Enhancing Climate Resiliency For Existing Buildings To Withstand and Live With Water

Study program:

Aalborg University – Department of Sustainability and Planning

Cities and Sustainability

Urban, Energy, and Environmental Planning

Project:

Internship project, Central Denmark Region

(Region Midtjylland)

Project duration:

September 2023 – January 2024

Author:

Negin Hosseinzadeh Gharajehnarlou

Supervisor:

Martin Lehmann

Simon Wyke

Anna Sofie Munk Bonven

Total pages:

65

End date:

12 January 2024

Abstract

This project examines how can build resiliency for the existing properties located in Lemvig town. In order to develop resiliency and minimize the effect of Climate Change (CC) on the building scale the types of floods and their depth have been projected in this report. Moreover, practical Climate Change Adaptation (CCA) measures by employing design criteria and assessing their transformability and adaptability are proposed. Such design ensures the robustness of CCA on a building scale to live with water. Additionally, a theoretical framework has been developed to help in understanding what defines a resilient measurement on a building scale.

AALBORG UNIVERSITET

Preface

This report is written during an internship in the 3rd semester of a master's program in Urban, Energy, and Environmental planning within the specialization of Cities and Sustainability at Aalborg University. The internship started in September 2023 and continued until December 2023 at the host organization Region Midtjylland located in Viborg. The project I was involved in as an intern was performed in a small Climate and Water (Klima og Vand) group as a part of RESIST project which is funded by the EU Mission Adaptation to Climate Change which aims to assist EU regions, cities, and local authorities in enhancing their resilience against the impacts of climate change.

The defined task was quite specific with a focus on finding solutions for the existing buildings in Lemvig town to be resilient against floods. Furthermore, before and during my internship at Region Midtjylland I attended some workshops including National Climate Meeting (Nationalt klimamøde) and climate adaptation and the coastal cities (klimatilpasning og kostbyerne) which helped me to boost my knowledge about the solutions that can be implemented in a building scale.

Acknowledgment

As a student, I have experienced different challenges in writing my first independent scientific report. However, several people helped me in this journey and in writing my scientific report and here I have this opportunity to appreciate their help. First, I want to thank my AAU supervisors Martin Lehman who helped me with the technical part of my report, and Simon Wyke for his suggestions and comments on my report. Second, my Region Midtjylland supervisor, Anna Sofie Munk Bonven, who helped me and guided me a lot through my internship journey and enrolled me in different workshops to gain new and fresh knowledge. Third, I want to thank Ask Raun and Torsten Sack-Nielsen from VIA University because of their guidance and their comments on my report. Finally, I want to thank my colleagues from Region Midtjylland for providing a nice and friendly working place for me and helping me to learn the Danish language.

Contents

I. *List of Figures*

II. *List of tables*

III. *List of abbreviations*

AR6: Six Assessment Report

CCA: Climate Change Adaptation

CC: Climate Change

COP: Code Of Practice

GHG: Green House Gass

GI: Green Infrastructure

IPCC: Intergovernmental Panel on Climate Change

NBS: Nature Based Solution

NFIP: National Flood Insurance Program

RCP: Representative Collective Pathway

PFR: Property Flood Resilience

SRQ: Sub-Research Question

SSP: Shared Socioeconomic Pathway

SLR: Sea Level Rise

1. Introduction

Cities are at risk of Climate Change (CC) with more extreme cases of Sea Level Rise (SLR), heavy participation, storm surges, and drought which can be exacerbated in urban environments, especially vulnerable areas (IPCC, 2022b). In the last decades, the globe has experienced the fastest increase in Greenhouse Gas (GHG) concentration in the atmosphere compared to the pre-industrial era. Human activities due to utilizing fossil fuel along with net land use change emissions caused an increase in the atmospheric concentrations of CO2, methane, and nitrous oxide (IPCC, 2013). These GHG concentrations have caused earth warming and CC which is affecting weather and climate extremes in many societies (Calvin et al., 2023). Not only is the earth getting warmer but also the mean SLR and heavy precipitation have been getting more frequent since 1950 (Calvin et al., 2023). The global mean SLR has faced a faster enhancement than any other century in the last 3000 years with a 0.20 (0.15 to 0.25) m between the period 1901 and 2018 (Calvin et al., 2023). The effect of CC is not uniform, different regions based on their geographical location will experience different events. Some will experience a rise in the sea level and storm surges, heavy precipitation, and an increase in flooding while in others drought and heat waves will occur (IPCC, 2022a).

2. Problem analysis

According to the United Nations Intergovernmental Panel on Climate Change (IPCC) Six Assessment Report (AR6), more than 3 billion people live in areas vulnerable to CC (Calvin *et al.*, 2023) and approximately more than half a billion people live in low-lying coastal areas that are less than 10 meters above sea level and it is expected to increase to more than one billion by 2050 (IPCC, 2019; McMichael *et al.*, 2020). The global population, ecosystems, and infrastructures that are located in coastal zones are threatened by future SLR (Colgan *et al.*, 2022)

Denmark is a coastal nation and is considered the second lowest-lying country in Europe (C2C, 2022). The height of the land and the sea level in Denmark is approximately less than 2 meters and even minor SLR in many places (C2C-CC, 2022). Additionally, relatively 17% of Danish population lives within 6 m of sea level that are threatened by floods from SLR (Colgan *et al.*, 2022)

In the last decades, Denmark has faced severe storm surges from the sea and Limfjorden in many cities like Lemvig town which caused damages to many properties, infrastructures and other habitants (DMI, 2018a). In Lemvig town numerous storm surges including Bodil in 2013 which led to rise the water level to 1.83 m above normal water level, Egon in 2015 that can be known as a violent storm surge which caused a rising sea level to 1.95 m above normal water level and evacuation in most of the areas in Lemvig town, and Urd in 2016 (Klimatorium, 2020). Additionally, due to an increase in temperature by approximately 1.5°C (DMI, 2023c) , Denmark has experienced heavy precipitation which led to flooding in properties located in the low-lying areas (DMI, 2018a) including Lemvig Municipality which faced heavy rainfall, and precipitation in the autumn 2019. Ivan Møller Sørensen head of Lemvig municipality's roads said "*I don't think we have ever experienced it this bad before. There is water in many fields, and the water stays on the road when it cannot drain away*"(Jesper Lundsgaard, 2019). This disaster occurred again in October 2023 which highlighted a potential risk of flooding along streams and lakes in the central part of Jutland (Anja Bodholdt, 2023).

It is inevitable that CC in Denmark will become more challenging. Denmark will experience warmer temperatures, heavy precipitation, and stronger winds which cause storms, and will continue to experience increase water pressure from all directions as a direct consequence of global CC (Danish board of technology, 2021). Based on (DMI, 2023a), Denmark will experience warmer weather in the future. Figure 1, illustrates the annual temperature in Denmark under scenario RCP 4.5 and RCP 8.5 for the period 2041-2070. As illustrated in the picture the expected change for the mid-century between 2041-2070 under a high emission scenario is 2°C and for RCP 4.5 the expected change is 1.5°C.

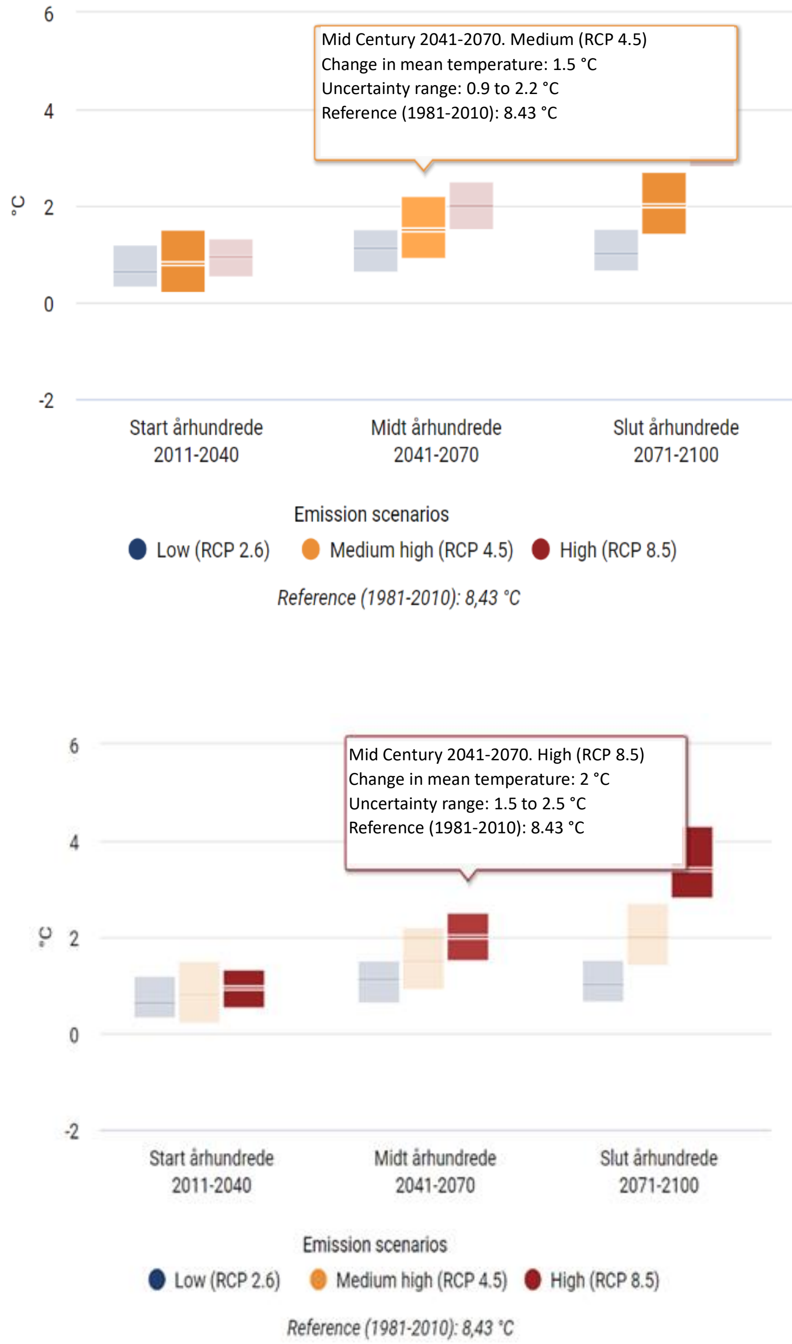


Figure 1. Changes in average temperature in Denmark under high and medium emission scenarios on reference period of 1981-2010. Source adopted from (DMI, 2023a)

Denmark has felt heavy precipitation and storm surges as the yearly average temperature has enhanced by 1.5 °C, the SLR enhanced 2 mm per year (Danish board of technology, 2021). The average annual precipitation has increased by approximately 100 mm over the past 100 years

(DMI, 2023c) and it is expected that the Central Jutland compared to Kattegat region experience more and heavier precipitation (DMI, 2023b). Figure 2, illustrates the annual precipitation from 1880 to 2020. Based on figure below it can be seen that the overall precipitation from historical to most recent years has been increased; therefore, it is expected that in the future Denmark experience, severe precipitation.

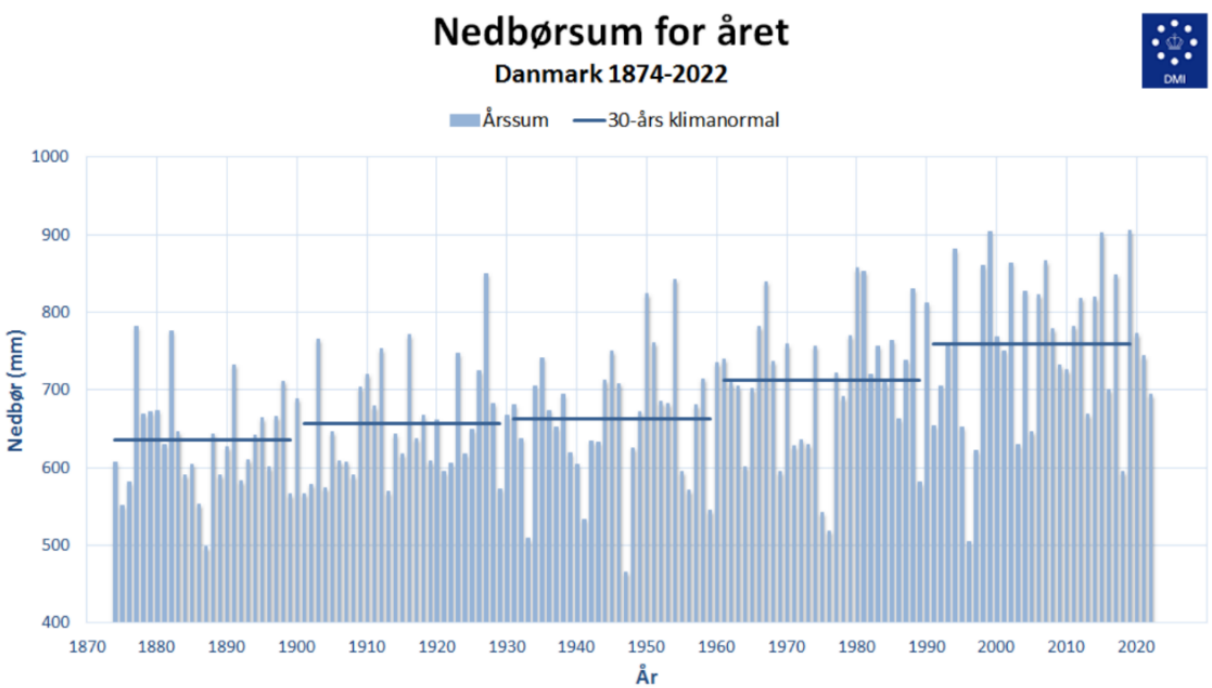


Figure 2. Illustration of annual precipitation over the past 100 years. The blue line is a normal climate indicator per 30 years. Source adopted from (Klimatilpasning, 2023)

The sea level around Denmark has been rising since the first measurement has been made and the rise has been higher than average in recent years. It is projected that the change in water level will increase with approximately between 24 cm and 28 cm towards the mid-century under medium and high emission scenarios Figure 3 (Klimatilpasning, 2023) and it poses a threat to the cities located near the water to experience flooding.

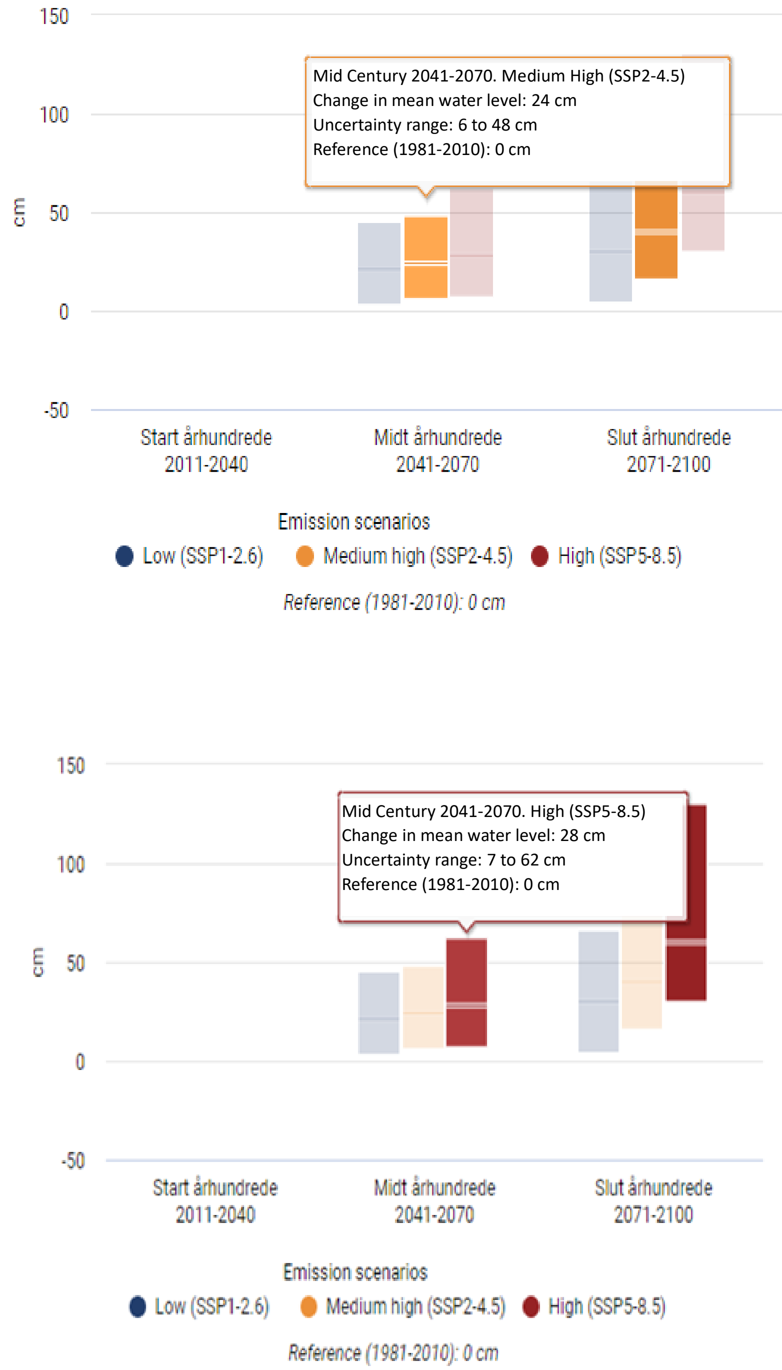


Figure 3. Changes in SLR in Denmark under high and medium emission scenarios based on the reference period of 1981-2010 (Source: adapted from (DMI, 2023a)

By enhancing the effects of CC like heavy precipitation, and storm surges (C2C-CC, 2022), researchers and professionals have begun to concentrate on increasing resiliency in communities by bringing resilience approaches in spatial planning (Doberstein, Fitzgibbons and Mitchell, 2019). Climate strategies are different depending on the area including:

- Protect: Is an approach which secures the land with engineering construction to keep the water away from properties, infrastructures, and critical facilities
- Accommodate: Is a strategy which allows communities to use the flood prone areas by constructing houses or improving buildings materials which can withstand being flooded.
- Retreat: Is a strategy to relocate properties and infrastructures to safer areas
- Avoid: Is an attitude to identify flood-prone areas to prevent new development in those areas. Figure 4, illustrates the flood resilience approaches.

(Doberstein, Fitzgibbons and Mitchell, 2019)

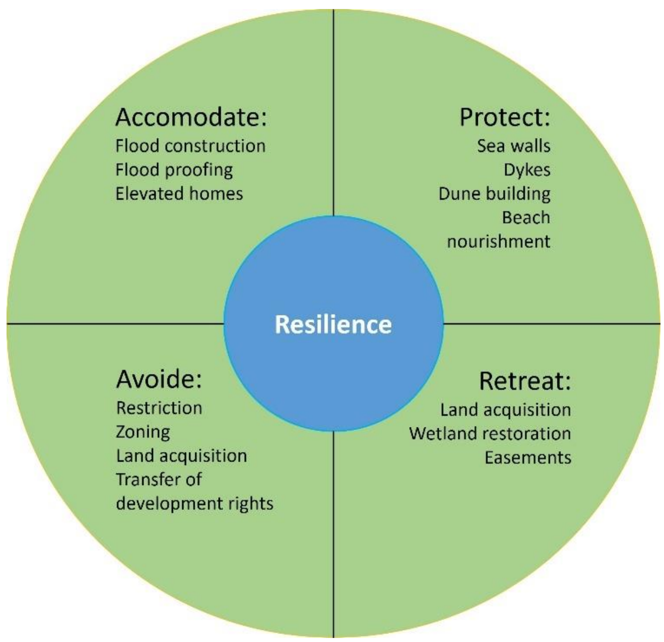


Figure 4. The flood resiliency approach based on PARA framework. Source: adapted from (Doberstein, Fitzgibbons and Mitchell, 2019)

In Denmark almost 1,800 km of 8,750 km coastlines are protected by protection strategy (Faragò *et al.*, 2018). The coastal protection measures including hard technical installation (dikes, sluice, and groins) and soft solutions (terps and sand nourishment) developed in 19th century after the impactful storm surge that happened in 1872 in the southern part of Denmark and caused extreme rising sea level in much of the cities.(Faragò *et al.*, 2018).

Most recent coastal Climate Change Adaptation (CCA) is also following the historical adaptation intervention which is the use of hard technical solutions to minimize the consequences of SLR with one exception that is related to the tendency of utilizing these adaptation by facilitating multi-functionality like multifunctional floodwall at Lemvig town (Faragò et al., 2018).

2.1 The consequences of protection strategy

There are consequences of only using protection strategy, one could argue that, the Danish coasts will be affected by frequent and stronger storm surges in the future which leads to increase coastal erosion and decreasing in safety of low-lying areas (John Jensen and Søren Bjerre Knudsen, 2008). During the storm surges more inland areas, even coasts that are not directly exposed to onshore winds can be affected by storm surges, this is because the water level gets high enough to penetrate far inland. Some areas that are located below sea level are protected by coastal protection, however, if the water level gets high enough the land behind the protection will be flooded immediately which causes severe damages to properties and may require evacuation for the entire area (Lemvig Kommune, 2023a).

