. (2016). *Extreme rain in Horsens: Over 200 years between such violent cloudbursts*. https://vejr.tv2.dk/2016-06-16-ekstrem-regn-i-horsens-over-200-aar-mellem-saa-voldsomme-skybrud

Brown, R. R., Keath, N., & Wong, T. H. F. (2009). Urban water management in cities: Historical, current and future regimes. *Water Science and Technology*, *59*(5), 847–855. https://doi.org/10.2166/wst.2009.029

Butala, S. (2023). *What are the Environmental Issues of Wastewater?* https://rsbenv.com/what-are-the-environmental-issues-of-wastewater

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Péan, C. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* (First). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

Carlos Arias, Mirko Haenel, Andres Acosta, & Claudia Fernandez. (2023). *Wastewater-fertigated Short Rotation Coppice (wfSRC) Systems for domestic wastewater treatment*. https://sswm.info/pavitr-toolkit/get-know-pavitr-technologies/water-reclamation-solutions/wastewater-fertigated-short-rotation-coppice-%28wfsrc%29-systems-for-domestic-wastewater-treatment

Chapman, S., Watson, J. E. M., Salazar, A., Thatcher, M., & McAlpine, C. A. (2017). The impact of urbanization and climate change on urban temperatures: A systematic review. *Landscape Ecology*, *32*(10), 1921–1935. https://doi.org/10.1007/s10980-017-0561-4

Chen, W., Wang, W., Huang, G., Wang, Z., Lai, C., & Yang, Z. (2021). The capacity of grey infrastructure in urban flood management: A comprehensive analysis of grey infrastructure and the green-grey approach. *International Journal of Disaster Risk Reduction*, *54*, 102045. https://doi.org/10.1016/j.ijdrr.2021.102045

CONCITO. (2023). *Klimatilpasning i danske kommuners klimahandlingsplaner*. https://concito.dk/files/media/document/Klimatilpasning%20i%20danske%20kommuners%20klimahandlingsplaner_29.11.2023.pdf

Council of the European Union. (2023). *DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning urban wastewater treatment (recast)*. https://data.consilium.europa.eu/doc/document/ST-14271-2023-INIT/en/pdf

Cronholm, S., & Hjalmarsson, A. (2011). Experiences From Sequential Use of Mixed Methods. *Electronic Journal of Business Research Methods*, *9*(2).

Cross, K., Tondera, K., Rizzo, A., Andrewa, L., Nature Conservancy, & Science for Nature and People Partnership (Eds.). (2021). *Nature-based solutions for wastewater treatment*. IWA Publishing.

Danish board of technology. (2021). *Klimatilpasning for fremtiden. Udfordringer, dilemmaer og l'sningsveje.*

DANVA. (2007). *Effects of future climate change on water resources in Denmark*. https://www.danva.dk/media/2945/effectsplusofplusfutureplusclimatepluschangeplusonpluswaterplusresourcesplusinplusdenmark.pdf

Darja Istenič. (2022). *Wastewater treatment and nature-based solutions: How is the Central and Eastern European region doing?* https://ceenergynews.com/voices/wastewater-treatment-and-nature-based-solutions-how-is-the-central-and-eastern-european-region-doing/

Dark,T. (2016). *Do you remember the weather on 2 July 2011: Historic cloudburst hit Copenhagen*. https://vejr.tv2.dk/2016-07-02-husker-du-vejret-den-2-juli-2011-historisk-skybrud-ramte-koebenhavn

Davis, L. & USA (Eds.). (2015). *General considerations*. U.S. G.P.O., Supt. of Docs.

Dean. (2022). *A Practical Guide to Multi-Criteria Analysis*. https://www.researchgate.net/profile/Marco-Dean/publication/358131153_A_Practical_Guide_to_Multi-Criteria_Analysis/links/61f198a98d338833e398624c/A-Practical-Guide-to-Multi-Criteria-Analysis.pdf

Dean, M. (2020). Multi-criteria analysis. In *Advances in Transport Policy and Planning* (Vol. 6, pp. 165–224). Elsevier. https://doi.org/10.1016/bs.atpp.2020.07.001

DMI. (2018). *Vejledning i anvendelse af udledningsscenarier. Udarbejdet af DMI i samarbejde med MST.* https://www.dmi.dk/fileadmin/user_upload/Bruger_upload/Raadgivning/Vejledning_i_anvendelse_af_udledningsscenarier.pdf

DMI. (2023a). *Klimaatlas*. https://www.dmi.dk/klima-atlas/data-i-klimaatlas/?paramtype=sea&maptype=kyst

DMI. (2023b). *The weather in Denmark is getting warmer, wetter and wilder*. https://www.klimatilpasning.dk/viden-om/fremtidens-klima/klimaaendringeridanmark/

DMI. (2024a). *Climate Atlas*. https://www.dmi.dk/klima-atlas/data-i-klimaatlas?paramtype=prec2&maptype=kom

DMI. (2024b). *DMI- Change of weather*. https://www.dmi.dk/lokationarkiv/show/DK/2617812/Lemvig/#arkiv

DMI. (2024c). *The weather in Denmark is getting warmer, wetter and wilder*. https://www.dmi.dk/klimaatlas

DNNK, Region Nordjylland, Region Midtjylland, Region Syddanmark, Region Hovedstaden, & Region Sjælland. (2021). *National undersøgelse af klimatilpasning i et borger- og virksomhedsperspektiv De fem regioner, DNNK og Danske Regioner*. https://www.regionh.dk/klima-og-miljoe/Documents/Rapport%20National%20unders%C3%B8gelse%20om%20klimatilpasning.pdf

EPA. (2019). *Wastewater lagoon construction guidelines*. https://www.lga.sa.gov.au/__data/assets/pdf_file/0033/554685/EPA-Wastewater-lagoon-construction-Guidelines-2019.pdf

European Commission. (2022). *Nature-based solutions* [dataset]. https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions_en

European Commission. Directorate General for Environment. & University of the West of England (UWE). Science Communication Unit. (2021). *Science for environment policy: The solution is in nature.* Publications Office. https://data.europa.eu/doi/10.2779/656087

Farthing, S. (2016). *Research Design in Urban Planning: A Student's Guide, SAGE*. https://ebookcentral.proquest.com/lib/aalborguniv-ebooks/detail.action?

Fratini & Jensen. (2014). *Grøn omstilling af byens vand*. https://core.ac.uk/download/60596149.pdf

Fryd, O & Jørgensen, G. (2019). *Byerne og det stigende havvand innovative planlægningstilgange*. file:///C:/Users/Asus/Downloads/Ole-Fryd--Gertrud-Jrgensen--Innovative-planlgningstilgange.pdf

Gómez-Baggethun, E., & Barton, D. N. (2013). Classifying and valuing ecosystem service for urban planning. *Ecological Economics*, *86*, 235–245. https://doi.org/10.1016/j.ecolecon.2012.08.019

Hans Brix & Carlos A Arias. (2011). *Use of willows in evapotranspirative systems for onsite wastewater management? Theory and experiences from Denmark*. https://www.researchgate.net/publication/303210067_Use_of_willows_in_evapotranspirative_systems_for_onsite_wastewater_management_theory_and_experiences_from_Denmark/citations

HIP. (2023). *HYDROLOGISK INFORMATIONS- OG PROGNOSESYSTEM* [Map]. HIP. https://hip.dataforsyningen.dk/

Holbæk kommune. (2023). *Pileanlæg-What is a willow plant and can I build one?* https://holbaek.dk/borger/teknik-og-miljoe/vand/spildevand/spildevand-i-det-aabne-land/forskellige-renseloesninger/pileanlaeg/

IPCC. (2014). *Climate change 2014. Impacts, Adaptation, an Dunlerability. Summary for Policymakers*. https://www.ipcc.ch/site/assets/uploads/2018/02/ar5_wgII_spm_en.pdf

IPCC. (2020). *The concept of risk in the IPCC Sixth Assessment Report: A summary of cross Working Group discussions*. https://www.ipcc.ch/site/assets/uploads/2021/01/The-concept-of-risk-in-the-IPCC-Sixth-Assessment-Report.pdf

IPCC. (2022). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009325844

Istenič, D., & Božič, G. (2021). Short-Rotation Willows as a Wastewater Treatment Plant: Biomass Production and the Fate of Macronutrients and Metals. *Forests*, *12*(5), 554. https://doi.org/10.3390/f12050554

IUCN. (2020). *IUCN Global Standard for Nature-based Solutions: A user-friendly framework for the verification, design and scaling up of NbS: first edition* (1st ed.). IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2020.08.en

Jensen. Trine S & Hjotnæs Daniel. (2022). *Humus—The unknown climate buffer against extreme rain etc*. https://pro.ing.dk/watertech/holdning/humus-den-ukendte-klimabuffer-mod-ekstremregn-mm

Justino, S., Calheiros, C., Castro, P., & Gonçalves, D. (2023). Constructed Wetlands as Nature-Based Solutions for Wastewater Treatment in the Hospitality Industry: A Review. *Hydrology*, *10*(7), 153. https://doi.org/10.3390/hydrology10070153

KAMP. (2023). *Klimaatlas*. https://kamp.klimatilpasning.dk/

Kaushal, S., & Singh, J. S. (2017). Wastewater Impact on Human Health and Microorganism-Mediated Remediation and Treatment Through Technologies. In J. S. Singh & G. Seneviratne (Eds.), *Agro-Environmental Sustainability* (pp. 235–250). Springer International Publishing. https://doi.org/10.1007/978-3-319-49727-3_12

Kjærgaard, Ch. (2013). *Konstruerede vådområder til målrettet reduktion af næringsstoffer i drænvand*. https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/NLK/kontruerede_vaadomraader.pdf

Klimatilpasning. (2023a). *Precipitation and climate change* [Https://www.klimatilpasning.dk/viden-om/fremtidens-klima/klimaaendringeridanmark/%C3%A6ndringer-i-havniveau/].

Klimatilpasning. (2023b). *Temperature and climate change*. https://en.klimatilpasning.dk/knowledge/climate/denmarksfutureclimate/changes-in-temperature/

Klimatorium. (2020). *WISE MANAGEMENT OF WASTEWATER: CLIMATE SOLUTION FULLY IN PLACE IN LEMVIG MUNICIPALITY*. https://klimatorium.dk/en/klog-haandtering-af-spildevand-klimaloesning-helt-paa-plads-i-lemvig-kommune/

Labadz, J, Allot, Tim, Evans, Martin, Butcher, David, Billet, Mike, Stainer, Simon, Yallop, Adrian, Jones, Peter, Innerdale, Mike, Harmon, Neasa, Maher, K, Bardbury, R, Mount, D, O'Brien, H, & Hart, R. (2010). *Peatland Hydrology*. https://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/Review%206%20Peatland%20Hydrology_0.pdf

Lehmann, M., Major, D. C., Fitton, J. M., Doust, K., & O'Donoghue, S. (2021). Towards a typology for coastal towns and small cities for climate change adaptation planning. *Ocean & Coastal Management*, *212*, 105784. https://doi.org/10.1016/j.ocecoaman.2021.105784

Lemvig kommune. (2013). *SPILDEVANDSPLAN 2013—2021*. https://www.lemvig.dk/Files/Files/Teknik%20og%20Milj%C3%B8/Spildevandsplan%202013-2021/Lemvig_Spildevandsplan_rev13_-_vedtaget_plan_-_rev_27-02-2018.pdf

Lemvig Kommune. (2014). *Klimatilpasningsplan 2014—2017*. https://www.lemvig.dk/files/files/teknik%20og%20milj%c3%b8/planer/klimatilpasningsplan.pdf

Lemvig kommune. (2020). *The municipality in numbers*. https://lemvig.dk/kommunen/fakta/kommunen-i-tal

Lemvig kommune. (2022). *Spildevandsplan 2021-2028*. https://www.lemvig.dk/Files/Files/Teknik%20og%20Milj%C3%B8/Spildevandsplan%202021-28%20-%20G%C3%A6ldende/Lemvig%20Spildevandsplan%202021-28%20rev%2009-05-2022%20-%20Endelig%20vedtaget%20den%2022-06-22.pdf

Lemvig Kommune. (2023). *Klimatilpasningsplan*.

Lemvig Water. (2024). *Lemvig water* [Map]. https://drift.kortinfo.net/map.aspx?site=lemvigvand&page=Ledningsdata%20Lemvig%20Vand

Liang, M.-Y., Han, Y.-C., Easa, S. M., Chu, P.-P., Wang, Y.-L., & Zhou, X.-Y. (2020). New solution to build constructed wetland in cold climatic region. *Science of The Total Environment*, *719*, 137124. https://doi.org/10.1016/j.scitotenv.2020.137124

Lundsgaard, J. (2019). *Several roads are under water*. https://folkebladetlemvig.dk/lemvig/flere-veje-staar-under-vand

Marchau, V. A. W. J., Walker, W. E., Bloemen, P. J. T. M., & Popper, S. W. (Eds.). (2019). *Decision Making under Deep Uncertainty: From Theory to Practice*. Springer International Publishing. https://doi.org/10.1007/978-3-030-05252-2