In the Lemvig municipality, storm surges will affect to a greater extent as several areas are low-lying on coastal stretches including Lemvig town (Lemvig Kommune, 2023a). As mentioned before, in the town of Lemvig, severe storm surges occurred from the Limfjord (Lemvig Kommune, 2021). Therefore, a protection system, a high-water wall 'Le Mur' with an elevation of 2.1 - 2.4 m along the harbor has been erected to protect the area against storm surges. However, it is estimated that the 100-year storm surge event in 2070 will raise the fjord water which will penetrate to the land behind the water wall and potentially affect properties, infrastructures, and many more (Lemvig Kommune, 2022b).

Another issue of protection strategy is that they have a negative impact on the natural dynamic and cause effect on the landscape and biodiversity. Hard solutions are undoubtedly known as well-organized way to minimize the consequences of floods and storm surges; however, these solutions may often negatively influence the land and restrict the opportunities for multifunctional values (Dansk Regioner, 2021).

3. Problem formulation

As described in the previous section climate is rapidly changing and each society experiences different CC like SLR, storm surge events, heavy precipitation, and drought. Denmark is threatened by heavy precipitation which caused water accumulation in low-lying areas and storm surges. In Denmark, it is common to establish buildings and infrastructures in the harbor areas. Considering the uncertainty in CC it can be argued that following implementation of a protection strategy as CCA is not an ideal and proper solution. This could have consequences for cities in Denmark that are threatened by storm surges and heavy precipitation. Potentially can create harmful and severe issues, especially in coupled events combining heavy precipitation and storm surges. Dealing with these hazards requires thinking of a new and holistic approach like 'accommodation' strategy. There is a high demand to transform adaptations for the building scale located in high-prone areas to flooding to improve their resiliency to live and withstand floods. This internship project, therefore, investigates how to use the accommodate approach as a CCA for improving climate resiliency for existing buildings. Therefore, this project seeks to investigate the following main research question:

How can minimize the consequences of climate change in a building scale located in a high-risk flood-prone area in order to increase their resiliency and live with water?

3.1 Sub-Research Questions

In order to answer the main research question the following Sub-Research Questions (SRQ) have been formulated:

- **What is the meaning of flood resiliency in relation to building scale?**

  Resilience has many definitions. Most definitions address transformative adaptation in the landscape and city scale. The flood resilience on the building scale means constructing a property in a way that lives with water instead of against it. To investigate resiliency according to this project, I would argue that it is necessary first to understand what the meaning of resiliency is and how this can be connected to the building scale which is addressed in the theoretical framework.

- **How can high risk areas of flooding be identified?**

- **Which adaptations are more suitable for existing buildings?**

The following second sub-RQ will help to identify the types of flooding, and the depth of flood based on actual data and addresses which area is the most high-prone area to flooding based on land use map data. These considerations when designing resilience strategy for properties are important and will help to answer the third sub-RQ. This will provide solution strategies for existing houses to withstand climate hazards.

3.2 Research design

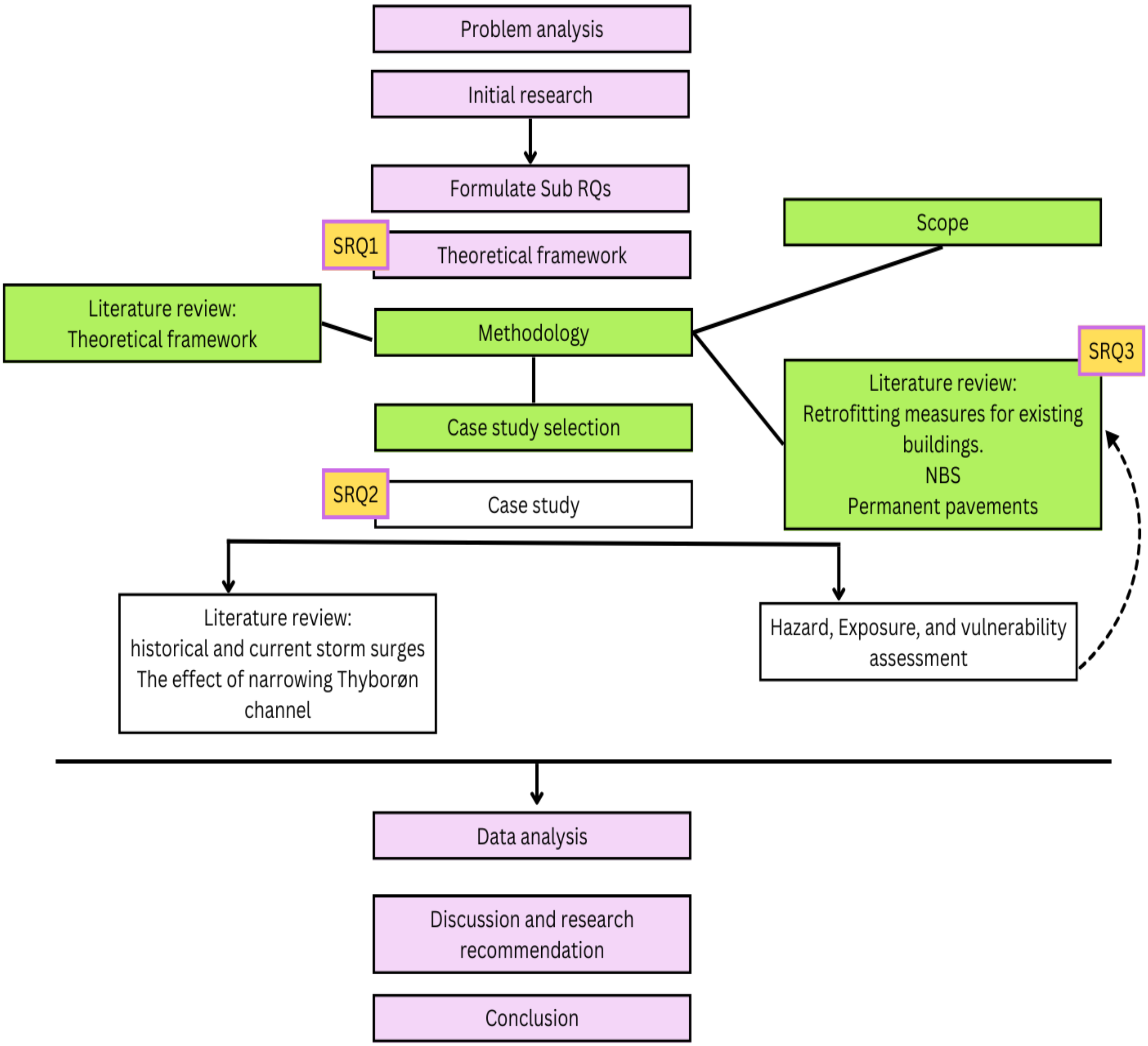


Figure 5. Illustration of research design

4. Theoretical and conceptual framework

This chapter will introduce the theoretical and conceptual framework on which the report is based. As described in chapter one climate is changing rapidly, and due to disasters, many properties got damaged. Therefore, there is a need to provide resiliency for houses which are the basic need for living. This section consists of frameworks which describes the concept of climate resilience in general and then deep into property flood resilience. Finally, will describe the co-benefits of CCA.

4.1 The concept of building climate resilience

The concept of resilience has gained attention among different literature on cities and CC and has a linkage between social and ecological systems. Although there are different definitions of resilience, however, there is a common concept that transforming cities into resilient hubs capable of withstand of shocks and stresses in order to be prepared for CC impacts (Leichenko, 2011). According to Hegger resilience is a widely discussed concept, therefore, in this project it is chosen to evaluate the concept through two major capacities:

- Capacity to absorb and recover
- Capacity to transform and adapt

(Hegger et al., 2016)

4.1.1 Capacity to absorb and recover

Capacity to absorb and recover can be defined as the ability of flood-prone areas that can absorb climate disturbances without shifting into serious damages. This notion of resiliency is referring to 'the ability of a social or ecological system to absorb disturbances while returning the same basic structure and ways of functioning, the capacity of self-organization, and the capacity to adapt to stress and change' (Tyler and Moench, 2012). According to this definition a resilient property is characterized by its ability to absorb, recover, and accommodate climate shocks to minimize the consequences of disturbances.

4.1.2 Capacity to transform and adapt

This notion refers to the importance of dealing with complexity and uncertainty regarding rapid global CC. The ability of social ecological system to adapt to stresses and shocks refers to the long-term and CC uncertainties. Therefore, there is a need for a robust adaptation strategy to deal with shocks and stresses in the long term. CC is one of the stresses that cities face and climate shocks refers to the disturbances like extreme weather events, storm surges, and SLR (Hegger et al., 2016). Transformability refers to the opportunities which cause changes and promote innovative solutions. The transformational adaptation argues that the traditional CCA alone are not sufficient to manage future hazardous. Therefore, a transformational adaptation is "adaptation that changes the fundamental attributes of a system in response to climate and its effects" (IPCC, 2014a).

4.2 Operationalize planning for building climate resilience

As described before, building climate resilient requires measurement that absorb climate shocks and have the capacity to transform and deal with climate future. This section describes the concept of property flood resilience and design approaches which help to design appropriate solutions based on some criteria.

4.2.1 The concept of property flood resilience

Property Flood Resilience (PFR) is an important and new concept in managing and minimizing the consequences of floods to people, businesses, and households and help in speeding the recovery after the flooding. In addition, it is important to know this concept is useful for areas where it is not practical to be protected by structural flood defenses or where there is a requirement to increase resiliency for properties where the existing defenses and hard technical solutions like Lemvig water wall is not sufficient (Kelly, D *et al.*, 2021b). Additionally, the PFR can be implemented in different circumstances including retrofit of measures as a safeguard before flooding and repairing of flood damages in properties after flooding (Kelly, D *et al.*, 2021b).

Since it is important to know which measurements are more appropriate and standard for the high-risk properties the PFR code of practice is mentioned. The aim of Code of Practice (COP) is to provide standards for the measurements to be well implemented. There are three phases that need to be considered including:

- Design phase
- Construction phase
- Operation phase

Each of the phases has their unique process or stages to deliver the standard output. However, In the scope of this project the main focus is to analyze the hazardous and propose solutions for the existing houses in Lemvig to make them resilient to floods. Therefore, there is a need to deep into stages of first phase "Design" including hazard assessment, property survey, options development and design table 1 (Kelly, D *et al.*, 2021b)

Table 1. The stages of design phase.

Stage	Action and outcomes
Hazard assessment	• Flood maps and climate forecasting information • History of flood in the specific area • Nature of flood in the location (depth and frequency) • Personal experience of residents, communities etc.

Property survey	• Survey of potential areas for improvement
Options development and design This stage has two parts: - The first part is based on hazard assessment and range of PFR options. - The selected options need to be designed and ready for construction.	• Operational performance • Cost and benefits • Performance and ability of property individuals. • Degree of resilience of each options delivers relative to other options.

(Adopted from (Kelly, D *et al.*, 2021b))

Limitation: The COP just applies for individual houses, public, commercial, and industrial properties and does not cover the use of social flood plan or sustainable drainage system (Kelly, D *et al.*, 2021b)

4.2.2 Design approaches

This chapter discusses the various factors that demand consideration when crafting solutions for buildings located in flood-prone areas. A comprehensive grasp of flood characteristic, coupled with insights into anticipated flood levels, enables designers to shape a strategic approach for proposing effective adaptation measures that minimize the impact of floods on buildings (Bowker, Escarameia and Tagg, 2007). The first stage in the design strategy is to determine the type of flood which is described in section 6. The third step is to determine practical measures that cover both resistance and resilience approaches will be worthwhile options for existing buildings to withstand storm surges. Further detail will be investigated to understand the difference between resilience and resistance approaches:

- Resistance measures: The aim of this measurement is to prevent floodwater entering into the residential part of the buildings with a primary objective of minimizing direct flood damage to structures and affording occupants additional time to relocate ground floor contents. These measures prove most effective for short duration and low depth flooding. (Bowker, Escarameia and Tagg, 2007)

- Resilience measures: They can either be an integral part of the building structure or interior features. These elements can be considered in combination with resistance measures or employed in situation where resistance measures are not an option (Bowker, Escarameia and Tagg, 2007).

As described before the 'accommodation' strategy centers on formulating solutions for constructing buildings that can withstand the impact of flooding. Therefore, to avoid damage to the properties there are various approaches linked to the accommodation strategy that can be implemented at the building scale and are basically categorized into three strategies including, avoid, water exclusion, and water entering (Proverbs and Lamond, 2017; Doberstein, Fitzgibbons and Mitchell, 2019). Avoidance can be achieved through landscaping, retention features, and also can be achieved in the building by elevating the building itself through rising on pillars, extend foundation walls, or extend the property walls (Proverbs and Lamond, 2017). Water exclusion is known as resistance and dry-flood proof measure and the aim of this measurement is to prevent the inflow of water into the building. Water entry approach is known as resilience measure and accepting the water in a way to use some methods to minimize the damage when the water inflow into the buildings (Proverbs and Lamond, 2017).

In order to decide which measure would be an appropriate option it is necessary to understand the potential depth of flood which is described in section 6.1.4 and 6.1.5. Moreover, to streamline the development of a straightforward design strategy, table 2 describes the guidance regarding resistance and resilience measures applies to flood depth outside of buildings. Additionally, it is necessary to consider that the moisture in capillary wall structures can rise up to 0.3 m above the actual flood level. Hence, the protection should be approximately 0.3 m above water level projected (Klara Geywitz, 2022)

Table 2. Overall guidance for design strategy

Guidance for design strategy	
Water depth	**Approach**
Water depth from 0.3 to 1 m	Keep the flood water out (water exclusion strategy including dry-flood proofing). When the flood water rise above 1 m depth it is not recommended to use this strategy, because the pressure of water can cause damages on building's structures.
Water depth above 1 m	Allow water to enter the property to avoid risk of structural damages. (water entry strategy)

Source: Adopted from (Garvin, Reid and Scott, 2005; Bowker, Escarameia and Tagg, 2007)

4.3 Co-benefits of CCA

CCA can be defined as adapting to both current and anticipated CC impacts, with the goal of minimizing detrimental effects on human, natural, and urban system, while simultaneously fostering additional benefits (IPCC, 2014b). As mentioned before, Denmark is facing with challenges of storm surges and heavy precipitation. Floods are known as a hazard and as a notion of transform and adaptive which refer to the implementation of adaptation measures to both prevent flooding while simultaneously providing benefits and opportunities there is a need to integration of adaptation that have benefits. As a result, co-benefits need to take into account to establish sufficient decision making for selecting the most appropriate solutions (Choi, Berry and Smith, 2021). The following section will present environment, health, and economic co-benefits of CCA.

Environment co-benefits Health co-benefits Economic co-benefits

Visualization of co-benefits of CCA (my own observation)

Environmental co-benefits

CCA will provide multiple environmental co-benefits depending on the characteristic of the different measures. Many CCA will reduce the effect of CC namely heavy precipitation and SLR. Introducing CCA which adds green elements can enhance resiliency to the buildings and help combat climate disturbances like floods while adding more value. The presence of green spaces and increasing vegetation will infiltrate the pollutions of run of storm water and also act as noise reduction (Hewitt, Ashworth and MacKenzie, 2020). Additionally, Green Infrastructures (GI) will contribute in reducing stormwater runoff in many locations that threatened from heavy precipitation while reducing urban heat island and also improve biodiversity (Choi, Berry and Smith, 2021).

Health co-benefits

Another benefit of adding green elements to CCA is that this strategy will influence on physical health like reducing respiratory illness since, this will restrict the growing of molds in the property (Venkataramanan *et al.*, 2019) and will effect on mental health by reducing the stresses among citizens of being flooded during heavy events. This will have both immediate and long-term positive influence on public health (Cheng and Berry, 2013) and have significantly economic payoff which will be described in further detail. It should be noted that since this project is not focusing on GHG emissions and its effect on human health, therefore, the benefits of GI on reducing CO2 has not been mentioned.

Economical co-benefits

An economic co-benefit of utilizing CCA in the building scale is the potential to increase the property value and it will increase house sale price. Additionally, CCA plays a pivotal role in minimizing the damage caused by floods to properties, thereby safeguarding their long-term financial viability (Venkataramanan *et al.*, 2019)

5. Methodology

This section will explain the scope of the project and the case selection. Finally, describe which methods have been used to collect empirical knowledge and conduct analyses aims to answer the sub-research questions.

5.1 Scope

In this report the focus is on providing climate resilience for existing buildings to be resilient against the impact of storm surges from the Limfjord and heavy precipitation. The scope is limited to the specific area of interest in Lemvig town. Therefore, the climate hazards including storm surges and the changes in precipitation rates and vulnerability mapping are limited to case selection. This report concentrates on how aspects of different design approaches align with the concept of resilience and whether they can provide co-benefits can be implemented in the building scale. Therefore, solutions that are related to minimizing the consequences of storm surges and heavy precipitation in the building scale are proposed. The intention of this report is not to calculate the potential reduction in rainwater runoff and flood consequences through specific measurements. Rater, its aim is to describe and illustrate the essential consideration and methodologies vital for comprehending appropriateness of different measures and how they can be implemented.

Limitation

As mentioned in the concept of property flood resilience in the theoretical section, property survey is one of the stages of design phase. It is important to understand the owner's desires for implementing different solutions. However, due to the scope of the project and timing this is not considered in this report.

5.2 Case selection

This report aims to address the main research question by assessing a specific location. The case study is a method that is commonly used across different fields of research. The utility of case studies is a subject of considerable debate among academic scholars. On the one hand, Case study opponents argue that cases are biased, challenging to summarize, and lacking in generalizability. In contrast, Flyvbjerg argues that such claims are common misunderstanding, and the case studies hold great relevance for scientific purpose (Flyvbjerg, 2006).

The Resist project which is funded by the EU Mission Adaptation to CC concentrates on supporting EU regions, locals, and cities that have the aim of implementing CC resilient. Central Denmark is one of the other European countries that will work on improving resiliency. The noted city is Lemvig where is threatened by floods from heavy precipitation and Limfjord even after establishing the multifunctional water wall 'Le-Mur'. Therefore, this section tries to find the case at high risk of flooding based on some criteria.

5.2.1 Case study selection process

Lemvig is a small municipality on the west coast, in the Midtjylland region of Denmark. The municipality has a negative population growth and more 15% of the residents are aged over 65 years (Lemvig Kommune, 2022a). The Lemvig town is located in North Jutland between Limfjord and Lemvig Lake and has a population of 6,978. Lemvig has always been at risk of water accumulation caused by heavy precipitation and storm surge events from the Limfjord. The most recent research shows that the future sea level will rise and penetrate into the city and effects most of properties (Lemvig Kommune, 2023a). Therefore, to narrow down the case area further, a vulnerable location was chosen. This was done according to different criteria.

The first criterion is the location with less elevation which is most vulnerable to storm surges and heavy precipitation. As shown in Figure 6 the low-elevation land with an elevation of less than 2.50 m in Lemvig town will experience flooding.

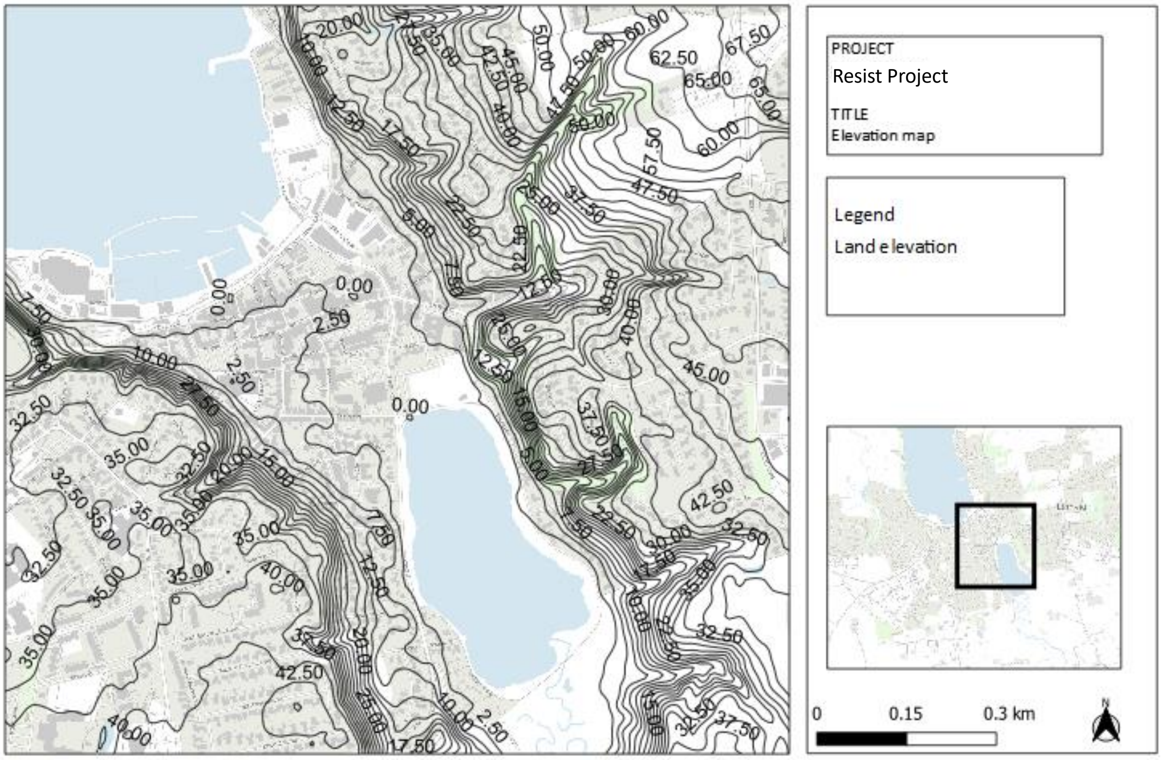


Figure 6. Identified the elevation of the area (Source: (KAMP, 2023)

Lastly, it was a choice to conduct the analysis on the small location because of the scope of the project which covers both residential houses and business properties where floods potentially impacts on residential daily lives and contains two kinds of buildings including property with and without basement which will be describe in detail in section 6.2. Figure 7, illustrates the local plane of Lemvig harbor.