Mashuri, S, Sarib, M, Rasak, A, lhabsyi, F, & Syam, H. (2022). *Semi-structured Interview: A methodological reflection on the development of a qualitative research instrument in educational studies*. https://d1wqtxts1xzle7.cloudfront.net/81693133/Semi_structured_Interview_A_Metho dological_Reflection-libre.pdf?1646470054=&response-content-disposition=inline%3B+filename%3DSemi_structured_Interview_A_Methodologic.pdf&Expires=1713789185&Signature=XCBlKZ356UyokQQaNAOKnj2ldJoK4Achp68rqAsf2GotC~zznD7W2WridT2VpQrgGSLxR1n~XQZl9-1QFAIqwMhx~pYabcUPN65kf3HhD6tQJoyZV1s0CIZvJFJVccRihOeWOBKnuLDiamKgZTJqc3Z2TEh4PsE1TRXBKtWz4fmZvhVrTN7gKvIQeCSRNnZmq~T9eMi4591ToM-wE3tydnvqA5YYpCL9l1yCnFjGTE4ZCYfkeWBCNRAd5XH80WvkSDAUnAcUR-WvsJPEINsDHkM057kQXXtN4qbsWL9GZpaK8A1Sczd3Ic7JhDbvZkxgV1a9CQVMYrWHDpbw1Udc9A__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

Masi, F., Rizzo, A., & Regelsberger, M. (2018). The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm. *Journal of Environmental Management*, *216*, 275–284. https://doi.org/10.1016/j.jenvman.2017.11.086

Miljøministeriet. (2003). *Etablering af pileanlæg– Baggrundsrapport. Økologisk Byfornyelse og Spildevandsrensning Nr. 27*.

Miljøministeriet. (2004). *Retningslinier for etablering af beplantede filteranlæg op til 30 PE*. https://www2.mst.dk/udgiv/publikationer/2004/87-7614-454-2/pdf/87-7614-455-0.pdf

Miljøministeriet. (2023). *Coastal Planner* [Map]. https://gis.nst.dk/portal/apps/webappviewer/index.html?id=7d399b34b9ef42d7895569d0ccc0046b

Miljøstyrelsen. (2001). *12 wastewater, Danish Environmental Protection Agency*. https://www2.mst.dk/udgiv/publications/2001/87-7944-519-5/html/kap12_eng.htm#top

Miljøstyrelsen. (2003). *Sustainable Urban Renewal and Wastewater Treatment no. 38, 2003 Biomass Plantations Irrigated and Fertilised with Wastewaters*. https://www2.mst.dk/udgiv/publications/2003/87-7972-744-1/html/helepubl_eng.htm

Miljøstyrelsen. (2018). *Spildevandsvejledningen til bekendtgørelse om spildevandstilladelser m.v. Efter miljøbeskyttelseslovens kapitel 3 og 4*. https://mst.dk/media/tvyb2pfb/spildevandsvejledningen.pdf

Muttil, N., Nasrin, T., & Sharma, A. K. (2023). Impacts of Extreme Rainfalls on Sewer Overflows and WSUD-Based Mitigation Strategies: A Review. *Water*, *15*(3), 429. https://doi.org/10.3390/w15030429

Odense kommune. (2022). *Solutions for improved wastewater treatment*. https://www.odense.dk/borger/miljoe-og-affald/spildevand-og-regnvand/spildevand-fra-ikke-kloakerede-ejendomme/loesninger-til-forbedret-spildevandsrensning-i-det-aabne-land

OECD. (2020). *Cities in the World*. OECD. https://doi.org/10.1787/d0efcbda-en

Oral, H. V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., Hullebusch, E. D. V., Kazak, J. K., Exposito, A., Cipolletta, G., Andersen, T. R., Finger, D. C., Simperler, L., Regelsberger, M., Rous, V., Radinja, M., Buttiglieri, G., Krzeminski, P., Rizzo, A., Dehghanian, K., …

Zimmermann, M. (2020). A review of nature-based solutions for urban water management in European circular cities: A critical assessment based on case studies and literature. *Blue-Green Systems*, *2*(1), 112–136. https://doi.org/10.2166/bgs.2020.932

Rahman, M. E., Bin Halmi, M. I. E., Bin Abd Samad, M. Y., Uddin, M. K., Mahmud, K., Abd Shukor, M. Y., Sheikh Abdullah, S. R., & Shamsuzzaman, S. M. (2020). Design, Operation and Optimization of Constructed Wetland for Removal of Pollutant. *International Journal of Environmental Research and Public Health*, *17*(22), 8339. https://doi.org/10.3390/ijerph17228339

Raudaskoski, P. L. (2020). *Observationsmetoder (herunder videoobservation). In S. Brinkmann & L. Tanggaard (Eds.), Kvalitative metoder: En grundbog (3rd ed., pp. 117–135). Hans Reitzels Forlag*. https://vbn.aau.dk/da/publications/observationsmetoder-herunder-videoobservation

Rhys Gustafsson. (2014). *Constructed Wetland Design: Wastewater Polishing of Denmark Wastewater Treatment Plant Effluent*. https://www.academia.edu/12972436/Constructed_Wetland_Design_Wastewater_Polishing_of_Denmark_Wastewater_Treatment_Plant_Effluent

SCALGO LIVE. (2023). *Scalgo Live* [Map]. https://scalgo.com/live/denmark?res=3.2&ll=8.311449%2C56.545211&lrs=datafordeler_skaermkort_daempet%2Cdenmark%2Fdenmark%3A25832%3Acurrent%3Asea%3Asealevels%3Adhm2015%2Cw300721%3Aedits&tool=export&WaterLevel=2.11&WaterDepth=0

S.E. Jørgensen, N. Ladegaard, S. Kayombo, T.S.A. Mbwette, & J.H.Y Katima. (2004). *WASTE STABILIZATION PONDS AND CONSTRUCTED WETLANDS DESIGN MANUAL*. https://wedocs.unep.org/bitstream/handle/20.500.11822/8380/-Waste%20Stabilization%20Ponds%20and%20Constructed%20Wetlands_%20Design%20Manual-20043595.pdf?sequence=3&isAllowed=y

Slagelse kommune. (2017). *Spildevand—I det åbne land-Miljø, Plan og Teknik*.

Sowińska-Świerkosz, B., & García, J. (2022). What are Nature-based solutions (NBS)? Setting core ideas for concept clarification. *Nature-Based Solutions*, *2*, 100009. https://doi.org/10.1016/j.nbsj.2022.100009

Statista. (2022). *Urbanisierungsgrad in EU und Euro-Zone bis 2021*.