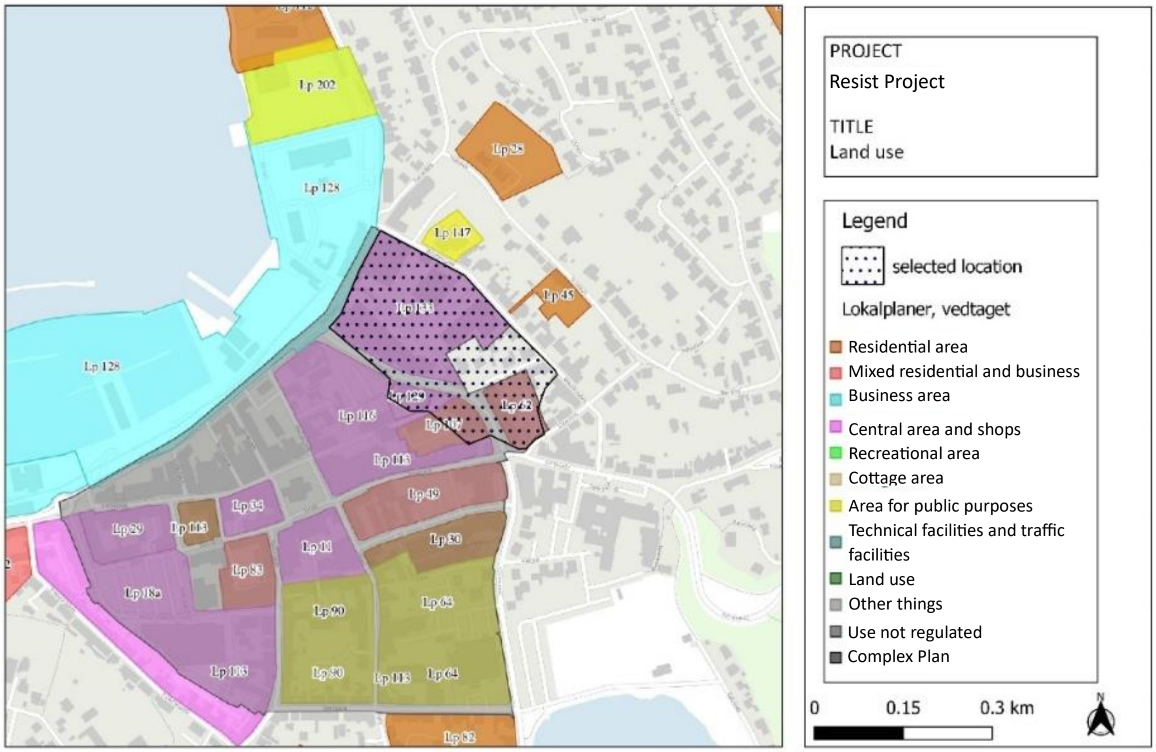


Figure 7. Identified the land use (Source: (KAMP, 2023)

5.3 Methods

This section will describe the methods used in other to answer the sub-research questions. The mixed-method, combination of qualitative and quantitative method have been used in this project to strengthen the validity of the research (Cronholm and Hjalmarsson, 2011). A mixed-method was employed because of its capacity to handle a broader and more complete range of research questions since the research is not limited to a single research approach (Cronholm and Hjalmarsson, 2011).

The first and the third research questions have been answered by literature review. The second sub-research question has been answered by quantitative method which is hazard, exposure, and vulnerability assessment.

5.3.1 Literature review

The literature review has been used to collect qualitative data from literature and also this method provides a comprehensive overview of literature including journal article and scientific reports related to a theme, theory, or method (Paul and Criado, 2020). The literature review for collecting qualitative data was done in two ways: First the academic and scientific articles were used to form the problem analysis and research questions. Published and peer-reviewed articles are included in forming the basis of theoretical framework to build a robust foundation for developing a comprehensive understanding of the concept of resilience in relation to building scale. Second, the grey literature including reports which focused on the existing guidance and information in the UK was used and addresses the ways and approaches to limit the effect of flooding on buildings. Finally, both academic and grey literature used to find the most appropriate solutions which increase the resiliency of the buildings to withstand flooding.

Initially the research was carried out using databases on journals, academic articles, and books. The amount of literature focusing on measures to reduce the impact of flooding on existing buildings compared to the new properties was quite limited. Most of them highlighted flood warning information. To further limit the search the FEMA and CIRIA guidance which have accurate information have been used.

To calculate accurate and most recent data about CC in Denmark all the scientific articles that were limited to the year from 2021-2023 were used. Moreover, the data about the current situation of storm surges in Lemvig Havn were limited to 2022 since the resent data (2023) could not be found. The literature review was conducted from various platforms including ResearchGate, Google, and Google Scholar. The research in this project is performed with search of keywords in the research engines to identify the most relevant and resent document accessible. The keywords including:

> Run off, resilience, vulnerability, exposed population to SLR, storm water management, raingarden, CC, green infrastructure, green roof, climate resilience, flood resilience, permanent pavement, retrofit, CCA cost-benefits, resilient construction, CCA environmental-benefits, CCA health-benefits, reducing flood losses.

The research was mostly concentrated on finding documents, reports, papers, and articles containing relevant keywords. Moreover, the references list of the selected literature was also another way to find relevant information. To enhance the efficiency of the review process between multiple sources their abstract, and conclusion were skimmed to find the most essential literature.

5.3.2 Assessment of hazard, exposure, and vulnerability

In chapter 6 the second sub-research question is answered through analysis of the current and future climate hazardous of the case area. Data utilized to understand the hazardous of CC in the case area is collected from multiple sources including, Klimaatlas a Danish online website which contains data for temperature, precipitation, water level and storm surges in expected future by considering scenario RCP 8.5 in the Limfjord at Lemvig coastline. Klimatilpasningsplan for Lemvig Municipality is used to have a deep understanding of their plan for Thyborøn channel which will have direct impact on the result of storm surges in the case area. Moreover, Scalgo live, an online digital tool is used to simulate and visualize the future condition of flooding events in the case area and assessing the depth of water on the surface which helps in answering the third sub-research question. HIP, an open web-based user which provides a free public data for hydrological information, modeling the calculation and forecast the future climate adaptation, water management, and planning (HIP, 2023) has been used for understanding the future changes in groundwater level to the terrain. A special resolution of 100 m grid under high emission scenario (RCP8.5), for the seasonal variation of summer and winter for period of 2041-2070 has been downloaded from Dataforsyningen (Dataforsyningen, 2023).This data is showcased and visualize in QGIS. Moreover, KAMP (Klimatilpasning) an online screening tool is used for understanding the current seasonal situation of groundwater level near the terrain in the selected area.

Data related to analysis the exposure is collected from KAMP (klimkatilpasning) which is a screening tool that provides data, calculation, and projections related to water impacts (KAMP, 2023). This tool is used to understand the type of communities and properties exposed to storm surge. Finally, data related to vulnerability has been collected from Coastal Planner (WebGIS) to understand the financial damages of 100 year-storm surges on properties and infrastructures in Lemvig town.

6. Analysis

This section will determine the hazardous including the types of flooding and their impacts on Lemvig town.

6.1 Hazard assessment

The first stage for the design phase is hazard assessment. Determining the types of flooding and their characteristics which will impact the properties are important (Bowker, Escarameia and Tagg, 2007). This section will present the storm surges from the Limfjord and heavy precipitation, and the depth of water above surface. Moreover, an estimation about the groundwater level in the selected area will be described in further detail. These measurements are important which help in determining the appropriate and effective solutions for susceptible properties to climate hazardous.

6.1.1 Flood maps

The weather is changing and as described in the introduction the main cause of changing climate is the concentration of GHG emissions in the atmosphere. The IPCC bases its work on emission scenarios including IPCCs fifth assessment report called Representative Collection Pathways (RCP) and sixth assessment report uses a new scenario called Shared Socioeconomic Pathways (SSP). In the Klimaatlas the atmospheric indicators has shown by RCPs and ocean indicators are based on SSPs (DMI, 2023b). The scenario RCP has been used in this project because this scenario is also used in Lemvig municipality klimatilpasningsplan (Lemvig Kommune, 2023a).

These four RCP scenarios including:

- RCP 2.6: This scenario is an ambitious scenario which describes what it will take to decrease global temperature to 2 degrees Celsius.

- RCP 4.5 and RCP 6.9: Are scenarios that global emissions are decreased and the effect on climate is maintained at the end of the century.

- RCP 8.5: High emission scenario with increasing emission

(DMI, 2018b)

Based on DMI recommendation RCP 4.5 scenario is used until 2050 and RCP 8.5 scenario is used beyond 2050 (DMI, 2018b). Additionally, (Klara Geywitz, 2022) argues that the design water level for properties is the highest elevation of water above ground that has one percent chance to occur during the given year. Therefore, analyzing the effect of 100-year storm surges for 2070 under scenario RCP 8.5 will be investigated in further detail. In this project the focus is on the effect of storm surges from the Limfjord and heavy precipitation for the mid-century to propose solutions for the existing houses to withstand flooding.

All the numbers presented are relevant for the Limfjord for Lemvig harbor. Therefore, the other parts of Denmark will experience different changes.

6.1.2 Historical and current storm surges

The historical examples of storm surges in Lemvig town have caused major floods. Based on (Kystdirektoratet, 2019) numerous storm surges happened in past which three of them are more famous including Bodil. Egon, and Urd. The water level is these three storm surges are shown in table 3.

Table 3. The storm surge events in the past

Date	Water level
December 2013	The water level increased to 183 cm above normal water level (the storm Bodil).
December 2016	The water level reached to 177 cm above normal water level and caused damages to materials (the storm Urd).
January 2015	The water level enhanced to 195 cm above normal water level as result of strong storm surge which caused 142 residents of Lemvig evacuate their properties. It was a 100-year storm surge events (the storm Egon)

Source: adopted from (Klimatorium, 2020)

Based on the information above it can be concluded that Lemvig town has been always threatened by storm surges from Limfjord. However, during the storm surge Bodil that the water raised to 183 cm above normal water level, the sea water wall 'Le-Mur' that has been stablished with elevation of 2.1 m and 2.4 m along the harbor (Lemvig Kommune, 2023b) protected the Lemvig town. Lis Ravn Sørensen says that "*during the storm Bodil there was no water in the streets because of the high-water wall. However, during storm Egon, back water came in north of the high-water wall, where a water tube was installed to limit the penetration, but flood water came into a few streets in the north-west part of the city*". Additionally, during the storm Malik that happened in 2022 several hundred meters of Lemvig town experienced flooding. Due to a misunderstanding the gates in the high-water wall were left open and the water penetrated into Havnegade (Lis Ravn Sørensen. 2023). Figure 8, illustrates the ingress of water during the storm surge Malik into the streets. Therefore, it can be concluded that the Lemvig high-water wall itself is not sufficient to protect Lemvig town from storm surges.

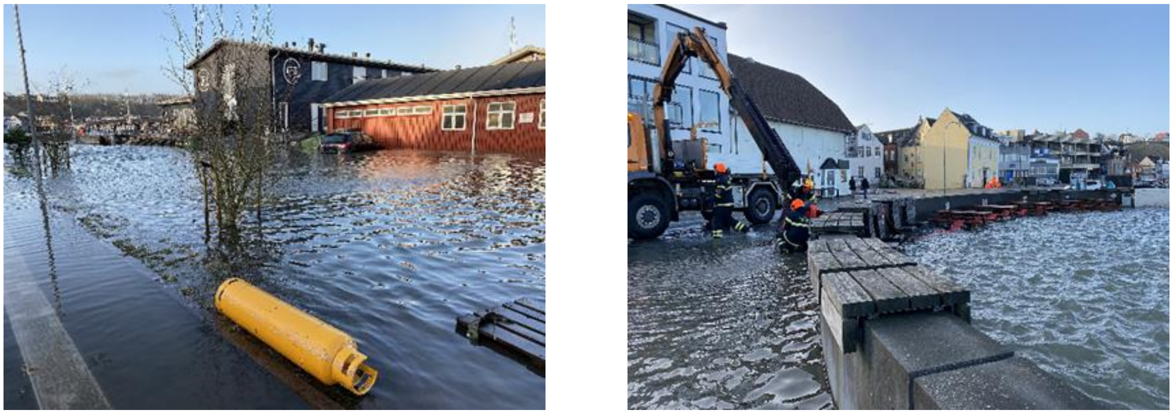


Figure 8. illustrates the penetration of water into the streets. Source adopted from (Martin Sodemann, 2022). Photo: Nielsen Bentsen

6.1.3 The effect of current storm surges

The current storm surges based on (Rambøll, 2022) indicates a projected storm surge height of 1.77 m for the 50-year return period and 1.85 m for the 100-year return period. A high-water wall with an elevation range of 2.1 m to 2.4 m along the harbor has been erected to secure the city. However, in the western part of the coast behind the industrial buildings the water can inflow into the area at a high-water level of 1.7 m. Moreover, behind the Klimatorium there is a possibility of ingress flood water at a high-water level of 1.75 m and penetrates to the city towards Lemvig Lake. Figure 9 illustrates the effect of 1.75 m water level on the surface. As can be seen this water level will impact some parts of the city that is located in the low-lying area and will experience flooding from the Limfjord.

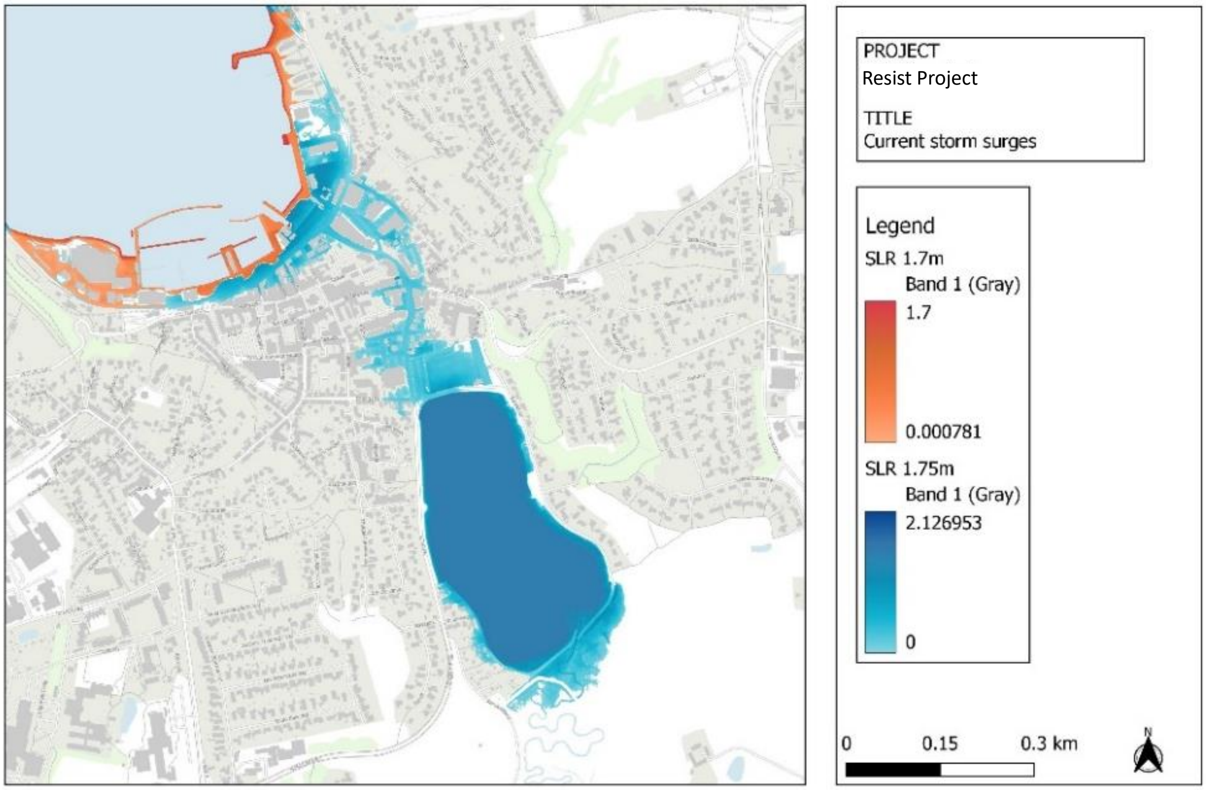


Figure 9. Projected water level. Data adopted from:(Scalgo Live, 2023)

6.1.4 The effect of 100-year storm surge event 2070

As mentioned before, Lemvig town has always been threatened by storm surges from the Limfjord. It is projected that in the future Lemvig town will experience severe storm surges which will cause damages to infrastructures, buildings, and people's well-being. During a 100-year storm surge event for the reference period 1981-210 the mean water level in Limfjorden has been raised up to 197 cm and the median change for the water level is 63 cm. Therefore, a 100-year storm surge in the 2070 under scenario RCP 8.5 will cause SLR up to 260 cm and the water will penetrate the land behind the Le-Mur (DMI, 2023a). According to (Lemvig Kommune, 2023a) by narrowing Thyborøn channel to 250 m the expected storm surge will decrease to 2.28 m which still cause the area be flooded and potentially affect 1.1 km of road and threatened many properties. Figure 10, illustrates the projected water level of 260 cm and 228 cm to show their differences.

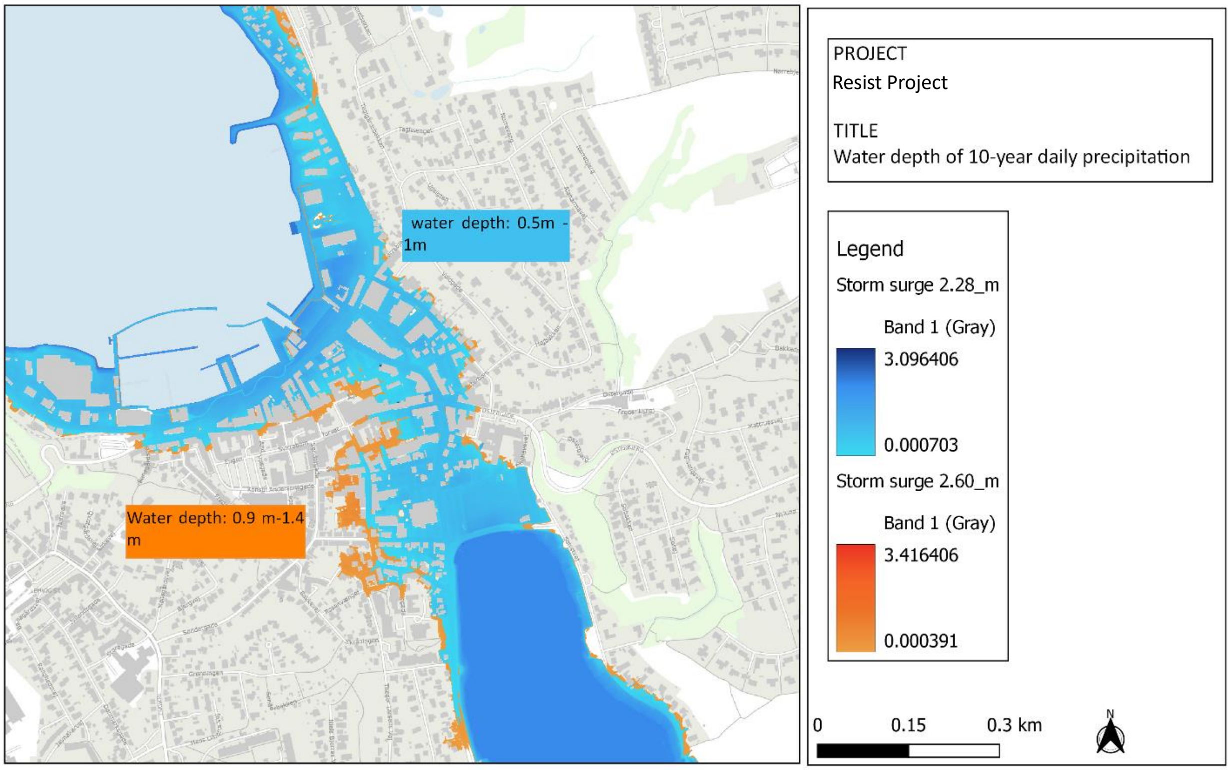


Figure 10. The projected water level of 260 cm and 228 cm (Scalgo Live, 2023)

As can be seen in the figure above, a storm surge with a water level of 2.60 m will have potentially severe consequences compared to 2.28 m. The water depth for the storm surge of 2.60 m is between 0.9 – 1.4 m. However, since Lemvig municipality has a plan to narrow the Thyborøn channel to 250 m width which can effect in future storm surge events of Lemvig municipality especially Lemvig town (Lemvig Kommune, 2023a) the effect of storm surges after narrowing Thyborøn channel will be investigated. Figure 11 will illustrate the effect of a 2.28 m storm surge on Lemvig town.