Teknik og miljø. (2024). *Teknik og miljø. TALERØR FOR DEN KOMMUNALTEKNISKE SEKTOR*. https://danskmiljoteknologi.dk/wp-content/uploads/pdf/teknikogmiljoe0420240522low.pdf

The Rockefeller Foundation & ARUP. (2015). *City Resilience Framework*. https://www.rockefellerfoundation.org/wp-content/uploads/City-Resilience-Framework-2015.pdf

Thisted kommune. (2022). *Wastewater plan 2022-2031*. https://thisted.viewer.dkplan.niras.dk/plan/82#/32584

Tyler, S., & Moench, M. (2012). A framework for urban climate resilience. *Climate and Development*, *4*(4), 311–326. https://doi.org/10.1080/17565529.2012.745389

USAID. (2013). *ANALYZING CLIMATE CHANGE ADAPTATION OPTIONS USING MULTI-CRITERIA ANALYSIS*. https://www.climatelinks.org/sites/default/files/asset/document/Multi-Criteria%2520Analysis_CLEARED_0.pdf

Veerkamp, C., Emiliano, R., Romanovska, L., Zandersen, M., Förster, J., Rogger, M., & Martinsen, L. (2021). *Assessment Frameworks of Nature-based Solutions for Climate Change Adaptation and Disaster Risk Reduction*. https://doi.org/10.25424/CMCC/NBS_ASSESSMENT_APPROACHES

Waly, M. M., Ahmed, T., Abunada, Z., Mickovski, S. B., & Thomson, C. (2022). Constructed Wetland for Sustainable and Low-Cost Wastewater Treatment: Review Article. *Land*, *11*(9), 1388. https://doi.org/10.3390/land11091388

World Bank. (2021). *A catalogue of Nature-Based Solutions for urban resilience*. https://documents1.worldbank.org/curated/en/502101636360985715/pdf/A-Catalogue-of-Nature-based-Solutions-for-Urban-Resilience.pdf

WSP, Smith, Teknologisk Institut, & g Lundgrens. (2021). *Terrænnært grundvand i danske byer Eksempelsamling – problemer, årsager og løsninger?* https://www.klimatilpasning.dk/media/1909341/terraennaert-grundvand-i-danske-byer.pdf

- ## *Appendix*

Appendix A

Interview

According to (Mashuri, S et al., 2022)the semi-structured interview needs to be conducted in a quiet place through face-to-face, phone calls, or online meetings. Therefore, in this thesis, the interviews both face-to-face and online meeting interview were utilized as a semi-structured interview. The following information describes the interview guide with semi-structured questions:

Identifying problem:

- Why some sewage systems in Lemvig municipality have experienced sewage overflows?
- Have you ever experienced sewage overflows in the Nørre Nissum pump station?

If yes the following questions will be asked:

- When was the last sewage overflow?
- What is the capacity of the Nørre Nissum pump station?
- How many pump stations are connected to the Nørre Nissum pump station?

Regarding the previous question, the following questions will be asked:

- Have you ever experienced sewage overflows in those pump stations? (Gudum and Febjerg)

Assessment of potential for the measurement:

The following question is based on criteria described in the analytical framework:

- What kind of criteria is more important for Lemvig municipality?
- Do you want the solution to be implemented in the near term or long term?
- What time horizon do you consider for the life of the measurement?

Observation

Data collected from the workshop was based on observation. The steps that were followed to collect data in the workshop were based on recommendations from (Raudaskoski, P. L, 2020), including,

1. How is an event unfolding and how is it perceived?
2. Where is an event taking place?
3. When is an event happening, considering both time and context?
4. Who is involved in an event?

The vision made by stakeholders is shown in Figure 19.

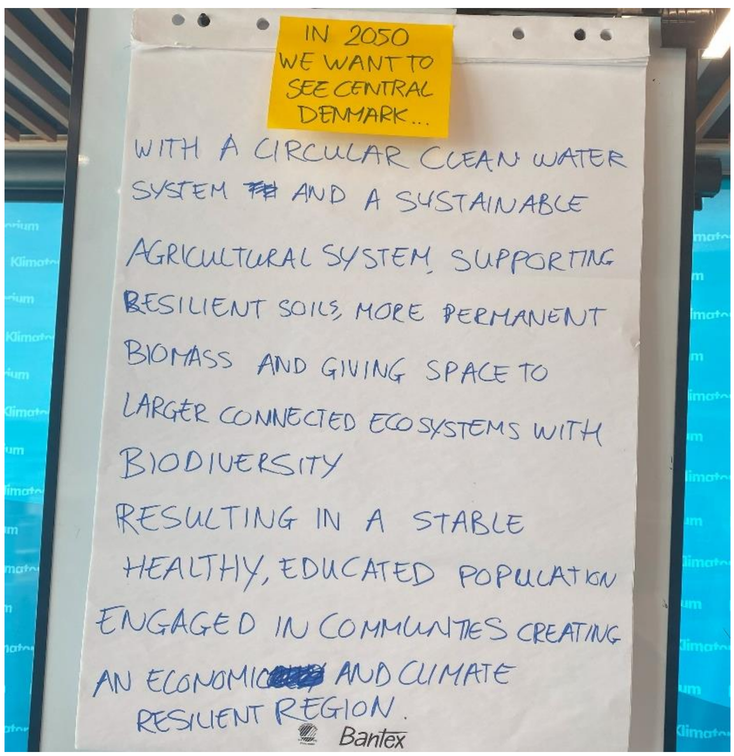

Figure 19. Illustration of stakeholder's vision. Took by author

Appendix B

Figures 20 and 21 illustrate data regarding the discharge rate of wastewater from two pump stations, Gudum and Febjerg to the Nørre Nissum pump station.

01-01-2023
Pumpesta

	P090 - Gudumvej 26 Før 11/9-2023 Regnmåler: Nr. Nissum				P090 - Gudumvej 26 Efter 11/9-2023 Regnmåler: Nr. Nissum				S1T - Havnegade 58 Regnmåler: Thyborøn			
	P1-Tid	P2-Tid	Flow	Regn	P1-Tid	P2-Tid	Flow	Regn	P1-Tid	P2-Tid	Flow	Regn
Dag	h	h	m3	mm	h	h	m3	mm	h	h	m3	mm
1	24,0	24,0	1116,0	3,9	0,0	0,0	0,0		2,5	2,5	1398,0	2,6
2	24,0	24,0	1106,0	6,9	0,0	0,0	0,0		2,3	2,2	1246,0	3,0
3	24,0	24,0	1100,0	13,0	0,0	0,0	0,0		2,4	2,3	1312,0	8,3
4	24,0	24,0	1118,0	6,3	0,0	0,0	0,0		3,8	3,6	2015,0	7,5
5	24,0	24,0	1124,0	2,3	0,0	0,0	0,0		2,6	2,6	1433,0	1,7
6	24,0	24,0	1121,0	8,8	0,0	0,0	0,0		3,3	3,2	1753,0	4,1
7	24,0	24,0	1105,0	2,4	0,0	0,0	0,0		2,4	2,3	1282,0	1,8
8	24,0	24,0	1071,0	0,1	0,0	0,0	0,0		2,1	2,0	1121,0	0,1
9	24,0	24,0	1035,0	3,5	0,0	0,0	0,0		2,1	2,1	1135,0	3,2
10	19,1	22,9	915,0	11,2	0,0	0,0	0,0		2,6	2,6	1380,0	6,8
11	24,0	24,0	1054,0	4,8	0,0	0,0	0,0		2,8	2,6	1449,0	2,0
12	24,0	24,0	1067,0	3,8	0,0	0,0	0,0		2,4	2,3	1278,0	2,3
13	24,0	24,0	1084,0	6,4	0,0	0,0	0,0		3,1	3,0	1603,0	5,8
14	24,0	24,0	1095,0	9,6	0,0	0,0	0,0		3,2	3,1	1675,0	5,6
15	24,0	24,0	1100,0	4,3	0,0	0,0	0,0		3,5	3,5	1894,0	5,3
16	24,0	24,0	1084,0	7,1	0,0	0,0	0,0		3,0	2,9	1562,0	5,7
17	24,0	24,0	1094,0	9,6	0,0	0,0	0,0		4,2	4,1	2173,0	9,1
18	24,0	24,0	1096,0	0,2	0,0	0,0	0,0		2,8	2,7	1474,0	0,2
19	24,0	24,0	1057,0	0,0	0,0	0,0	0,0		2,2	2,1	1144,0	0,1
20	23,9	23,9	1018,0	0,0	0,0	0,0	0,0		1,9	1,8	968,0	0,0
21	4,7	17,0	568,0	0,0	0,0	0,0	0,0		1,6	1,6	876,0	0,0
22	4,4	16,8	516,0	0,0	0,0	0,0	0,0		1,6	1,6	824,0	0,0
23	6,0	12,6	483,0	0,0	0,0	0,0	0,0		1,6	1,5	827,0	0,0
24	5,9	12,8	483,0	0,0	0,0	0,0	0,0		1,5	1,6	806,0	0,0
25	6,9	17,5	582,0	3,1	0,0	0,0	0,0		1,5	1,4	780,0	0,7
26	5,8	12,4	461,0	0,0	0,0	0,0	0,0		1,5	1,4	763,0	0,0
27	4,5	13,3	441,0	0,1	0,0	0,0	0,0		1,4	1,3	698,0	0,0
28	5,8	11,4	430,0	0,0	0,0	0,0	0,0		1,3	1,3	696,0	0,3
29	7,4	15,4	527,0	3,7	0,0	0,0	0,0		1,5	1,5	778,0	3,8
30	4,8	13,9	447,0	0,5	0,0	0,0	0,0		1,5	1,5	760,0	0,5
31	13,5	22,5	757,0	8,5	0,0	0,0	0,0		1,8	1,8	965,0	8,1
Total	544,5	644,4	27255,0	120,1	0,0	0,0	0,0	0,0	72,0	70,0	38068,0	88,6

Figure 20. The discharge rate of wastewater from the Gudum pump station to the Nørre Nissum pump station. Data was collected through an interview

01-01-2023 00:00
Pumpestations rapport : Måned

Dag	P093 - Brogade 4A Regnmåler: Brogade 4A				S6V - Engbjergvej 53B Regnmåler: Harboøre renseanlæg				P039 - Fabjregstad 87 Regnmåler: Nr. Nissum				Efter 11/9-2023
	P1-Tid	P2-Tid	Flow	Regn	P1-Tid	P2-Tid	Flow	Regn	P1-Tid	P2-Tid	Flow	Regn	Regn
	h	h	m3	mm	h	h	m3	mm	h	h	m3	mm	mm
1	11,0	11,2	365,0	1,7	13,1	6,9	2000,0	14,8	4,8	2,5	395,7	3,9	
2	6,7	15,4	366,0	6,5	2,7	0,6	330,0	1,8	4,1	2,4	349,7	6,9	
3	0,0	22,1	370,0	12,0	3,1	2,8	590,0	4,3	6,0	1,8	420,3	13,0	
4	8,0	14,4	363,0	4,5	16,4	13,1	2950,0	17,4	9,2	2,7	644,1	6,3	
5	11,0	11,2	367,0	2,9	5,2	2,1	730,0	2,9	3,5	2,2	306,9	2,3	
6	11,1	11,0	362,0	8,6	12,8	6,5	1930,0	6,1	6,6	2,8	505,9	8,8	
7	11,2	11,0	367,0	2,8	2,8	0,5	330,0	3,4	3,3	2,1	293,8	2,4	
8	11,2	11,0	368,0	0,3	1,0	0,4	140,0	0,4	3,0	1,7	256,8	0,1	
9	11,1	11,0	365,0	8,2	0,5	0,2	70,0	3,4	2,2	1,9	221,2	3,5	
10	11,3	11,0	357,0	9,8	4,3	1,1	540,0	11,2	4,7	2,6	395,6	11,2	
11	11,1	11,0	351,0	1,1	6,9	1,6	850,0	4,6	4,5	2,8	395,6	4,8	
12	11,1	11,0	348,0	5,5	6,2	1,0	720,0	3,3	4,2	2,4	356,3	3,8	
13	11,0	11,1	349,0	6,0	13,5	6,9	2040,0	8,1	4,7	2,9	407,0	6,4	
14	11,0	11,2	349,0	7,0	13,2	8,3	2150,0	9,1	6,6	2,9	509,9	9,6	
15	11,0	11,2	347,0	4,6	12,9	5,2	1810,0	6,7	6,1	2,7	474,9	4,3	
16	11,0	11,1	348,0	5,4	4,2	1,1	530,0	5,4	3,7	2,3	326,4	7,1	
17	11,0	11,2	342,0	6,9	14,3	4,5	1880,0	10,0	7,2	3,6	580,0	9,6	
18	11,0	11,2	346,0	0,0	6,6	0,7	730,0	0,6	3,9	2,5	344,0	0,2	
19	11,1	11,0	347,0	0,0	0,5	0,3	80,0	0,0	2,7	1,9	247,0	0,0	
20	11,2	11,0	352,0	0,0	0,3	0,1	40,0	0,0	2,4	1,4	206,1	0,0	
21	11,1	11,0	352,0	0,0	0,2	0,1	30,0	0,0	1,9	1,4	179,7	0,0	
22	11,2	11,0	355,0	0,0	0,2	0,1	30,0	0,0	1,8	1,2	161,5	0,0	
23	10,3	10,4	336,0	0,0	0,1	0,1	20,0	0,0	1,9	1,2	167,8	0,0	
24	8,1	7,2	257,0	0,0	0,1	0,1	20,0	0,0	1,6	1,0	140,5	0,0	
25	8,7	10,5	324,0	5,2	0,2	0,1	30,0	2,2	2,2	1,4	194,5	3,1	
26	10,1	6,6	279,0	0,0	0,1	0,0	10,0	0,0	2,0	1,0	161,8	0,0	
27	8,8	6,2	254,0	0,1	0,1	0,1	20,0	0,0	1,7	1,3	162,0	0,1	
28	7,1	7,8	255,0	0,1	0,1	0,0	10,0	0,1	1,8	1,0	152,4	0,0	
29	9,3	7,5	283,0	3,0	0,2	0,1	30,0	3,9	1,8	1,2	167,0	3,7	
30	6,0	9,5	263,0	2,0	0,2	0,1	30,0	1,5	1,8	1,2	162,1	0,5	
31	10,6	11,4	360,0	8,5	0,8	0,4	120,0	8,5	3,5	2,2	306,0	8,5	
Total	304,4	339,4	10447,0	112,7	142,8	65,1	20790,0	129,7	115,4	62,3	9592,5	120,1	0,0