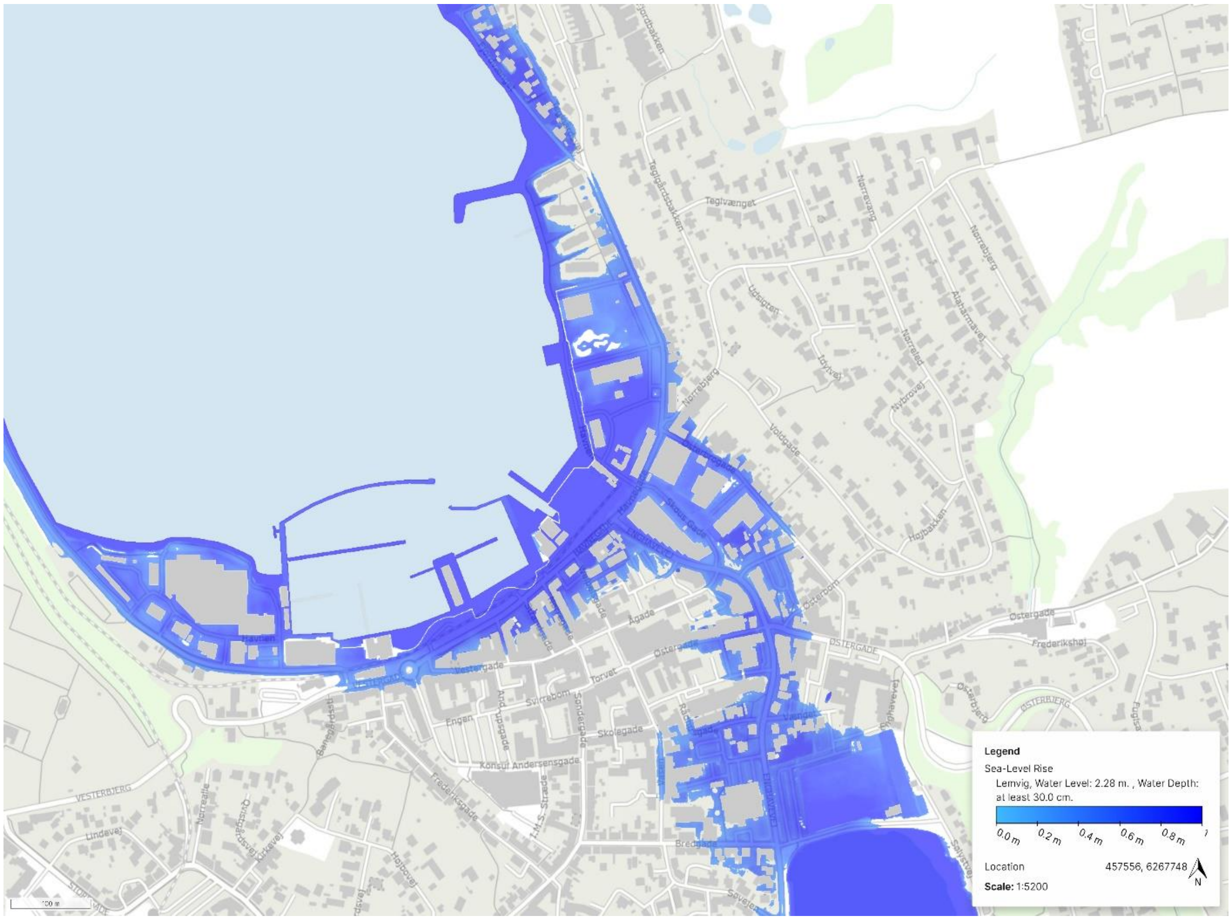


Figure 11. The projected water level including 250 m narrowing (Scalgo Live, 2023)

The depth of water in the selected area after narrowing Thyborøn channel will significantly decrease which will directly impact in designing solutions for the properties which are described in section 7. As can be seen in Figure 12, the blue line illustrates the depth of water on the surface which is approximately between 0.5 m to 1 m.

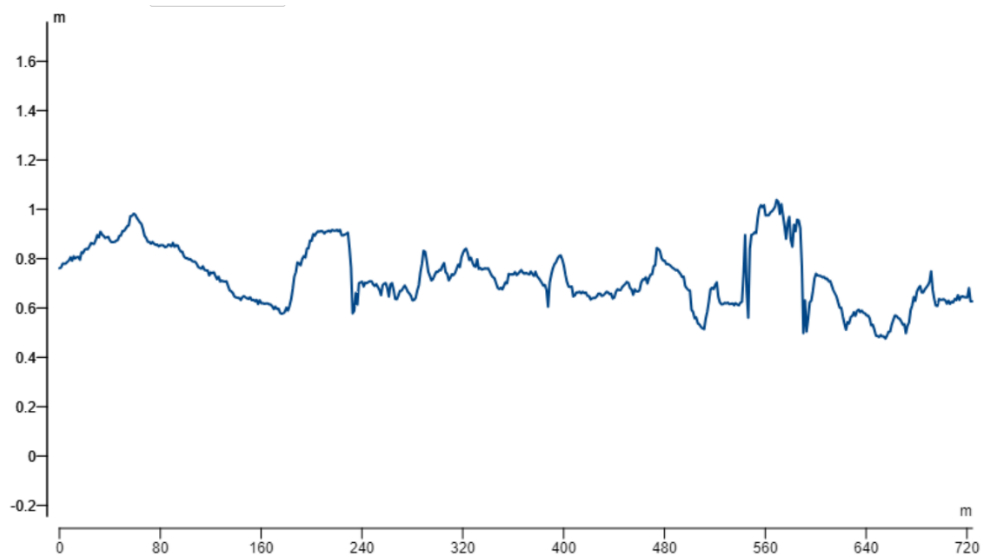


Figure 12. The projected water depth on the surface (Scalgo Live, 2023)

6.1.5 The effect of future daily precipitation

It is expected that future cloudburst events will occur more frequently. The dimensions of pipes in Lemvig Municiplaity are dimensioned according to 5-year return period. Therefore, in the future cloudburst events, which will happen more often than every five years, the pipes are not dimensioned to manage the immense volume of rainwater in such a short period. Consequently, excess rainwater is likely to overflow onto the surface, leading to flooding in low-lying areas (Lemvig Kommune, 2023a). This will cause an overflow of wastewater, and the lake on the ground, basements and houses located in the low-laying areas (Lemvig Kommune, 2023a). Laurits Bernitt says that “buildings with basement are facing flooding during heavy precipitation”.

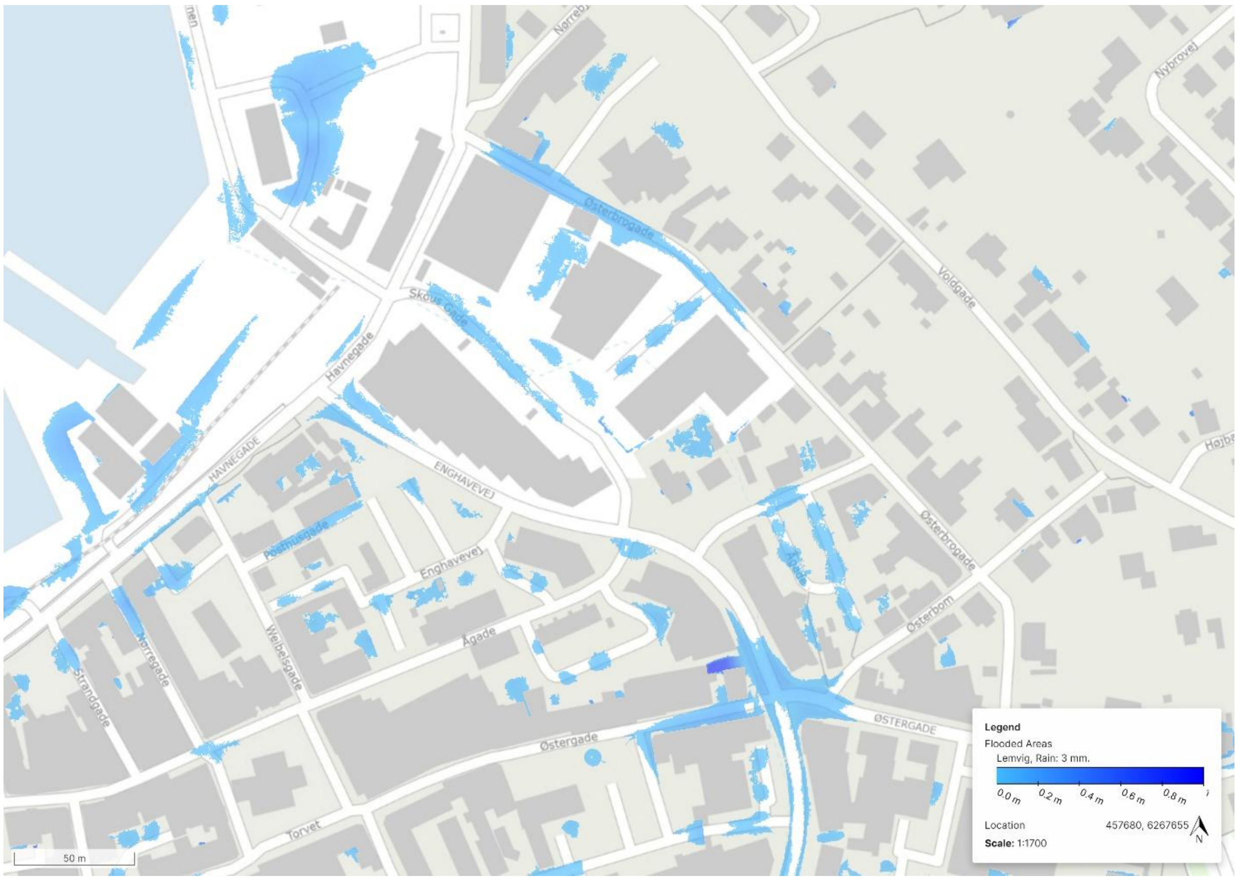
The estimation of current extreme precipitation event corresponds to 51 mm per day is a 5-year event for the period of 2011-2040 (DMI, 2023a). The future precipitation events are expected to enhance as can be seen in table 4. This enhancement will cause flooding in the case area. The effect of 100-daily precipitation is shown in Appendix A.

Table 4. The projected precipitation events under RCP8.5

Daily precipitation events	Reference (1981-2010)	Mid-century (2041-2070)
2-year daily precipitation	40.9mm/day	44mm/day
5-year daily precipitation	50.4mm/day	54mm/day
10-year daily precipitation	58.2mm/day	63mm/day

Source: adopted from (DMI, 2023a)

As mentioned before, the Lemvig municipality sewage systems can handle 24 mm/hour and 51 mm/day (DMI, 2023a). Therefore, in this analysis 51 mm is subtracted from Scalgo simulation. Figure13 will illustrate how a 5 and 10-year daily precipitation will impact the case area and cause floods.



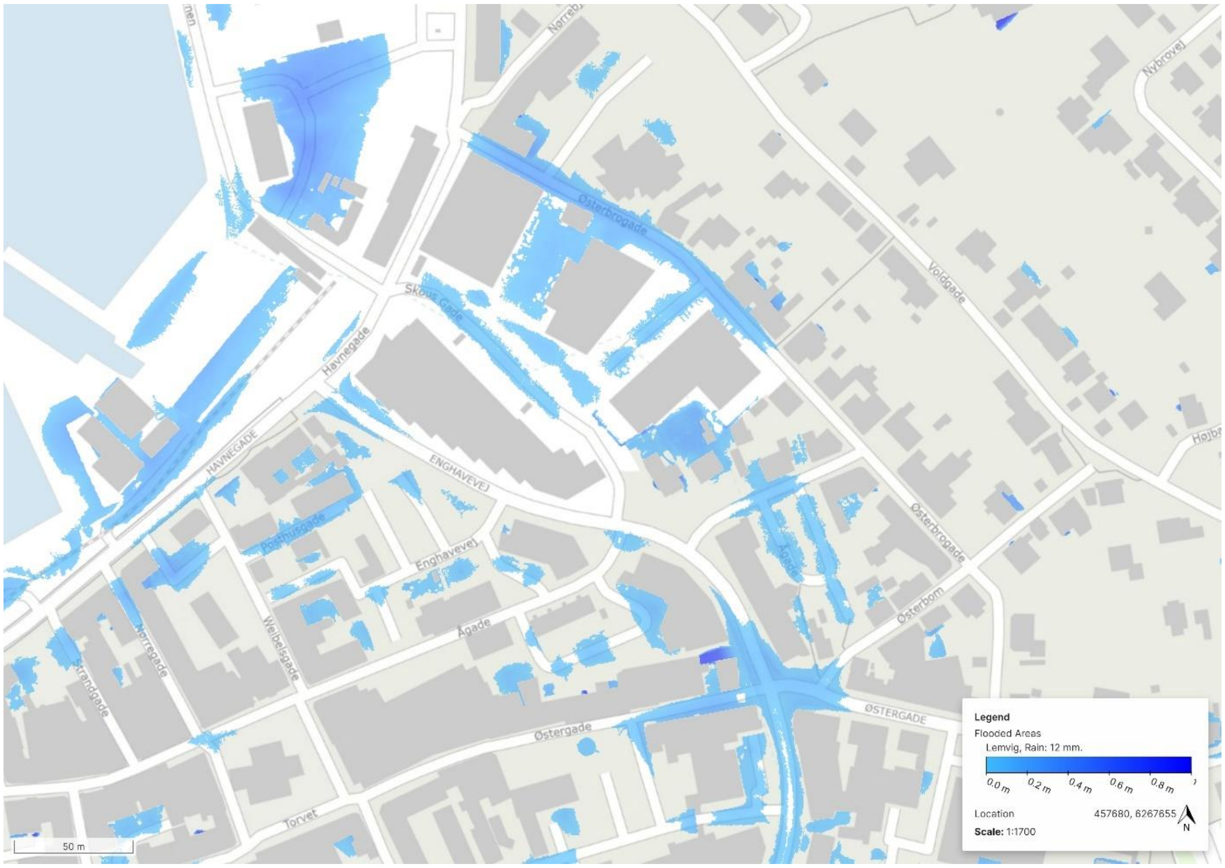


Figure 13. the projected precipitation by subtracting 51mm rainfall. The upper picture is 5-year daily precipitation, and the lower picture is 10-year daily precipitation. Own illustration at (Scalgo Live, 2023)

As can be seen in figure above, the 5-year daily precipitation for the mid-century will not significantly impact the properties, however, the impact of 10-year daily precipitation is significantly obvious, and it will cause flooding in most parts of selected area. To understand the detail of floods Figure 14, illustrates the depth and volume of 5-year daily precipitation in the selected area, highlighting that some areas due to depression on land will experience flooding. However, this water accumulation is not excessively intense, with the maximum water depth observed at only 12 cm.

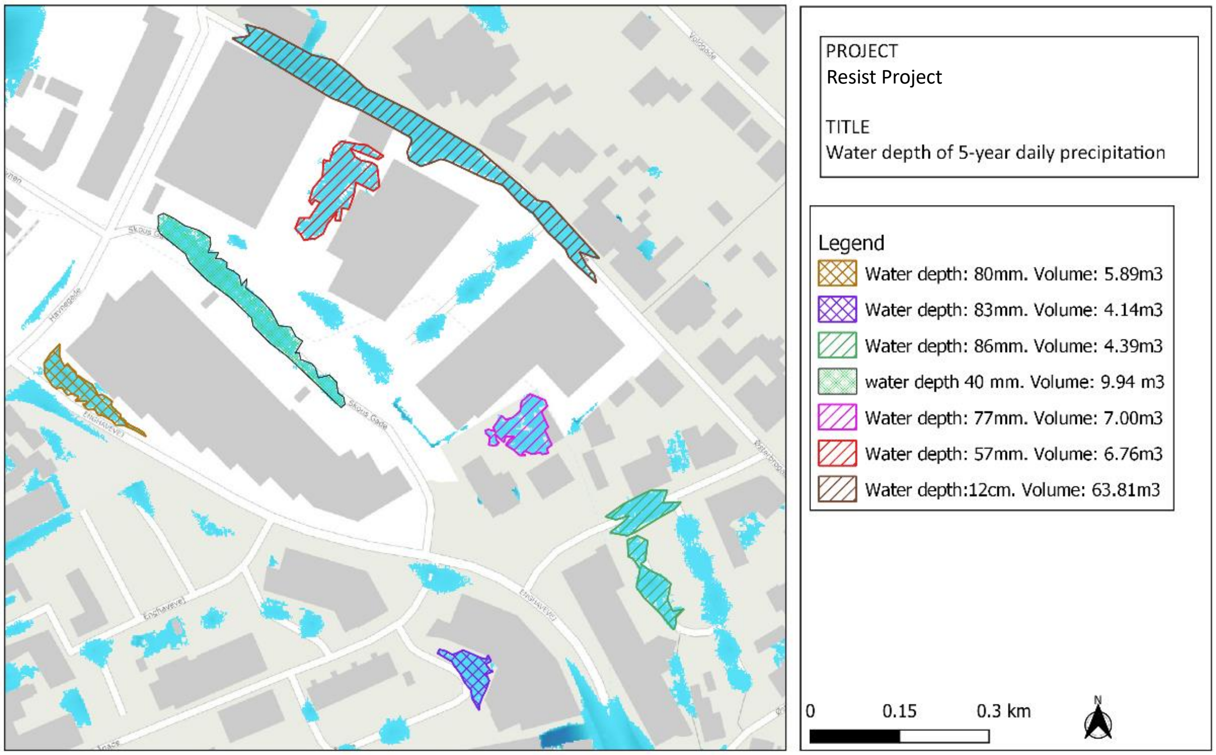


Figure 14. the projected water depth and volume of rainfall for 5-year daily precipitation

Figure 15, illustrates the depth and volume of 10-year daily precipitation in the selected location. As can be seen the water accumulation is significantly higher than 5-year daily precipitation, and most of the areas will experience floods. The depth of water in some areas is less than 1 cm, but the other locations will experience water depth of more than 12 cm.

Figure 15. the projected water depth and volume of rainfall for 10-year daily precipitation

6.1.6 Groundwater

CC in Lemvig town is expected to increase the precipitation. Observing historical, current and future groundwater will help in understanding how groundwater is affected by precipitation especially in summer and winter (C2C CC, 2015). Therefore, two maps of groundwater for the current situation, one for winter and one for summer, are illustrated in figures 16 and 17. Significant variations in groundwater levels between summer and winter are evident in the selected area. In summer most of the properties located in the selected area experiencing groundwater level between 0.5 to 2 m near the surface. Conversely, in winter these properties will experience groundwater level closer to 0-1 meter near the surface. This shift indicates an increased vulnerability to high groundwater levels during winter, posing a heightened threat to the effected properties.