Figure 21. The discharge rate of wastewater from the Febjerg pump station to the Nørre Nissum pump station. Data was collected through an interview

Appendix C

Calculation of inflow rate:

The inflow rate of wastewater is the sum of the total discharge from the Gudum pump station and Febjerg pump station and divided the obtained number by the number of days which is 31 days.

$$\frac{27255 + 9592{,}5}{31} = 1188{,}6\ m3$$

Volume calculation for the concrete basin is based on Figure 22. The height of the concrete basin is collected from (SCALGO LIVE, 2023)

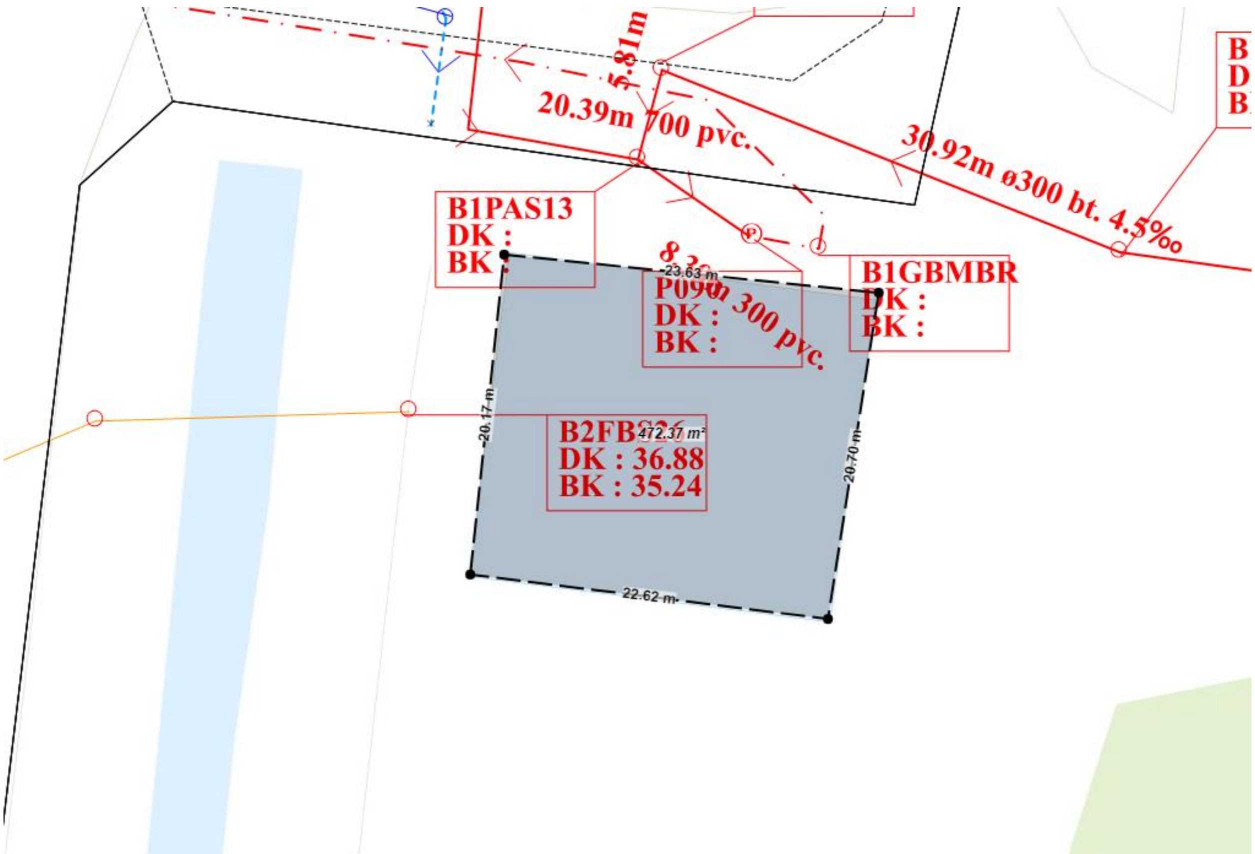

Figure 22. Illustration of the total area of the concrete basin. Figure adapted through an interview

$$Volume = Height \times Length \times Width$$

$$Volume = 1.3 \times 23.6 \times 20.7$$

$$Volume = 635.07 m3$$

Appendix D

Figures 23, 24, and 25 illustrate the amount of precipitation in Lemvig municipality in 2022, 2023, and 2024.

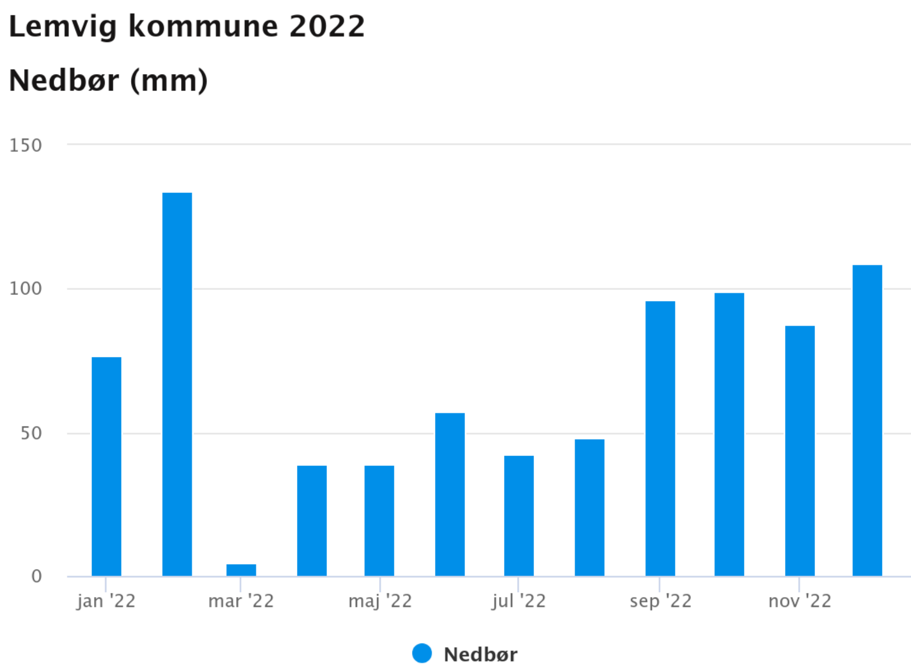

Figure 23. yearly precipitation in Lemvig municipality in 2022. Source adapted from (DMI, 2024b)