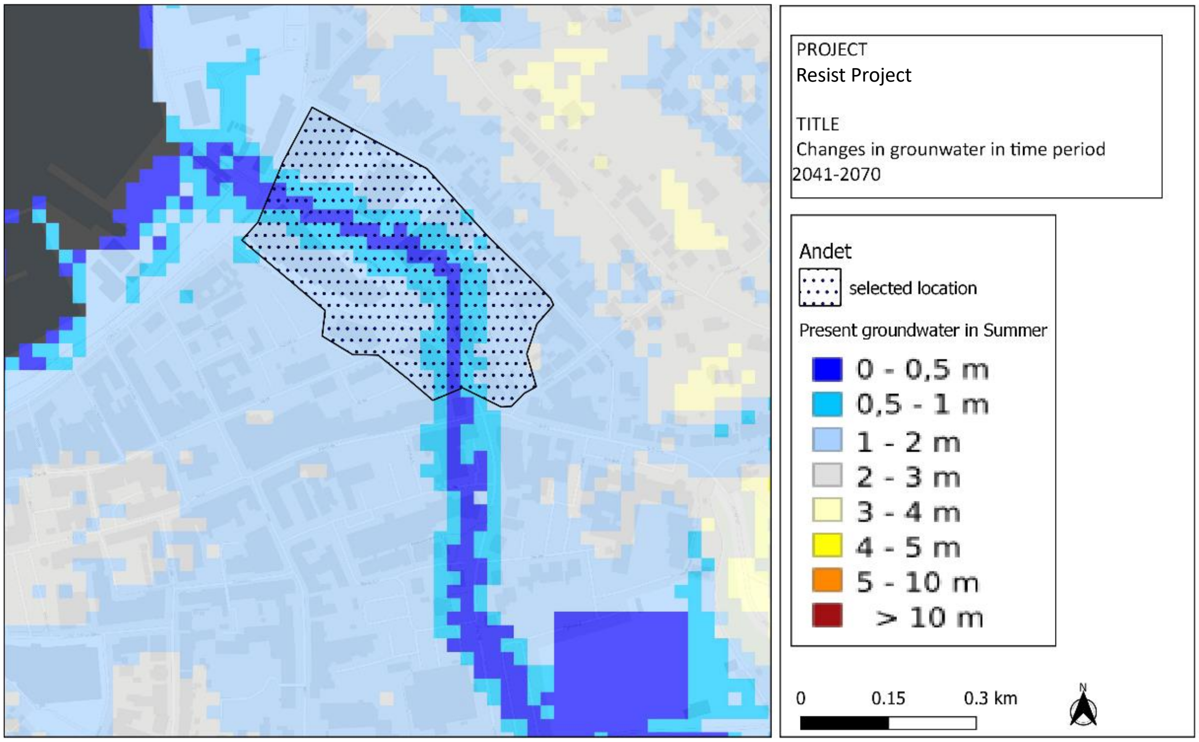


Figure 16. the projected groundwater in summer for Lemvig town with reference period of 1990-2019. Source adopted from (KAMP, 2023)

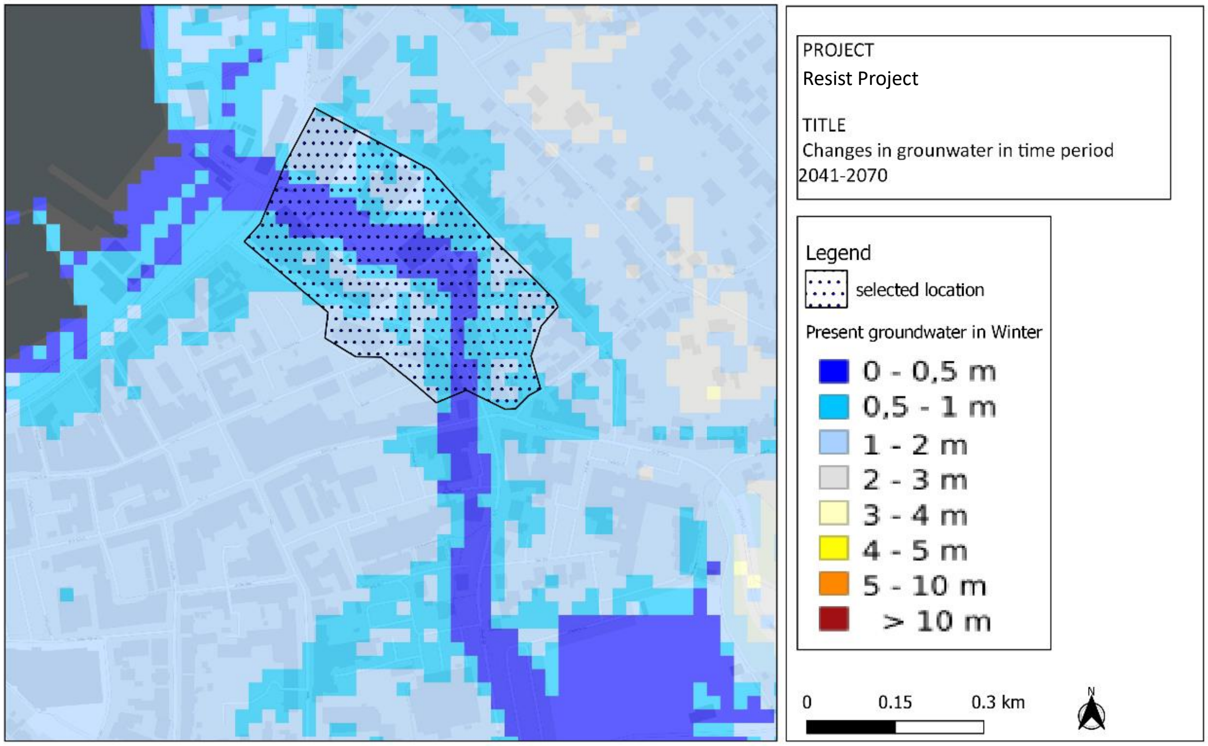


Figure 17. the projected groundwater in winter for Lemvig town for reference period of 1990-2019. Source adopted from (KAMP, 2023)

The future scenario for RCP 8.5, shown in Figure 18 and 19, it can be concluded that in summer most of the properties in the selected area compared to the current situation will experience a -0.10 m decrease in the groundwater level or will not experience any changes (0 m) for the period of 2041-2070. In contrast, in winter the selected area will see a 0.10 m increase in groundwater level. Meaning that, in the mid-term the groundwater situation in winter season will be more challenging.

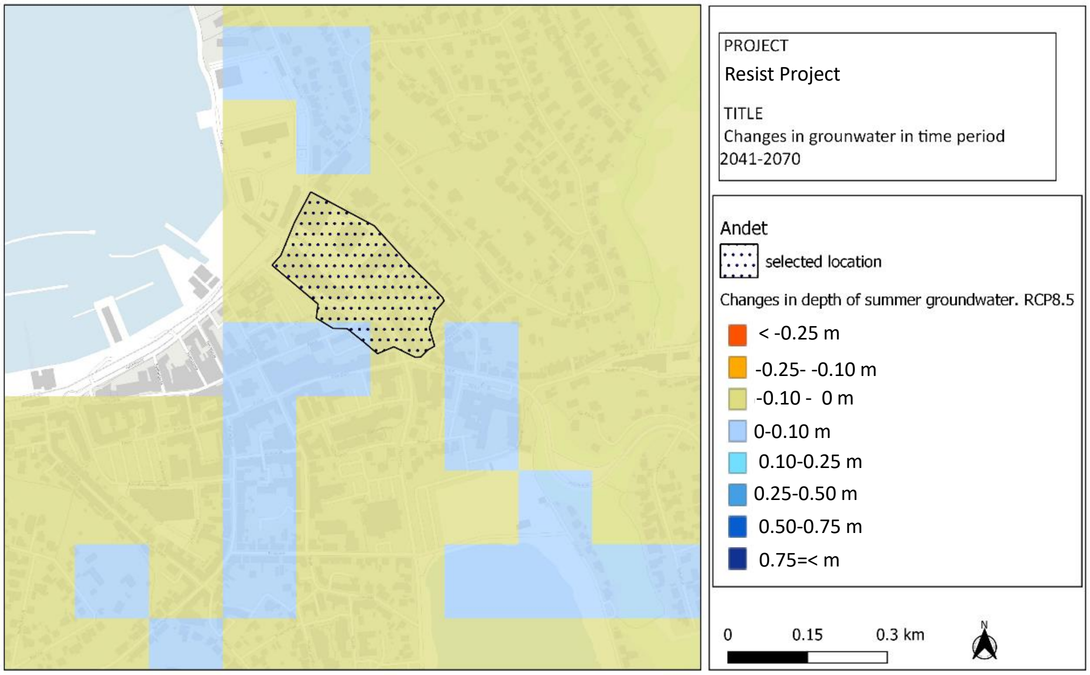


Figure 18. The projected changes in groundwater level in summer for Lemvig town under scenario RCP8.5. Source adopted from (Dataforsyningen, 2023)

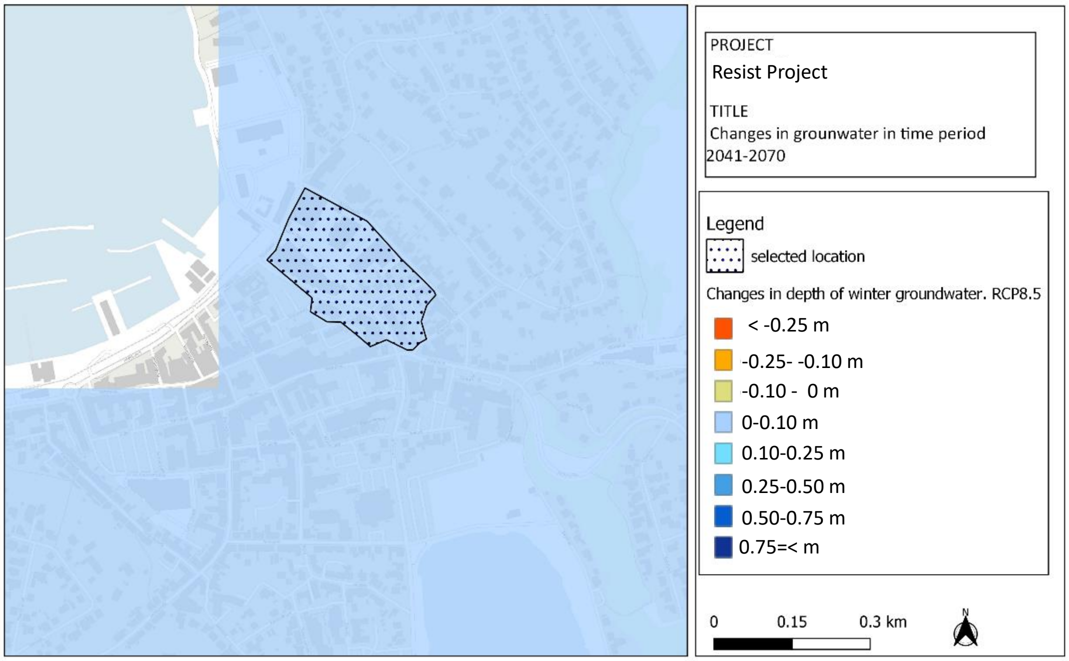


Figure 19. The projected changes in groundwater level in winter for Lemvig town under scenario RCP8.5. Source adopted from (Dataforsyningen, 2023)

6.2 Exposure

This section will describe the future exposure in the case area. Based on definition "who or what is likely to be impacted by hazards" (Lehmann *et al.*, 2021) and the aim of the project which is providing solutions for existing houses to withstand climate hazardous, this section will analyze the proportion of buildings effected by storm surges.

As described in section 6.1.4, the water level for 2070 will enhance to the point that the water wall with the height of 2.1 m and 2.4 m cannot protect the city and storm surge will affect properties. Moreover, heavy precipitation will cause accumulation of water, as a result areas that are located in the depression will experience flooding. It is projected that the 100-year storm surge will potentially impact on 126 buildings in the city of Lemvig (Lemvig Kommune, 2023b). To narrow down to the case area potentially 18 buildings, 11 buildings without basement and 7 buildings with basement are in danger of flooding (KAMP, 2023). Additionally, this will inadvertently impact the mental well-being and daily lives of local residents, subjecting them to stress. Figure 20, illustrates the types of buildings that are at risk of floods.

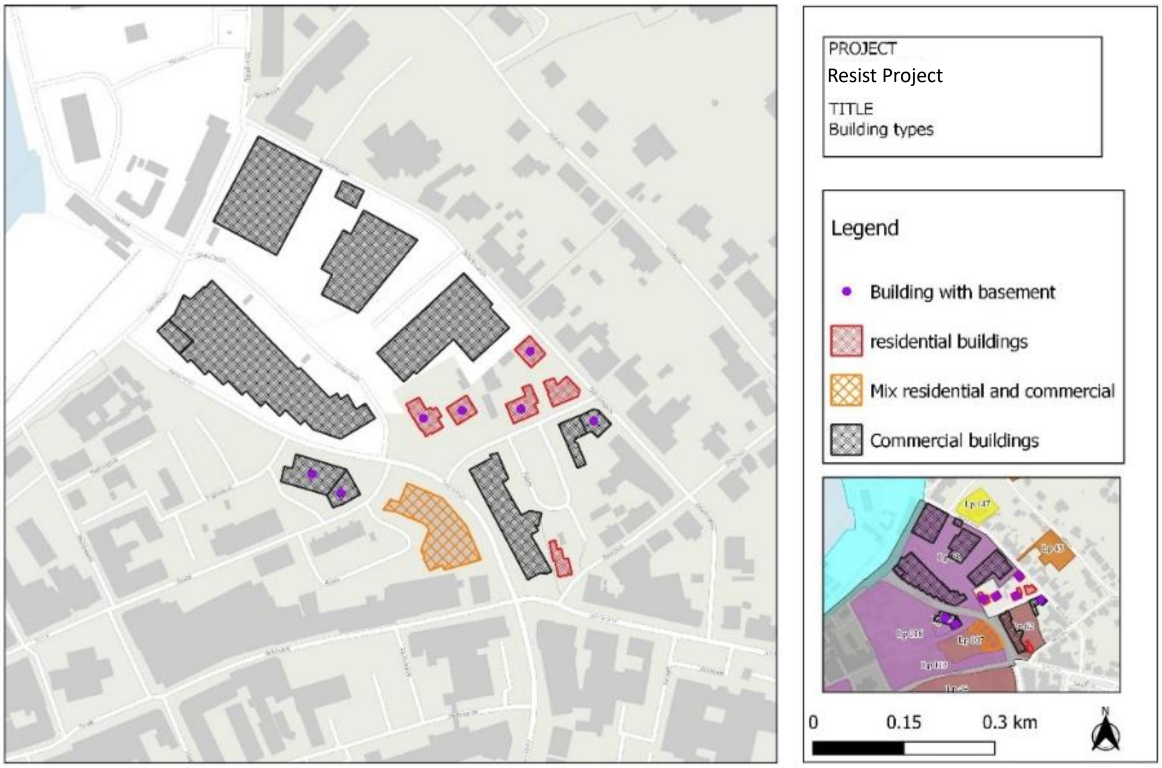


Figure 20. The projected buildings that will be affected by 100-year storm surges (Source: adopted from (KAMP, 2023)

6.3 Vulnerability

This section describes the vulnerability in the case area. Vulnerability has different definitions and is employed in many contexts. However, in the context of this project it refers to propensity of exposed elements like human well-being and their livelihoods to be diversly affected by hazard events (Jörn Birkmann *et al.*, 2012; IPCC, 2014a). Vulnerability is directly related to the concept of CC and describes the low capacity of the resistance of engineering structures to cope with and adopt to CC (Jörn Birkmann *et al.*, 2012). The future CC like storm surges will create a loss of economic value in Lemvig town. A 100-year storm surge event in 2070 will potentially damage many properties and infrastructures. As can be seen in Figure 21, the case selection will experience a financial damage of 25.000-240.000 kr per year.

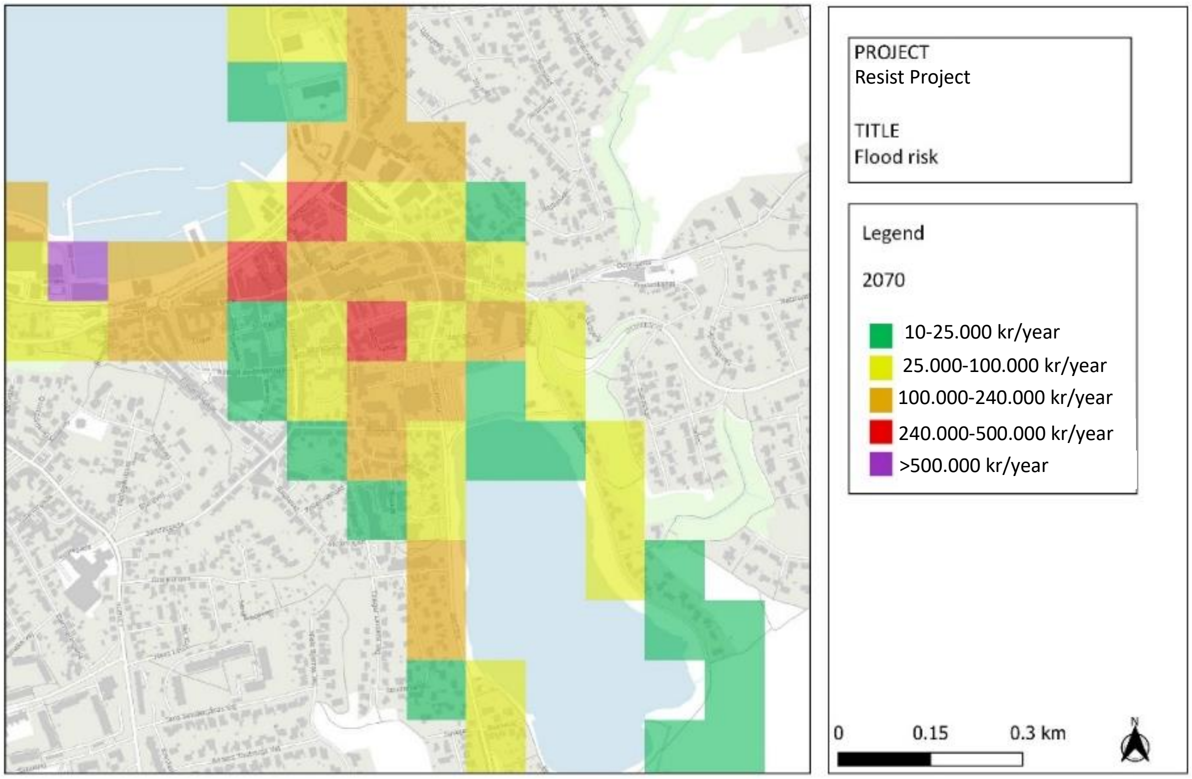


Figure 21. Identified the flood risk in Lemvig town (Source: (Miljøministeriet, 2023)

7. Results

This section will describe potential measures for increasing resiliency for buildings located in Lemvig town**.** Different approaches for designing solutions for retrofitting existing buildings by considering their benefits have been described, then the potential solutions which help in minimizing the rainwater runoff are mentioned.

7.1 Analysis different approaches

As described in the previous section, residents and business owners are confronted with the effect of floods. Therefore, there is a need to plan resilient measures including capacity to absorb and transform to withstand shocks and stresses. There are generally two types of community within the selected area Figure 7 section 5.2.1 susceptible to storm surges: mixed residential and business area, and residential area. (Pelsmakers Sofie, 2015) argues that designing solutions should be in a way to work and live with water rather than against it. Hence, in order to design solutions for retrofitting existing buildings to be resilient against floods in the selected flood-prone area there are some approaches need to consider including:

Dry-flood proofing Wet-flood proofing Elevation

Different approaches for building resilience for existing properties (my own observation)

It should be mentioned that these approaches are applicable to all flood-prone areas. However, the actual effectiveness measures depend on the depth of flood water.

7.1.1 Elevation-Elevating the floor

Elevating properties at or above flood level projected to allow the flow of floodwater into the property to minimize the consequences of floods. When the water pressure endangers the safety of the property the simplest and most effective way is to allow water to enter the building. This strategy refers to elevating the entire living area above the highest projected floodwater (Peter Ramsauer, 2013). For the existing buildings which are old and at risk of being affected by storm surges it is recommended to remove the roof and extend the walls of houses to establish new elevated living area and using the lowest laying area to surface for parking or storage (Marisa Lago, 2019). This solution is frequently used in the USA for making resiliency for properties. Additionally, this strategy requires to locate equipment and service facilities like electrical and heating services above flood water projected (ICC and FEMA, 2019). Figure 22, illustrates an elevated building above flood level projected.

Figure 22. Elevated house, New York city. Source adopted from (Marisa Lago, 2019)

To increase the safety of a building it is necessary the individual parts of the building design to withstand the increase water pressure like using concrete for foundation and the walls of the basement (Klara Geywitz, 2022). Moreover, using the basement or lower space as a flooded area, waterproofing materials are necessary. National Flood Insurance Program (NFIP) recommends that the elevated area should have at least two flood openings that allow automatically floodwater to enter and exit (ICC and FEMA, 2019). In relation to resilience framework this solution does not have flexibility as the measurement is permanent. However, this measure has a high level in absorbing floodwater because it can easily handle water depth of more than 1 m without any fundamental damage to the building and prevent the financial damages. Based on design approaches the water level less than 1 m is recommended to keep outside the building. Therefore, based on information about the depth of water on the surface described in section 6.1.4 and 6.1.5 the water level in most of the selected area is less or at 1 m, therefore, this strategy may not be an appropriate case for Lemvig Havn. This solution compared to other strategies is costly and requires additional cost for lifting structures and needs to clean and dry out the flooded area after the flood to prevent the growth of mold.

7.1.2 Dry-flood proofing

This strategy involves sealing the outer part of the buildings to prevent flood water from entering. Based on NFIP floodproofing measure requires performance of measures used to make properties potentially impermeable to the passage of water and providing resistant for buildings to reduce flood damages (ICC and FEMA, 2019). There are two types of dry-flood proofing including:

- Active
- Permanent

Active measures need removable elements to put into place before the event happens and it requires early warning for installation. Permanent measures like glazing systems that are new passive dry-flood proof productions, designs to withstand floods while providing natural light for occupants (FEMA, 2021) and are fixtures and systems integrated into the structure of buildings and do not need to deploy manually for flood prevention (Enterprise green communities, 2015). Figure 23 illustrates common types of dry-flood proof shields both active and permanent which requires to take into account for securing doors, windows and gate openings.

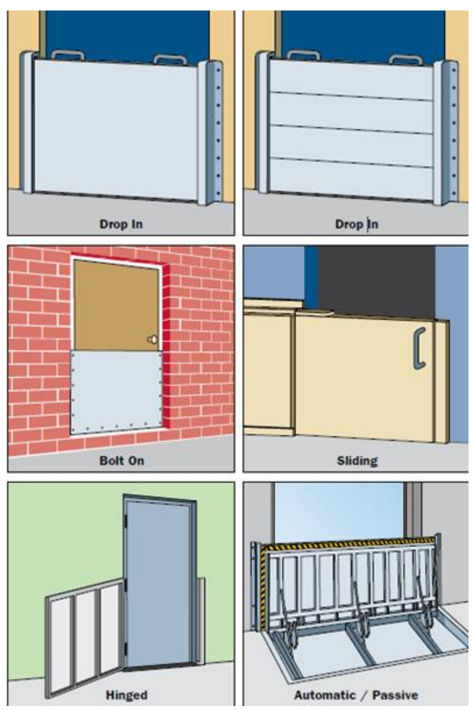


Figure 23. common types of dry-flood proof shields. (source: adapted from (FEMA, 2021)

In relation to resilience framework, the dry-flood proof measures are highly flexible and transformative measures. They can easily be installed or dismantled for the entrance of the building like doors and windows where the flood water can ingress to the building and also can be used for covering the exterior walls to minimize the damages caused by floods which is shown in figure 24. In relation to absorbance, this strategy requires a comprehensive sealing of the cracking and opening on the exterior walls and the foundation to prevent the stresses on the structures of the exterior walls (Peter Ramsauer, 2013) along with the use of dry-flood proof shields for the windows, doors and exterior walls. As a result, the absorption capacity increases significantly and will fundamentally reduce the financial damages to the properties caused by floods.

Figure 24. Illustrates the property covered with barriers (Source adopted from (Peter Ramsauer, 2013)

Based on design criteria in section 4.2.2 when the depth of water in the selected location is less than 1 m, the water exclusion strategy will be employed to absorb the water without any fundamental damages to the building construction. This strategy, compared to the elevation approach, is more cost effective and will reduce or somehow prevent damage to the buildings. Based on information discussed in section 6.2 the residential and commercial properties prone to storm urges that do not have basements can employ this strategy to increase the resistance of their buildings against storm surges. In relation to co-benefits, this strategy yields both economic and health advantages. It effectively prevents mold growth within properties and reduces the emotional stresses of being flooded among citizens. Moreover, it enhances the property values and minimizes flood-induced structural damages.

7.1.3 Wet-flood proof

This strategy refers to utilizing waterproof materials for walls, floors, and elevating electrical controls and construction methods above the flood protection elevation to allow flood water to enter the properties and will minimize the damage and moisture after flooding (JDA, 2020). However, it is essential to care about structures susceptible to flood water to be strong enough to withstand the forces of flood water.

In relation to resilient framework, this strategy does not have flexibility since all the actions are permanent. However, it is a transformative solution and can deal with climate uncertainties since this measure is applicable alone or combined with other measures like dry-flood proof solution (JDA, 2020). This measurement is mostly relevant for non-residential parts of the building for example, basements, garages, or warehouses (Enterprise green communities, 2015). Since the basement does not have the same value as the other parts of the building, it is recommended to let the water flow into the basement and relocate the electrical equipment to a flood-free space above the flood protection level. If the electrical and mechanical equipment cannot be elevated at or above protection level, it is an effective way to protect them with dry-flood proof measures such as enclosure made of impermeable materials from damages Figure 25 (Enterprise green communities, 2015). As can be seen in section 6.2 there are seven buildings in the case area that consist of the basement. Consequently, this strategy is an appropriate solution for them to be resilience to floods.

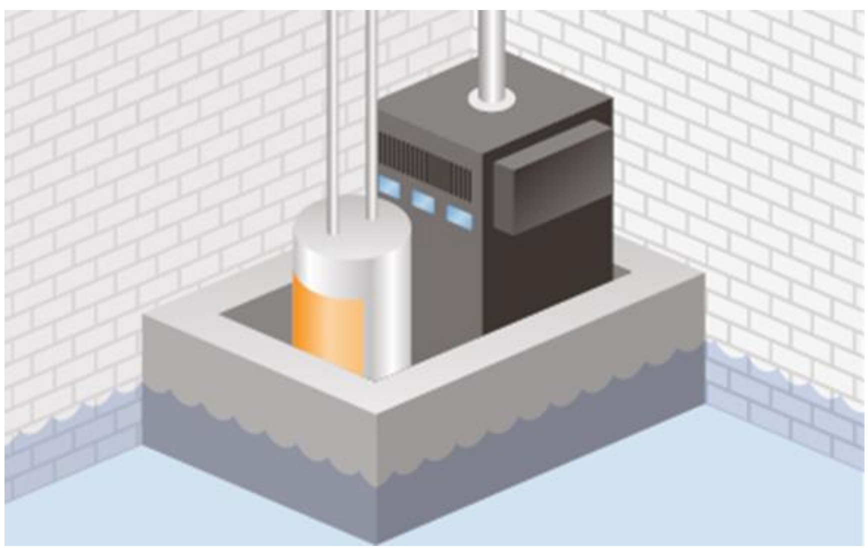


Figure 25. Dry-flood proof strategy for electrical equipment (source: adopted from (Enterprise green communities, 2015)

Additionally, it should be noted that whether the property is elevated or retrofitted by dry-flood proofed structures it is essential that all parts of the building exposed to floodwater be made of wetproofed materials such as foundational elements (FEMA, 2005).

In relation to absorbance, this strategy requires the incorporation of two openings in the basement to facilitate the ingress and egress of floodwater to ensure equal hydrostatic pressure on both interior and exterior of the structures (Garvin, Reid and Scott, 2005). Additionally, it is essential to utilize materials in the structures of the basement, or garage which will not be damaged and are stable to flood and minimize the damages by immersion. These actions all together will reduce the likelihood of damage to walls and structures and increase the resiliency of the building. Table 5, describes some examples of materials that the absorption are high but will not be damaged by immersion. These materials are stable but will dry slowly.

Table 5. Materials with different level of absorbency

Absorbency			
Class	**High**	**Moderate**	**Legend**
A	- Masonry - Concrete	-	A: materials that have minimal damage under most circumstances.
B	Plasterboard	- Plywood - Hardwood	B: Materials susceptible to physical damage when they are wet, otherwise no long-term damages.
C	-	- Low durability timbers - Low quality tiles - Water-based paints	C: Materials that are subject to physical damage after a prolong immersion, however, they will be recovered after effectively dried.

Source: adopted form (Hawkesbury-Nepean Floodplain Management Steering Committee, 2007)

In relation to co-benefits, this strategy will reduce the mental stresses of being flooded, however, for preventing mold growth it is essential to clean up the flooded area if the structures become wet and it can be done by pumping floodwater out of the basement. This strategy compares to dry-flood proof measure and elevation is more cost effective, but it is not much robust as dry-flood proof measure because it allows water to enter the structure and may have some damages to the structures. For this reason, this strategy is only preferable to non-residential areas.

7.2 Solution for reducing the rainwater runoff

CC pattern is uncertain and, in the future, as discussed in section 6.1.5 Lemvig town will experience more rainfall which causes water accumulation and flooding in low-lying areas. To manage rainwater, sustainable and environmentally friendly solutions are needed. Implementing permeable pavements and Nature Based Solutions (NBS) can fortify the resilience and adaptability of the buildings, while simultaneously fostering both well-being of the environment and society. These innovative strategies encompass interventions that harness or emulate natural processes and ecosystems to confront climate challenges. NBSs are known as multifunctional solutions for stormwater management through flash flood prevention. Examples of solutions that can be employed in the building scale to reduce the rainwater runoff and prevent the water accumulation in the basement of houses in Lemvig town include, rain gardens, green roofs, and permeable pavements. These kind of solutions are generally known as low impact development and refer to locate these techniques on a small-scale system at the source of runoff generation (Rezaei *et al.*, 2019). Additionally, these measures are known as sustainable storm water management due to their ability to manage storm water quantity and quality (Shafique, Kim and Kyung-Ho, 2018).

7.2.1 Rain garden

Rain garden is a simplistic depression that planted with native plants and fill with stormwater runoff from impervious urban areas like roofs, parking lots, and walkways and allow the water to slowly filter into the ground which reduces or restricts the runoff of rainwater on the surface Figure 26 (KWL, 2019). As can be seen in figure 20 in section 6.2, the buildings with bigger spaces are more efficient for implementing this solution since there are more vacant spaces for implementing rain garden to collect the runoff water. In relation to resilience framework, rain gardens are multifunctional solutions that absorb climate shocks and add more value to the property. They are also flexible and can be installed directly on the ground or in containers with different capacities and the capacity of green measures can relatively be adjusted (Bąk and Barjenbruch, 2022). There are two different rain gardens in general, raingardens that infiltrate the rainwater into the ground which calls infiltration raingarden, and raingarden that containment storm water runoff and then pipe the water elsewhere which calls filtration raingarden (Maria Cahill, Derek C. Godwin, and Jenna H. Tilt, 2018). Filtration raingarden used in areas where the level of groundwater to the terrain is less than 1m (Maria Cahill, Derek C. Godwin, and Jenna H. Tilt, 2018; Julie Troll Boding and Mette Jensen, 2023). Therefore, based on groundwater analysis in section 6.1.6, it can be concluded that it is preferable to utilize filtration rain garden as the groundwater level in winter in most of the selected area is relatively high. An underground storage tank can be implemented in the rain garden to storage rainwater which can pumped out for irrigation (Chen, Lin and Lin, 2022). In relation to absorbance, filtration rain gardens during heavy precipitation can temporarily collect water from impervious surfaces such as roofs, parking lots, and walkways (KWL, 2019). It enables runoff to permeate through both the upper and the middle mulch layer. Subsequently, the collected water is directed through a storage to pump the water in the designated point or area (Maria Cahill, Derek C. Godwin, and Jenna H. Tilt, 2018)

Figure 26. Rain Garden illustration. Source adopted from left picture: (Klimatilpasning, 2015) right picture:(Teknologisk Institut, 2012)

This multifunctional solution has beneficial effects on health, environment, and economy. During heavy precipitation the rainwater runoff on the impervious surfaces will significantly increase. Filtration rain gardens, which are beautiful and vibrant solutions, will reduce the volume of rainwater runoff from catchment areas (Tobias Robinson *et al.*, 2019). They will reduce the risk of property damage related to moisture and flooding and will add more value to the property which effect on house sale price. The other benefit of filtration rain gardens that is related to health is that they will absorb the pollution from surface water like sediments, nutrients, and heavy metals and prevent the entrance of pollutants into the property (Rezaei *et al.*, 2019). Additionally, this filtration process not only aids in enhancing the natural ecosystem but also contributes to the promotion of biodiversity (AirClim, 1997).

7.2.2 Green roofs

Green roofs are known as green infrastructures that minimize stormwater runoff while providing a multiple range of environmental and aesthetic values. These green infrastructures are usually covers with vegetation which infiltrate rainfall and evaporate the stored water in the warm days (NPDES, 2021). There are two main green roofs that are mostly used in Europe including extensive green roofs and intensive green roofs. Extensive green roofs have a maximum depth of 150 mm and usually cover with sedum species and is mainly for environmental benefits not recreation purpose. This kind can be established on slope surface as high as 45 degrees and is cheaper than intensive green roofs (NPDES, 2021). On the other hand, intensive green roofs have a depth of more than 150 mm but can be installed on slope surface of less than 10 degrees. Therefore, it is preferable to design this kind for buildings that have flat or gently sloping roofs, otherwise the design may have the opposite effect, potentially leading to increase overland flow

(NPDES, 2021). This kind can be covered by perennial herbs, shrubs, and large trees and is mostly used for recreation purposes and public accessibility (Mentens, Raes and Hermy, 2006).

As can be seen in section 6.2 there are commercial and residential buildings in the selected area that are appropriate for establishing extensive green roof since this kind due to its shallow depth have a minimum weight on the roof of buildings and minimal requirement for maintenance (Nickolaj Feldt Jensen, Thomas Cornelius, and Guangli Du, 2023). However, the construction of the building should take into account because a building must have the capacity to withstand the weight of green roof materials even when they are fully saturated, as well as any relevant snow loads (NPDES, 2021). Figure 27, illustrates the green roofs that are installed in Aarhus to help in reduction of rainwater runoff.

Figure 27. Green roof illustration in Aarhus. Source adopted from (Nature Impact, 2022)

In terms of resilient framework, green roofs will deal with stresses and climate uncertainties by reducing the runoff peak and utilizing the shocks caused by CC to promote multifunctional value to the property. In terms of absorbance, green roofs, which are also known as rooftop gardens, possess a substantial water storage capacity and may significantly minimize the peak runoff during the most precipitation events. They achieve this by delaying the initial time of runoff through water absorption and reduce the total runoff by retaining a portion of the rainwater (Mentens, Raes and Hermy, 2006).

Regarding to co-benefits which described in section 4.3 green roofs have widely environmental benefits which can simultaneously contribute to adaptation by minimizing stormwater runoff leads to prevention of flooding in the properties while enhancing urban biodiversity (Zhang and He, 2021). The green roofs also have economic advantages which minimize damage to the buildings caused by rainwater flooding and add more value to the property. Additionally, they will reduce noise pollution (EPA, 2023) and provide aesthetic enjoyment for citizens. As a result, cause reducing stress and proving mental health among them (Cheng and Berry, 2013).

7.2.3 Permeable pavements

Permeable pavements which are commonly made up of a matrix of concrete blocks or a plastic web-type structure filled with sand or soil represent a simple and effective systems, serving a dual purpose of providing stable surface for both pedestrian and vehicular traffic, as well as simultaneously facilitate storm water management through flow, infiltration, and runoff storage (Imran, Akib and Karim, 2013). A study in Seoul has shown that permeable pavements can reduce the rainwater runoff to approximately 30-60 % (Shafique, Kim and Kyung-Ho, 2018)

In relation to resilience framework, by changing the patterns of CC, Lemvig town will experience severe runoff in the future. Therefore, there is a need to replace impermeable pavements like impermeable asphalts with permeable pavements (Shafique, Kim and Kyung-Ho, 2018) to reduce the rainwater runoff and prevent flooding. Permeable pavements are flexible as retrofitting them is quite easy.

In relation to absorbance, permeable pavements possess the capability to capture water on the pavement surface and allow water to infiltrate into the subgrade layer and groundwater which can significantly reduce the surface runoff for a wide range of residential, commercial, and industrial areas (Imran, Akib and Karim, 2013). However, based on groundwater projected shown in section 6.1.6, the groundwater in Lemvig town is quite a big challenge, therefore there is a need to prevent rainwater from infiltrating to the ground. It can be inspired by the 'Climate Road' project which is located near Hedensted in Denmark. An impermeable bentonite membrane can be established on the bottom of permeable pavements to prevent ingress of rainwater to the groundwater (Andersen, Poulsen and Tordrup, 2022). The rainwater can be stored and used for heating, irrigation or colling (Andersen, Poulsen and Tordrup, 2022). Since this measurement would be more beneficial on the bigger space, it is recommended to use it in a parking lot of commercial and mix residential commercial properties that are shown in Figure 20, section 6.2.

Permeable pavements that is shown in Figure 28 compare to rain gardens and green roofs have a limited potential in reducing rainwater runoff and absorption (Pratt, Mantle and Schofield, 1989). As a result, it is advisable to be installed in the parking lots of mix commercial and residential and commercial properties that are shown in section 6.2, in conjunction with rain gardens or green roofs to insure the prevention of rainwater accumulation. Permeable pavements can provide variety of benefits for urban, residential, and commercial buildings including reducing the pollutions of surface water leads to positive impact on environment. It also contributes in reducing the peak flow of rainwater runoff which directly minimize the pressure on drainage system and reduce or somehow prevent flooding(Imran, Akib and Karim, 2013)

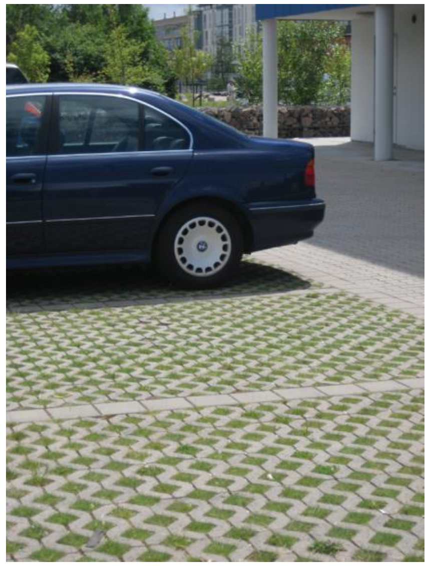


Figure 28. Illustration of permeable surface in a parking lot. Source adopted from (Teknologisk Institut, 2012)

8. Discussion

In this project the PFR has been used because it provides standards that should be considered for designing and delivering appropriate measures for properties. First stage of assessing how existing buildings can be resilient to floods in Lemvig town, it was necessary to assess the risk of flooding in the specific location. The risk of flooding has been assessed through analyzing the hazardous, exposure and vulnerability. Analysis hazardous helps in understanding the types and depth of flood water in the selected area which is important to design appropriate and suitable solution for properties. However, some challenges arose during the process. Initially, difficulties emerged in visualizing the impact of storm surges on Scalgo Live, primarily due to the penetration of water at the height of 1.75 m into the land behind high-water wall. This issue was significant as the high-water wall designed with an elevation of 2.1 m to 2.4 m was intended to safeguard the city. After discussion with Laurits Bernitt, it revealed that certain points in the western part of the high-water wall where water penetrated had subsided by 7 cm. This subsidence was identified as the underlying cause of the flooding.

The second stage involves conducting surveys with end users that help in understanding which properties have been affected by floods in the past. Moreover, survey will help to understand the end user desires and ensure their comprehensive understanding of various measurements (Kelly, D *et al.*, 2021a). However, Engagement with end users in this project has not been undertaken due to the scope of the project. (Kelly, D *et al.*, 2021a) discussed if user surveys are unavailable, it is important to understand the types of the buildings and the characteristic of flood hazard. Consequently, this project undertakes an analysis of building types, considering factors such as the presence of buildings with basements and without. This assessment is important because it will impact on shaping the proposed solutions. Moreover, to understand whether the properties have been affected by flood hazard, the past, and current situation of flood hazard have been assessed.

The third stage involves option development and design. Meaning proposing solutions that are more appropriate for the building located in the flood hazard. According to COP guidance proposing solutions should be designed to protect against or minimize structural damage up to specific maximum flood depth (Kelly, D *et al.*, 2021a). However, a critical question may arise: how can understand under which depth of water different approaches can be implemented at the building scale? This underscores the limitation in the COP, as this guidance lacks addresses on the depth of water at which design approaches should be considered. Recognizing this gap, there was a need to formulate a framework for design approaches which consider under which depth of water the water exclusion and entry strategy can be effectively implemented in the buildings.

Assumption:

It is difficult to talk only about ‘accommodation’ strategy for climate adaptation since CC has many uncertainties. In this project the accommodation strategy will minimize the consequences of storm surges if the Thyborøn channel narrowed in the period of 2041-2070. Otherwise, the selected area will experience huge and severe damage as the depth of water will be approximately 1.4 m. In that case the other strategies of PARA framework including combination of protection and accommodation, and retreat should be considered.

Combination of protection and accommodation: raising the height of the high-water wall is not sufficient, because the water penetrate from behind the Klimatorium and industrial area to the selected case. Therefore, there is a need to raise the height of the wall and extend it to the point to prevent the ingress of water. On the other hand, the precipitation is another challenge of Lemvig town, hence the accommodation strategy should be implemented in a building scale to make them resilient. However, raising the height of the sea wall has some negative consequences namely, acting as a huge barrier in the town and blocking the view to Limfjord.

8.1 Limitations and recommendation for the next step

Like any projects, there are limitations that are experienced. This section will address the limitations related to the analysis of hazardous, and survey.

This project concentrates on assessing the effect of storm surges after narrowing Thyborøn channel which will directly impact on the depth of water and design solutions. However, uncertainties arise concerning the financial risks associated with 100-year storm surges for 2070. Given that this information has been collected from WebGis (Miljøministeriet, 2023), there is uncertainty regarding assessing financial damages based upon whether the Thyborøn channel is narrowed or not.

The perspective of owners does not consider in this project because of the scope and the timing of the project. This stage as outline by (Kelly, D *et al.*, 2021a) is considered as an individual project due to its requirement to assess the different construction of the building, the detail of building services including electrical equipment, building fabrics, and assessing the interior construction of building. Furthermore, considering the assessment's focus on the year 2070 introduces an element of uncertainty regarding end-user perspectives. This should be noted that interview might influence the result and proposed solutions, as the final solutions are based on the desires of the owners.

An interesting avenue for further research can be analyzing the risk of flooding that can occur from groundwater and sewage systems. Another interesting topic can be assessing the risk of storm surges before narrowing Thyborøn channel which the depth of water on the surface will be more than 1 m. Moreover, proposing solutions based on that assessment to increase the resiliency. Furthermore, conducting interviews with owners, which provide insights into understanding their desires for different measures and their agreement on these measures is also an interesting topic for future research. Interviews will help to understand which sections of the building are more susceptible to floods and from where floodwater can penetrate to the building.

9. Conclusion

The aim of the project was to address construction methods and building technologies to make resiliency for existing properties. The changes in climate coupled with flooding that happened recently in Lemvig town led to further investigation and bring more sophisticated approaches to minimize the consequences of floods for each individual property. Within this process, sub-research questions were strategically employed to elucidate specific aspects of the main research question which bolstered the research conclusion by providing additional insights and clarity. The main research question that was proposed was:

How can minimize the consequences of climate change in a building scale located in a high-risk flood prone area in order to increase their resiliency and live with water?

To answer this question, three sub-research questions were proposed including: **What is the meaning of flood resiliency in relation to building scale?** The concept of resilience has a variety of definitions, especially in the city scale. In this project flood resiliency means to live with water and acknowledge the fact that floods cannot always be prevented by 'prevention' strategy when two climate hazardous combine. Therefore, there is a need to think about a more holistic approach, namely 'accommodation' strategy to improve property resiliency and the ability of a building to accommodate and cope with the floods. For this reason, two concepts of flood resiliency including capacity to absorb and recover; and capacity to transform have been chosen in this project. The capacity to absorb and recover in flood-prone areas implies the ability to absorb floods without causing fundamental damages to the structure and the capability to recover after the disturbance Additionally, resiliency in transformability should involve adaptations that adjust to climate uncertainties and incorporate innovative solutions.