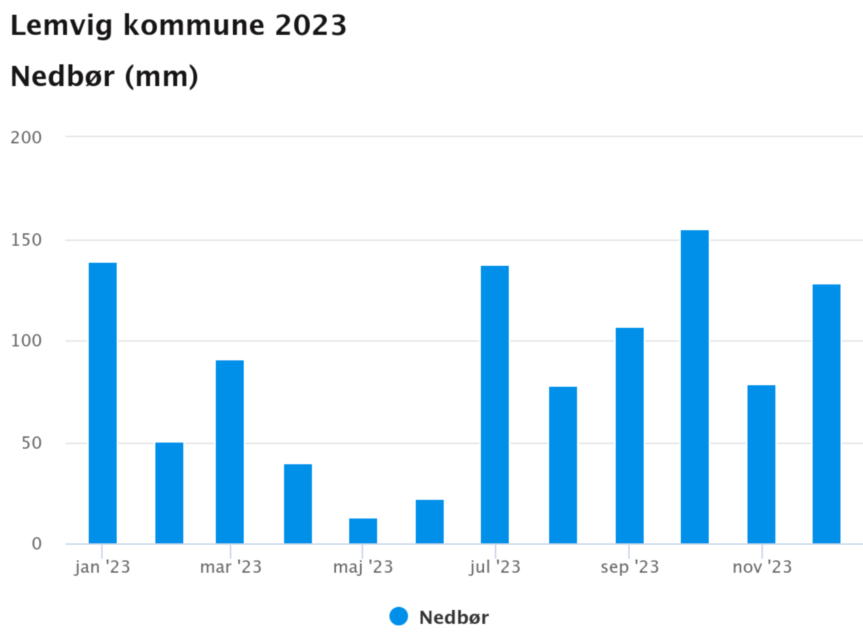

Figure 24. yearly precipitation in Lemvig municipality in 2023. Source adapted from (DMI, 2024b)

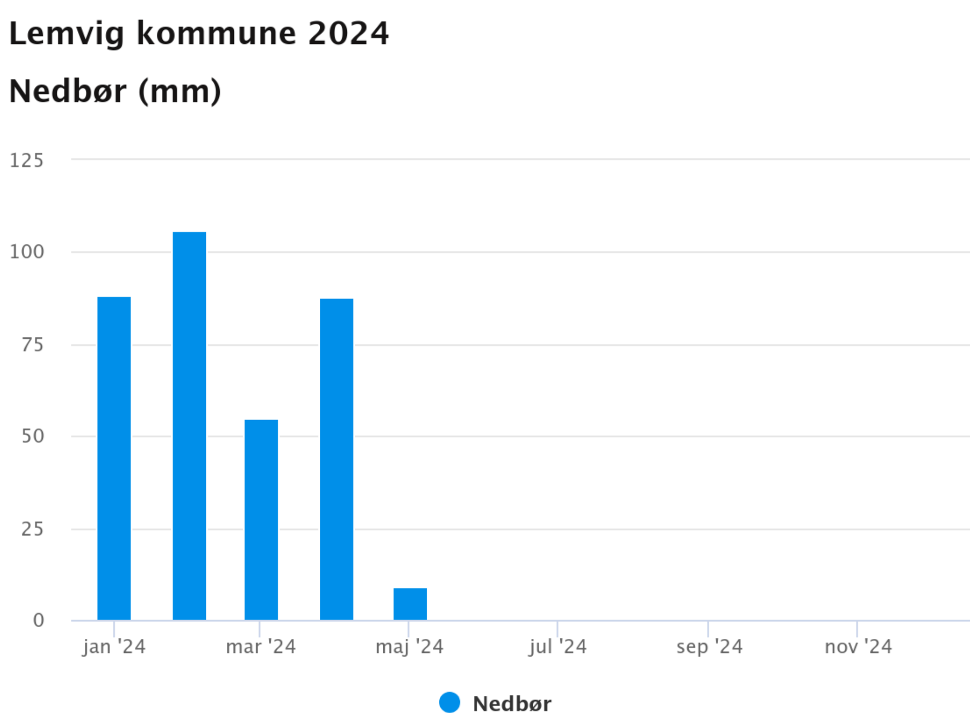

Figure 25. yearly precipitation in Lemvig municipality in 2024. Source adapted from (DMI, 2024b)

Appendix E

In this section, the calculation of the required capacity for the 20-year event for the period of 2041-2070 will be described. Through having an interview with person number 3, it is calculated that the required capacity to handle every day diluted wastewater in the Nørre Nissum pump station is 9 000 m^3. The correct dimension calculated in this thesis which is described in section 3.5.1 is 9 496.8 m^3. As mentioned in section 3.5.2 the 90th percentile of the 20-year event is 7% more than the calculated dimension. Therefore, based on successive calculations described in further detail will be 1 866 m^3.

$$D = \frac{A + B \times 3 + C}{5}$$

A= An expected dimension which is 9 000 m^3

B= The calculated dimension which is 9 496.8 m^3

C= Maximum amount based on the calculated percentage

D= The required capacity

$$D = \frac{9000 + 9\,496.8 \times 3 + 9\,496.8 \times 7\%}{5}$$

D= 7 631.01 m^3

Dimensioned capacity _ Required capacity= Actual capacity that required

9 496.8 m^3-7 631.01 m^3= 1 866 m^3

The 20-year event requires 1 866 m^3 more than the dimensioned capacity.

Appendix F

Figure 26, illustrates the capacity of the Nørre Nissum pump station. The data was collected by having an interview.

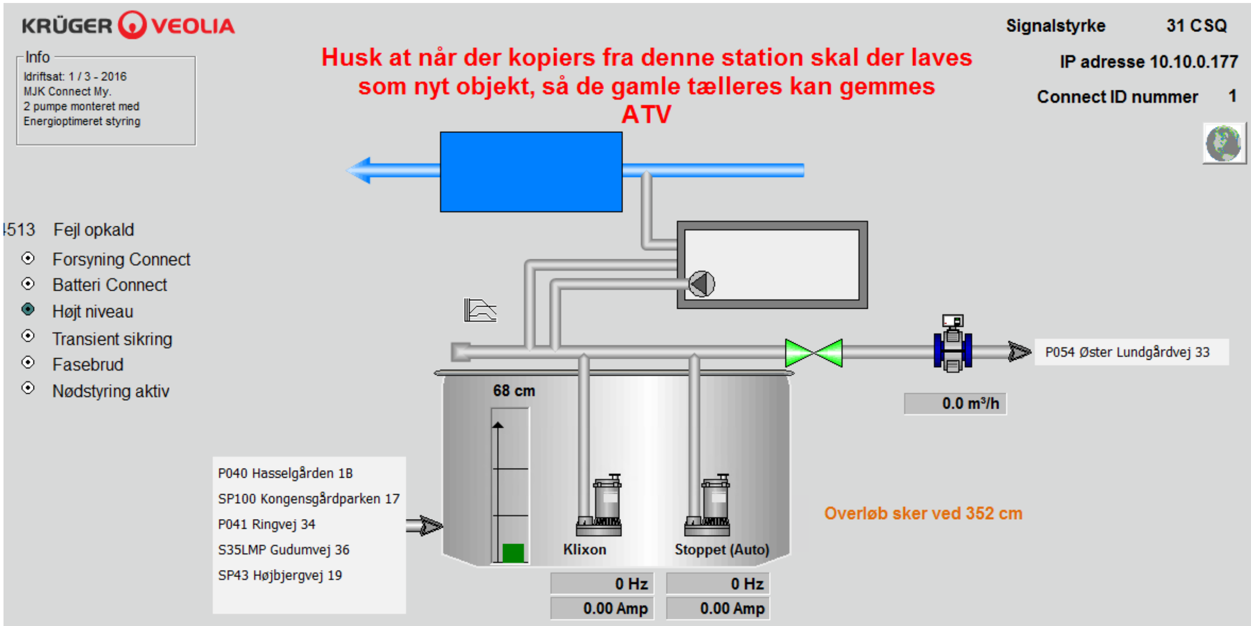

Figure 26. The capacity of the Nørre Nissum pump station. Figure adapted through an interview

As can be seen in Figure 27, the height of the diluted wastewater exceeds the capacity of the Nørre Nissum pump station and it reached 362 cm for approximately one month which caused sewage overflows.

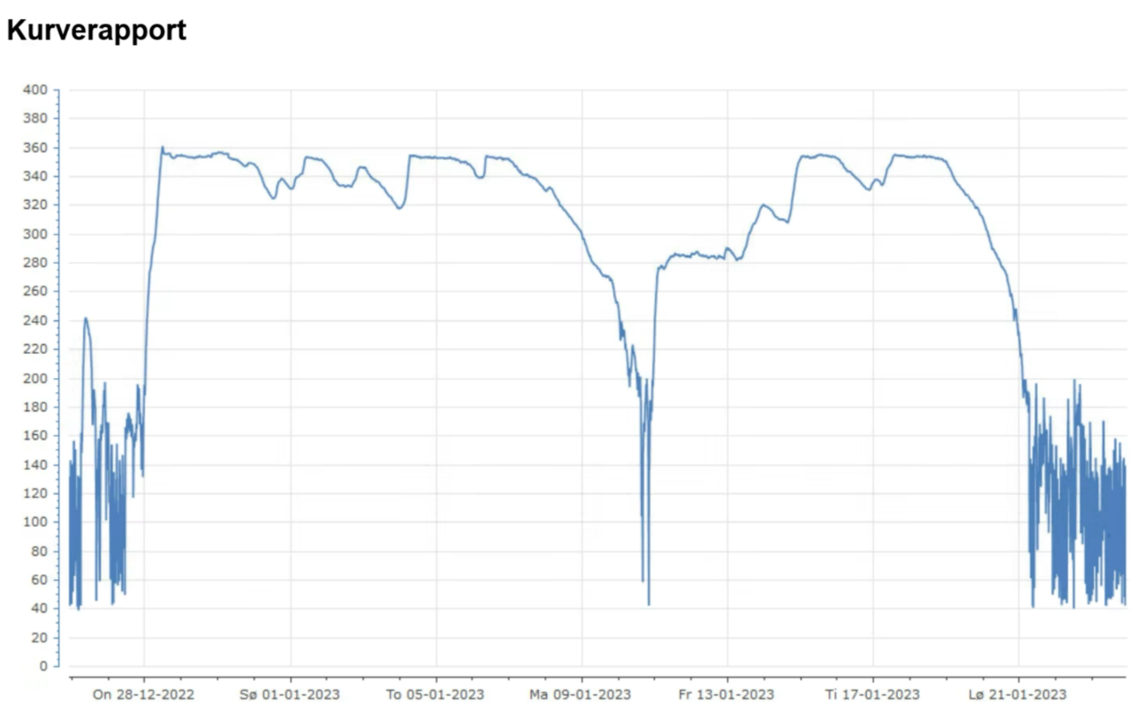

Figure 27. sewage overflows in the Nørre Nissum pump station. Figure adapted through an interviw

Appendix G

Figure 28 illustrates the total area of the lake located in the case area.

Figure 28. The total capacity of the lake. Figure adapted through an interview

Appendix H

Table 29, describes the implementation and maintenance costs of each measurement.

Table 29. The implementation and maintenance cost of the investigated measures

Measures	Implementation costs	Maintenance costs	Source
Sub-surface CW	60.000-100.000 DKK/ m3	2.500-5000 DKK/ m3/ year	(Slagelse kommune, 2017)

FWSCW	25.000 DKK-60.000 DKK/ m3	1000-5.000 DKK/ m3/ year	(Cross et al., 2021)
Willow treatment plants	44.000-80.000 DKK/ m3	1000-2000 DKK/m3/ year	(Cross et al., 2021; Slagelse kommune, 2017)

- *Annex*

Willow treatment plants

Negin Hosseinzadeh Gharajehnarlou
To 'post@ivarhaahr.dk'

Reply | Reply All | Forward

Mon 5/27/2024 12:59 PM

Hi,

I am a student at Aalborg University and for my thesis, I am working on designing willow treatment plants with zero discharge at rainfall-related outlets to purify diluted wastewater. I saw your website and I read the great work you do for the implementation of willow systems. I have some questions regarding the functionality of willows during summer and your experience in implementing them. Since you are an expert, I would really appreciate it if we have an online meeting or call to ask my questions. Your insight is meaningful for my project.

Thank you in advance for your precious time.

Best regards,
Negin Hosseinzadeh

Interview for thesis

Negin Hosseinzadeh Gharajehnarlou
To 'psg@pilerensing.dk'

Reply | Reply All | Forward

Fri 5/24/2024 1:58 PM

Dear Peder,

I am a student at Aalborg University and for my thesis, I am working on designing a big willow treatment plant that can handle 9000 m3 of mixed rainwater and wastewater per day with zero discharge. I got your contact information from a document regarding the establishment of willow systems in Faxe municipality. I have some questions regarding your experience in designing willow systems, and the functionality of these systems in the summer when there is not enough rain for willows to be grown. Do they still produce biomass during the summer when there is not enough rain?
Your input is essential for my project. I really appreciate it if we have an online meeting 😊
I am looking forward to hearing from you.

Best regards,
Negin Hosseinzadeh