The second sub-research question asked: **How can high risk areas of flooding be identified?** To provide flood resilienc it is crucial to identify areas at high risk of flooding and identify the nature of flooding. To answer this question the climate hazards including storm surges from Limfjord and flooding caused by heavy precipitation have been assessed. Based on analysis the future risk of hazardous and its impacts on the built environment were presented.

The answer to the second sub-research question has a direct impact on the third sub-research question which is **Which adaptations are more suitable for existing buildings?** To answer this question formulating a guidance for design approaches and resilience framework along with assessing the typology of different buildings in the selected area were developed. This analysis helped in understanding which buildings are with and without basement that this assessment directly effects on proposed solutions. Furthermore, analyzing the nature of flooding and the depth of water on the surface was crucial to propose solutions that are suitable for existing buildings. These assessments are important and will help in designing solutions including elevation, dry-flood proof, and wet-flood proof for retrofitting existing buildings along with green infrastructures and permanent pavement. Furthermore, evaluating the transformability, flexibility, and absorbency of each CCA along with the co-benefits was necessary to understand their suitability and their robustness for making resiliency for each individual building.

By answering these questions, an answer can be formulated for the main research question. Considering the fluctuation in climate conditions and increase the possibility of flooding for properties the necessity for an effective and robust solution which increase the resiliency of the existing buildings to withstand and live with water becomes apparent. As (Hegger et al., 2016) pointed out the resiliency cannot be achieved by implementing one of the aspects of resiliency strategy. For this purpose, the combination of wet flood and dry-flood proofing along with green infrastructure and permeable pavements is required to be implemented in the building scale to make the property withstand and live with water. The best practice visualization which is shown in appendix C is employed to illustrate how different solutions can be combined to improve the robustness.

Bibliography

AirClim (1997) 'Air pollution and biodiversity'. Available at: https://www.airclim.org/sites/default/files/documents/Factsheet_7_0.pdf.

Andersen, T.R., Poulsen, S.E. and Tordrup, K.W. (2022) 'The Climate Road—A Multifunctional Full-Scale Demonstration Road That Prevents Flooding and Produces Green Energy', *Water*, 14(4), p. 666. Available at: https://doi.org/10.3390/w14040666.

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

Bąk, J. and Barjenbruch, M. (2022) 'Benefits, Inconveniences, and Facilities of the Application of Rain Gardens in Urban Spaces from the Perspective of Climate Change—A Review', *Water*, 14(7), p. 1153. Available at: https://doi.org/10.3390/w14071153.

Bowker, P., Escarameia, M. and Tagg, A. (2007) *Improving the flood performance of new buildings: flood resilient construction*. London: RIBA. Available at: https://assets.publishing.service.gov.uk/media/602d673ee90e0709e8d085d8/Improving_the_Flood_Resilience_of_Buildings_Through_Improved_Materials__Methods_and_Details_Technical_Report.pdf.

C2C (2022) 'Coast to Coast Climate Challenge', *www.https://www.c2ccc.eu/english/*.

C2C CC (2015) 'LIFE 2015 INTEGRATED PROJECTS CLIMATE ACTION. EU LIFE IP C2C CC. Part C'. Available at: https://www.c2ccc.eu/siteassets/c2ccc/administration/bevillingsdokumenter/part-c-digital.pdf.

C2C-CC (2022) 'Coast to Coast Climate Challenge Lægmandsrapport'.

Calvin, K. *et al.* (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). Available at: https://doi.org/10.59327/IPCC/AR6-9789291691647.

Chen, C.-F., Lin, J.-W. and Lin, J.-Y. (2022) 'Hydrological Cycle Performance at a Permeable Pavement Site and a Raingarden Site in a Subtropical Region', *Land*, 11(6), p. 951. Available at: https://doi.org/10.3390/land11060951.

Cheng, J.J. and Berry, P. (2013) 'Health co-benefits and risks of public health adaptation strategies to climate change: a review of current literature', *International Journal of Public Health*, 58(2), pp. 305–311. Available at: https://doi.org/10.1007/s00038-012-0422-5.

Choi, C., Berry, P. and Smith, A. (2021) ‘The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review’, *Journal of Environmental Management*, 291, p. 112583. Available at: https://doi.org/10.1016/j.jenvman.2021.112583.

Colgan, W. *et al.* (2022) ‘Sea-level rise in Denmark: paleo context, recent projections and policy implications’, *GEUS Bulletin*, 49. Available at: https://doi.org/10.34194/geusb.v49.8315.

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

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

Dansk Regioner (2021) ‘Vanet kommer’. Available at: http://www.e-pages.dk/regioner/203/.

Dataforsyningen (2023) ‘Din indgang til frie offentlige geodata og kort.’ Available at: https://dataforsyningen.dk/data/3621.

DMI (2018a) ‘Historic storm surges in the North Sea and Denmark’.

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

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

DMI (2023b) *Klimaatlas-rapprt. Lemvig kommune*.

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

Doberstein, B., Fitzgibbons, J. and Mitchell, C. (2019) ‘Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience’, *Natural Hazards*, 98(1), pp. 31–50. Available at: https://doi.org/10.1007/s11069-018-3529-z.

Enterprise green communities (2015) ‘Strategies for multifamily building resilience.’ Available at: https://businesscontinuity.enterprisecommunity.org/sites/default/files/strategies-for-multifamily-building-resilience.pdf.

EPA (2023) *Green roofs*. Available at: https://www.epa.gov/green-infrastructure/what-green-infrastructure#raingardens.

Faragò *et al.* (2018) *Coastal protection technologies in a Danish context.*

FEMA (2005) 'National Flood Insurance Program. Floodplain Management Requirements. A study guide and desk reference for local officials.' Available at: https://www.fema.gov/sites/default/files/documents/fema-480_floodplain-management-study-guide_local-officials.pdf.

FEMA (2021) 'Requirements for the Design and Certification of Dry Floodproofed Non-Residential and Mixed-Use Buildings. Located in Special Flood Hazard Areas in accordance with the National Flood Insurance Program.' Available at: https://www.fema.gov/sites/default/files/documents/fema_technical-bulletin-3_1-2021.pdf.

Flyvbjerg, B. (2006) 'Five Misunderstandings About Case-Study Research', *Qualitative Inquiry*, 12(2), pp. 219–245. Available at: https://doi.org/10.1177/1077800405284363.

Garvin, S., Reid, J. and Scott, M. (2005) *Standards for the repair of buildings following flooding*. London: CIRIA. Available at: https://repository.tudelft.nl/islandora/object/uuid:2eed4dfa-8f65-4585-af40-a313a2323a28/datastream/OBJ/download+&cd=4&hl=en&ct=clnk&gl=uk.

Hawkesbury-Nepean Floodplain Management Steering Committee (2007) *Reducing vulnerability of buildings to flood damage: guidance on building in flood prone areas*. Parramatta, N.S.W.: The Committee.

Hegger, D.L.T. *et al.* (2016) 'Toward more flood resilience: Is a diversification of flood risk management strategies the way forward?', *Ecology and Society*, 21(4), p. art52. Available at: https://doi.org/10.5751/ES-08854-210452.

Hewitt, C.N., Ashworth, K. and MacKenzie, A.R. (2020) 'Using green infrastructure to improve urban air quality (GI4AQ)', *Ambio*, 49(1), pp. 62–73. Available at: https://doi.org/10.1007/s13280-019-01164-3.

HIP (2023) 'HYDROLOGISK INFORMATIONS- OG PROGNOSESYSTEM'. HIP. Available at: https://hip.dataforsyningen.dk/.

ICC and FEMA (2019) 'Reducing Flood Losses Through the International Codes. Coordinating Building Codes and Floodplain Management Regulations.' Available at: https://www.fema.gov/sites/default/files/2020-07/fema_reducing_flood_losses_rfl_5th-ed.pdf.

Imran, H.M., Akib, S. and Karim, M.R. (2013) 'Permeable pavement and stormwater management systems: a review', *Environmental Technology*, 34(18), pp. 2649–2656. Available at: https://doi.org/10.1080/09593330.2013.782573.

IPCC (2013) 'Summary for policymakers. Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change'.

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

IPCC (2014b) 'IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change'.

IPCC (2019) 'Special Report on the Ocean and Cryosphere in a Changing Climate. Summary for Policymakers.' Available at: https://www.ipcc.ch/site/assets/uploads/sites/3/2022/03/01_SROCC_SPM_FINAL.pdf.

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

IPCC (2022b) 'IPCC_AR6_WGIII_SummaryForPolicymakers'.

JDA (2020) *Flood resilient guide to retrofitting your home*.

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

John Jensen and Søren Bjerre Knudsen (2008) 'Klimaændringers effekt på kysten - Danish Coastal Authority'.

Jörn Birkmann *et al.* (2012) 'Determinants of Risk: Exposure and Vulnerability'. Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap2_FINAL-1.pdf.

Julie Troll Boding and Mette Jensen (2023) 'How to build a rain bed in the garden'. Available at: https://www.bolius.dk/saadan-anlaegger-du-et-regnbed-i-haven-20933.

KAMP (2023) 'Klimaatlas'. Available at: https://kamp.klimatilpasning.dk/.

Kelly, D *et al.* (2021a) 'Guidance on the code of practice for property flood resilience.'

Kelly, D *et al.* (2021b) 'Quidance on the code of practice for property flood resilience'.

Klara Geywitz (2022) 'Hochwasserschutzfibel. Objektschutz und bauliche Vorsorge.' Available at: https://www.fib-bund.de/Inhalt/Themen/Hochwasser/2022-02_Hochwasserschutzfibel_9.Auflage.pdf.

Klimatilpasning (2015) *Five rain gardens in Gladsaxe spread inspiration*. Available at: https://www.klimatilpasning.dk/cases-overview/fem-regnhaver-i-gladsaxe-spreder-inspiration/.

Klimatilpasning (2023) ‘Precipitation and climate change’.

Klimatorium (2020) ‘Klima og vand’. Available at: https://klimatorium.dk/klima-uden-graenser/.

KWL (2019) ‘Rain Gardens: Design, Implementation, and Maintenance Considerations’. Available at: https://www.kwl.ca/wp-content/uploads/2019/07/8-1a.pdf.

Kystdirektoratet (2019) ‘Højvandsstatistikker. 2017’. Available at: https://kyst.dk/media/80372/hoejvandsstatistikker2017revideret11022019.pdf.

Lehmann, M. *et al.* (2021) ‘Towards a typology for coastal towns and small cities for climate change adaptation planning’, *Ocean & Coastal Management*, 212, p. 105784. Available at: https://doi.org/10.1016/j.ocecoaman.2021.105784.

Leichenko, R. (2011) ‘Climate change and urban resilience’, *Current Opinion in Environmental Sustainability*, 3(3), pp. 164–168. Available at: https://doi.org/10.1016/j.cosust.2010.12.014.

Lemvig Kommune (2021) *Designnotat Å-ledningens pumpestation*.

Lemvig Kommune (2022a) ‘Datakatalog’.

Lemvig Kommune (2022b) *vandstandsstatistik i Lemvig Kommune input til klimatilpasningsplan*.

Lemvig Kommune (2023a) ‘Klimatilpasningsplan’.

Lemvig Kommune (2023b) ‘Stormflodsscenarier for 8 lokaliteter i Lemvig Kommune’. Available at: https://www.lemvig.dk/Files/Files/Teknik%20og%20Milj%C3%B8/Planer/Klimatilpasningsplan/Bilag%204%20-%20Stormflodsscenarier%20for%208%20lokaliteter%20i%20Lemvig%20Kommune.pdf.

Maria Cahill, Derek C. Godwin, and Jenna H. Tilt (2018) ‘Rain Gardens: Lo-impact development. An establishment rain garden in Portland, Oregon.’ Available at: https://extension.oregonstate.edu/sites/default/files/documents/12281/rain-gardens-fact-sheet.pdf.

Marisa Lago (2019) *Zoning for coastal flood resiliency. Planning for resilient neighborhoods*. Available at: https://www.nyc.gov/assets/planning/download/pdf/plans-studies/flood-resiliency-update/zoning-for-flood-resiliency.pdf.

Martin Sodemann (2022) ‘Water penetrated several hundred meters into Lemvig: - I don’t know what has tricked us’. Available at: https://www.tvmidtvest.dk/lemvig/vand-traengte-flere-hundrede-meter-ind-i-lemvig-jeg-ved-ikke-hvad-der-har-snydt-os.

McMichael, C. *et al.* (2020) ‘A review of estimating population exposure to sea-level rise and the relevance for migration’, *Environmental Research Letters*, 15(12), p. 123005. Available at: https://doi.org/10.1088/1748-9326/abb398.

Mentens, J., Raes, D. and Hermy, M. (2006) ‘Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?’, *Landscape and Urban Planning*, 77(3), pp. 217–226. Available at: https://doi.org/10.1016/j.landurbplan.2005.02.010.

Miljøministeriet (2023) ‘Coastal Planner’. Available at: https://gis.nst.dk/portal/apps/webappviewer/index.html?id=7d399b34b9ef42d7895569d0ccc0046b.

Nature Impact (2022) *Nature Impact provides examples of what you may not yet know about green roofs*. Available at: https://www.byggematerialer.dk/det-vidste-du-ikke-om-groenne-tage-297531/nyhed.html.

Nickolaj Feldt Jensen, Thomas Cornelius, and Guangli Du (2023) ‘Grønne tage status på viden og erfaringer om grønne tage’. Available at: https://vbn.aau.dk/ws/portalfiles/portal/552431461/Gr_nne_tage.pdf.

NPDES (2021) *Stormwater Best Management Practice*. Available at: https://www.epa.gov/system/files/documents/2021-11/bmp-green-roofs.pdf.

Paul, J. and Criado, A.R. (2020) ‘The art of writing literature review: What do we know and what do we need to know?’, *International Business Review*, 29(4), p. 101717. Available at: https://doi.org/10.1016/j.ibusrev.2020.101717.

Pelsmakers Sofie (2015) *The Environmental Design Pocketbook*. Available at: https://books.google.dk/books?hl=en&lr=&id=cMm4DwAAQBAJ&oi=fnd&pg=PT8&dq=Pelsmakers+S.+2012.+The+Environmental+Design+Pocketbook.+London:+RIBA+Publishing&ots=Zp-mHq9wTO&sig=HpmVXpPRW9vDVli2UT5RWG1Sm2I&redir_esc=y#v=onepage&q=Pelsmakers%20S.%202012.%20The%20Environmental%20Design%20Pocketbook.%20London%3A%20RIBA%20Publishing&f=false.

Peter Ramsauer, (2013) ‘Hochwasserschutzfibel Objektschutz und bauliche Vorsorge’.

Pratt, C.J., Mantle, J.D.G. and Schofield, P.A. (1989) ‘URBAN STORMWATER REDUCTION AND QUALITY IMPROVEMENT THROUGH THE USE OF PERMEABLE PAVEMENTS’, in *Urban Discharges* *and Receiving Water Quality Impacts*. Elsevier, pp. 123–132. Available at: https://doi.org/10.1016/B978-0-08-037376-8.50017-4.

Proverbs, D. and Lamond, J. (2017) ‘Flood Resilient Construction and Adaptation of Buildings’, in Proverbs, D. and Lamond, J., *Oxford Research Encyclopedia of Natural Hazard Science*. Oxford University Press. Available at: https://doi.org/10.1093/acrefore/9780199389407.013.111.

Rambøll (2022) ‘VANDSTANDSSTATISTIK I LEMVIG KOMMUNE INPUT TIL KLIMATILPASNINGSPLAN.’ Available at: https://www.lemvig.dk/Files/Files/Teknik%20og%20Milj%C3%B8/Planer/Klimatilpasningsplan/Bilag%201%20-%20Vandstandsstatistik%20i%20Lemvig%20Kommune.pdf.

Rezaei, A.R. *et al.* (2019) ‘A Quantity–Quality Model to Assess the Effects of Source Control Stormwater Management on Hydrology and Water Quality at the Catchment Scale’, *Water*, 11(7), p. 1415. Available at: https://doi.org/10.3390/w11071415.

Scalgo Live (2023) ‘Scalgo Live’. Available at: 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.

Shafique, M., Kim, R. and Kyung-Ho, K. (2018) ‘Rainfall Runoff Mitigation by Retrofitted Permeable Pavement in an Urban Area’, *Sustainability*, 10(4), p. 1231. Available at: https://doi.org/10.3390/su10041231.

Teknologisk Institut (2012) ‘ANVISNING FOR HÅNDTERING AF REGNVAND PÅ EGEN GRUND’. Available at: https://www.klimatilpasning.dk/media/330326/r_rcenter-anvisning_016._anvisning_for_h_ndtering_af_regnvand_p__egen_grund__maj_2012.pdf.

Tobias Robinson *et al.* (2019) *Raingardens for stormwater management Potential of raingardens in a Nordic climate*.

Venkataramanan, V. *et al.* (2019) ‘A systematic review of the human health and social well-being outcomes of green infrastructure for stormwater and flood management’, *Journal of Environmental Management*, 246, pp. 868–880. Available at: https://doi.org/10.1016/j.jenvman.2019.05.028.

Zhang, G. and He, B.-J. (2021) ‘Towards green roof implementation: Drivers, motivations, barriers and recommendations’, *Urban Forestry & Urban Greening*, 58, p. 126992. Available at: https://doi.org/10.1016/j.ufug.2021.126992.

Appendix A

The future daily precipitation, 100-year event for 2070 under high emission scenario RCP 8.5 based on (DMI, 2023a) is projected to be 109 mm (uncertainty: 83-144m/day) per day based on reference period 1981-2010. Figure 29, illustrates the impact of 109 mm precipitation for a 100-year event in the case area and illustrates certain areas tend to be flooded due to depressions in the land. Consequently, the 100-year daily event will impact the properties located in the case selection.

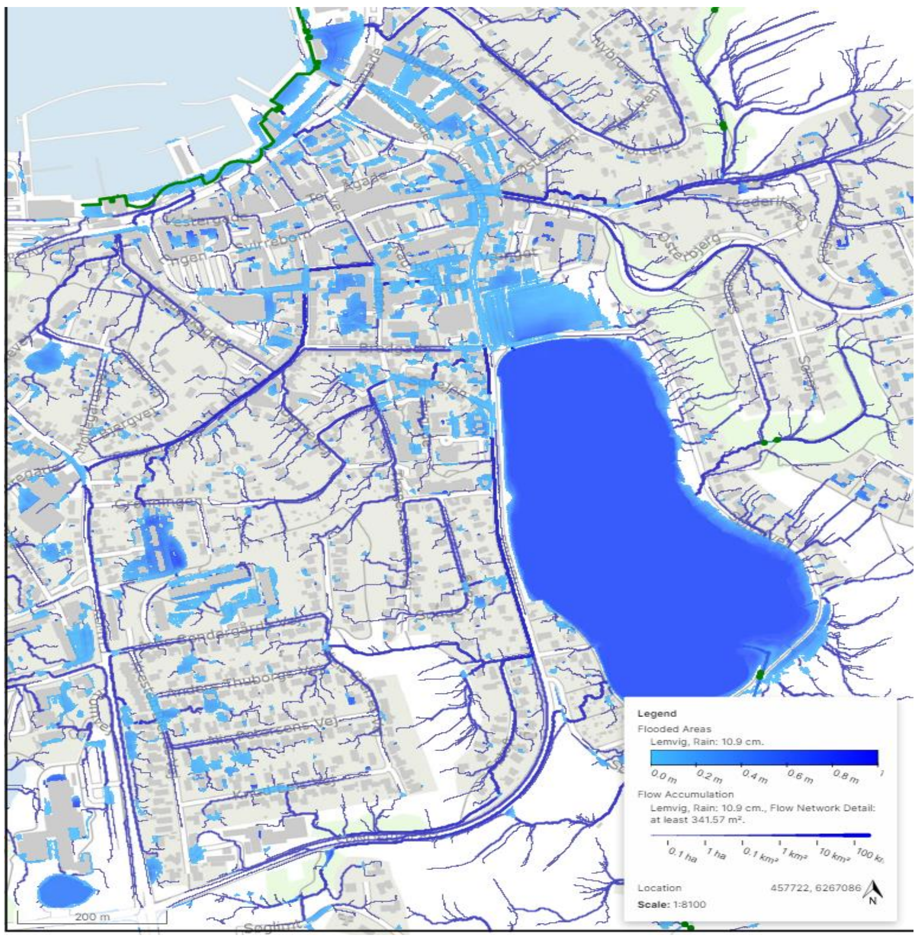


Figure 29. The projected 100-year daily precipitation illustration (Scalgo Live, 2023)

As can be seen in figure 30. the 109 mm daily precipitation will cause flooding in the case area selection. The depth of water is shown in the picture below. Some properties will experience flooding with more than water depth of 14 cm which need immediate action in that areas to minimize damages caused by flooding.

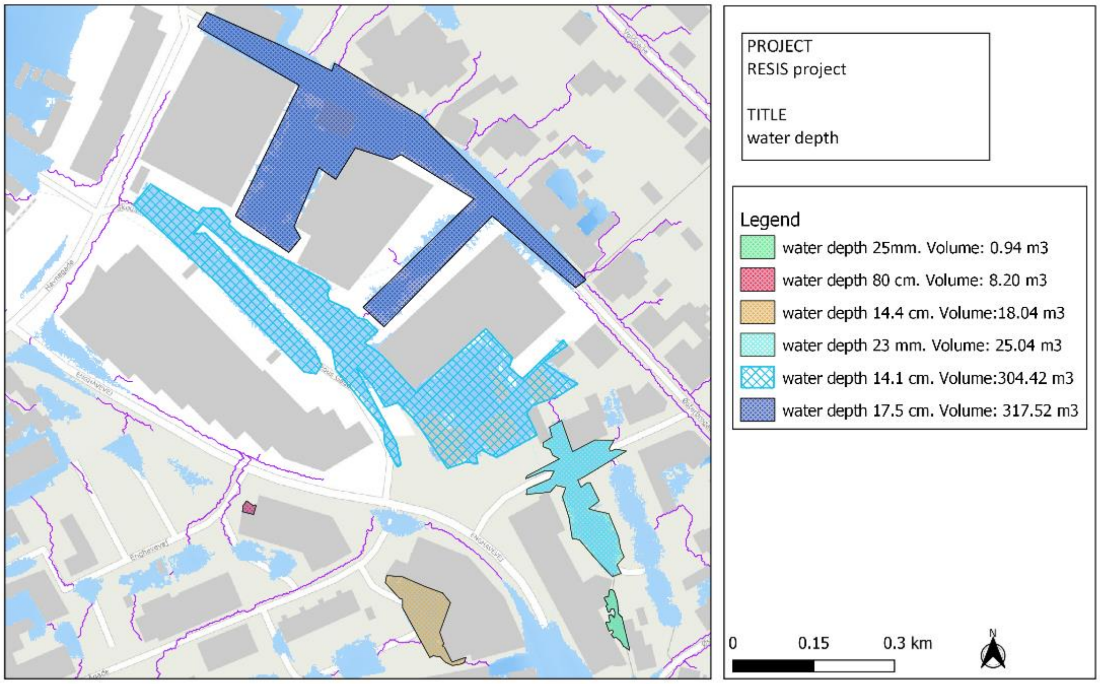
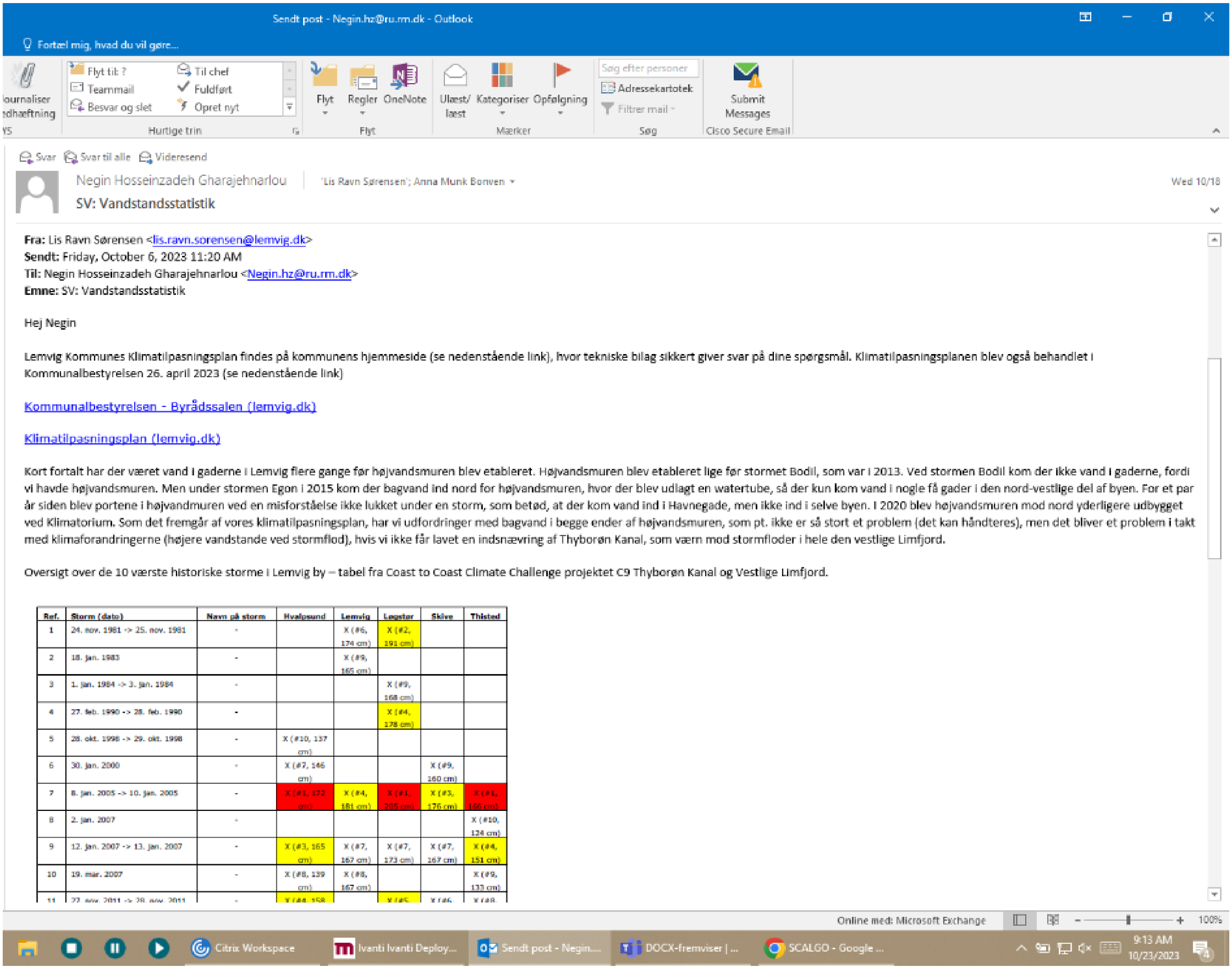


Figure 30. Illustrates the projected 100-year daily precipitation water depth on the surface (Scalgo Live, 2023)

Appendix B.

An interview with Lis Ravn a person who is working in Lemvig Municipality to understand the previous and recently storm surge happened in Lemvig Havn and its impacts.



Sendt post - Negin.hz@ru.rm.dk - Outlook

Negin Hosseinzadeh Gharajehnarlou | 'Lis Ravn Sørensen'; Anna Munk Bonven | Wed 10/18

SV: Vandstandsstatistik

Fra: Lis Ravn Sørensen <lis.ravn.sorensen@lemvig.dk>
Sendt: Friday, October 6, 2023 11:20 AM
Til: Negin Hosseinzadeh Gharajehnarlou <Negin.hz@ru.rm.dk>
Emne: SV: Vandstandsstatistik

Hej Negin

Lemvig Kommunes Klimatilpasningsplan findes på kommunens hjemmeside (se nedenstående link), hvor tekniske bilag sikkert giver svar på dine spørgsmål. Klimatilpasningsplanen blev også behandlet i Kommunalbestyrelsen 26. april 2023 (se nedenstående link)

Kommunalbestyrelsen - Byrådssalen (lemvig.dk)

Klimatilpasningsplan (lemvig.dk)

Kort fortalt har der været vand i gaderne i Lemvig flere gange før højvandsmuren blev etableret. Højvandsmuren blev etableret lige før stormet Bodil, som var i 2013. Ved stormen Bodil kom der ikke vand i gaderne, fordi vi havde højvandsmuren. Men under stormen Egon i 2015 kom der bagvand ind nord for højvandsmuren, hvor der blev udlagt en watertube, så der kun kom vand i nogle få gader i den nord-vestlige del af byen. For et par år siden blev portene i højvandmuren ved en misforståelse ikke lukket under en storm, som betød, at der kom vand ind i Havnegade, men ikke ind i selve byen. I 2020 blev højvandsmuren mod nord yderligere udbygget ved Klimatorium. Som det fremgår af vores klimatilpasningsplan, har vi udfordringer med bagvand i begge ender af højvandsmuren, som pt. ikke er så stort et problem (det kan håndteres), men det bliver et problem i takt med klimaforandringerne (højere vandstande ved stormflod), hvis vi ikke får lavet en indsnævring af Thyborøn Kanal, som værn mod stormfloder i hele den vestlige Limfjord.

Oversigt over de 10 værste historiske storme i Lemvig by – tabel fra Coast to Coast Climate Challenge projektet C9 Thyborøn Kanal og Vestlige Limfjord.

Ref.	Storm (dato)	Navn på storm	Hvalpsund	Lemvig	Løgstør	Skive	Thisted
1	24. nov. 1981 -> 25. nov. 1981	-		X (#6, 174 cm)	X (#2, 191 cm)		
2	18. jan. 1983	-		X (#9, 165 cm)			
3	1. jan. 1984 -> 3. jan. 1984	-			X (#9, 168 cm)		
4	27. feb. 1990 -> 28. feb. 1990	-			X (#4, 178 cm)		
5	28. okt. 1998 -> 29. okt. 1998	-	X (#10, 137 cm)				
6	30. jan. 2000	-	X (#7, 146 cm)			X (#9, 160 cm)	
7	8. jan. 2005 -> 10. jan. 2005	-	X (#1, 172 cm)	X (#4, 181 cm)	X (#1, 205 cm)	X (#3, 176 cm)	X (#1, 166 cm)
8	2. jan. 2007	-					X (#10, 124 cm)
9	12. jan. 2007 -> 13. jan. 2007	-	X (#3, 165 cm)	X (#7, 167 cm)	X (#7, 173 cm)	X (#7, 167 cm)	X (#4, 151 cm)
10	19. mar. 2007	-	X (#8, 139 cm)	X (#8, 167 cm)			X (#9, 133 cm)
11	27. nov. 2011 -> 28. nov. 2011	-	X (#4, 158		X (#5,	X (#6,	X (#8,

Online med: Microsoft Exchange

Appendix C

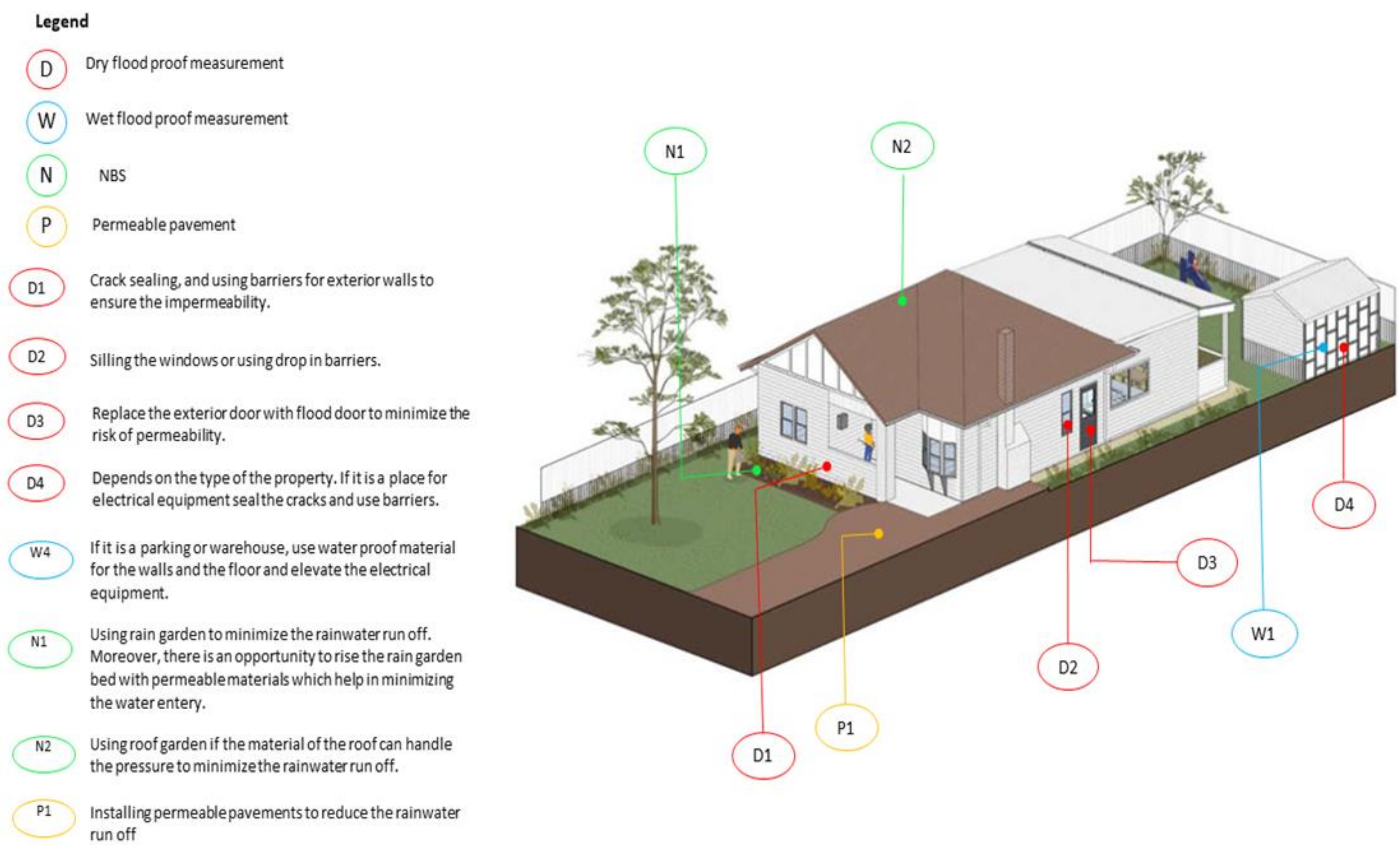


Figure 31. Illustrates how different approaches can be employed on the building scale to make it resilient to floods. The figure of building adapted from (JDA, 2020)

The best practice visualization is employed to illustrate how different solutions can be combined to improve robustness. Figure 31, illustrates and describes the different measurements that can be established in the building scale. It should be noticed that as mentioned before (section 4.2.2) the dry-flood proof shields and wet-flood proof materials need to be established up to 30 cm above water level projected to prevent the moisture in capillary wall structures and limit the damages.

When designing dry-flood proof measurements for buildings, it is necessary to consider how people can exit the building during emergency situations. There are different options but in this project, based on described measures in the previous section, one solution that is more appropriate will be expressed. The residential access of the building where is susceptible to the flood water required to be equipped with wet-flood proofed strategy. This means that elevating electrical equipment including washing machines, power outlets, switchboards and raising cabinets above floodwater projected or replace them with flood resilient materials or using wet-flood proof materials described in section 8.1.3 for walls and floor. Figure 32, illustrates an

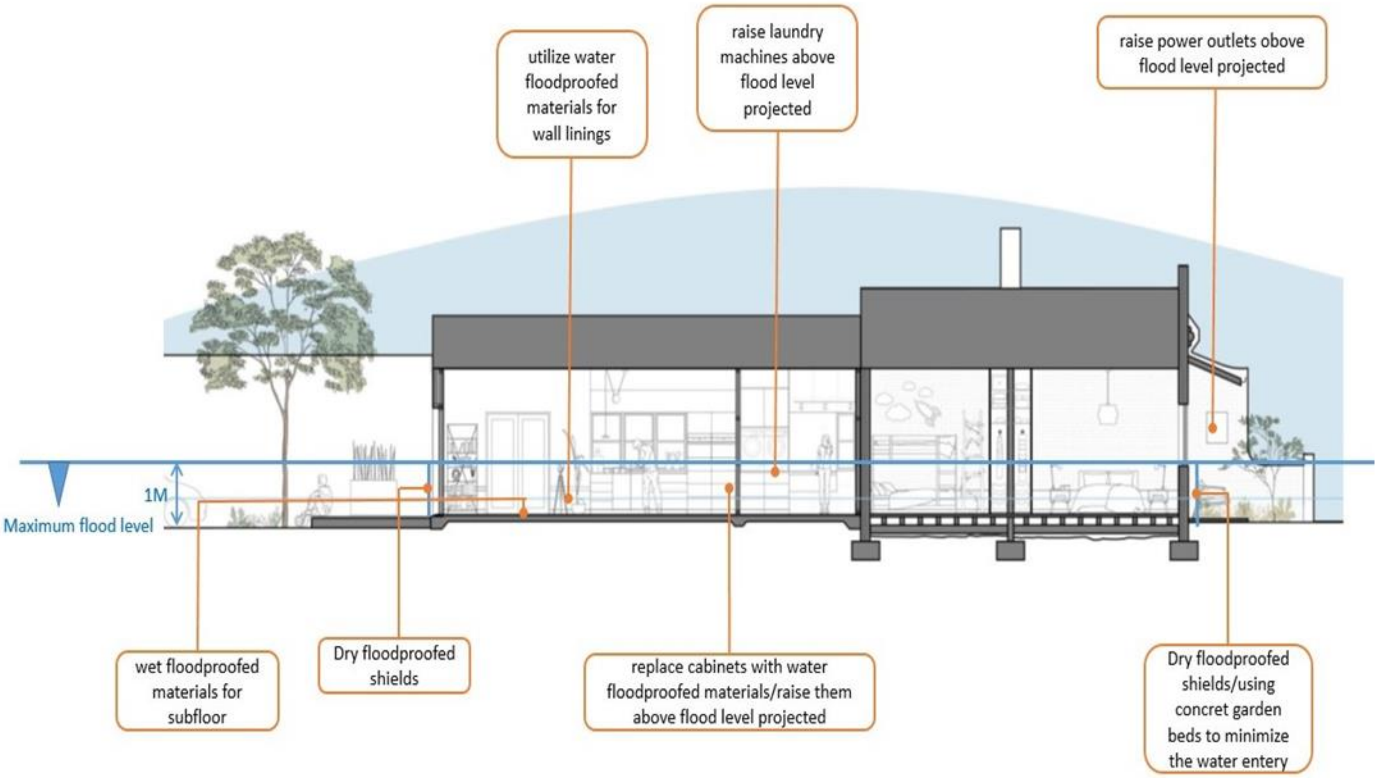


Figure 32. Illustrates how water floodproof strategy can be installed in a building with combination of dry-flood proof shields. (Figure of the building adopted from (JDA, 2020)

This solution may have a negative impact on human health due to mold growth. To prevent such disaster a drainage system required to pump out the flood water. Moreover, surface water contains pollutions, hence, all the structures and places in flooded area should be cleaned immediately after the flooding (Enterprise green communities, 2015)

Appendix D

The effect of 20-year storm surge events

During the 20-year storm surge events the water level in Limfjorden has been raised up to 185 cm (uncertainty 9-51 cm) for the reference period of 1981 until 2010. Under scenario RCP 4.5 the change in water level is 26 cm (uncertainty 16-40 cm) in the period of 2041-2070. Hence, a 20-year storm surge event for the period of 2041-2070 will increase SLR up to 211 cm (DMI, 2023a). Figure 33 shows a 20-year storm surge events for the mid-century.

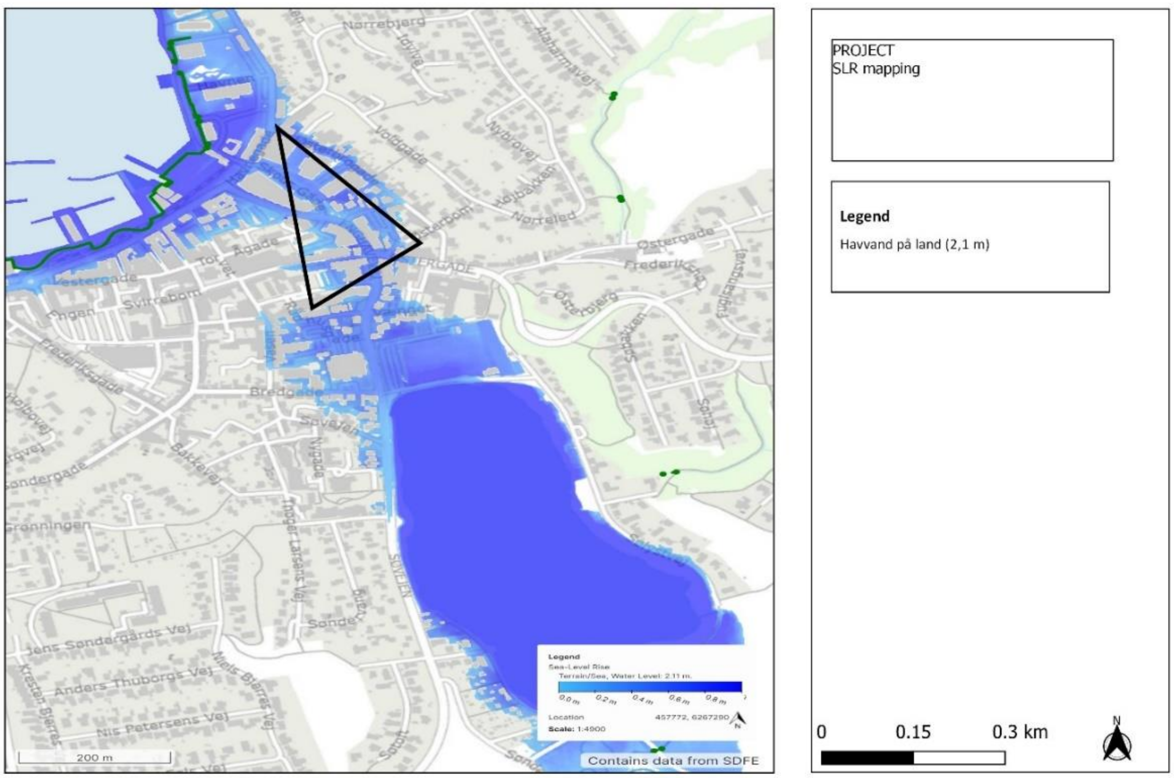


Figure 33. The effect of 20-year storm surge event for the period of 2041-2070 (Scalgo Live, 2023)