# Northern European Enclosure Dam (NEED)

## Financial feasibility of large-scale adaptation strategies for future SLR in Northern Europe: NEED vs Dike Reinforcement

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Technische Universiteit Delft

Delft University of Technology

Challenge the future

# Northern European Enclosure Dam

## Financial feasibility of large-scale adaptation strategies for future SLR in Northern Europe: NEED vs Dike Reinforcement

by

**Hugo Kim Nota**

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at the Delft University of Technology,
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# Preface

In front of you is the thesis '*Northern European Enclosure Dam; Financial feasibility of large-scale adaptation strategies for future SLR in Northern Europe: NEED vs Dike Reinforcement*', written to obtain the degree of Master of Science in Hydraulic Engineering at the TU Delft. Although this thesis was written during a worldwide pandemic, making this project fairly challenging from time to time, I look back on the process satisfied.

Firstly, I would like to express my gratitude to all members of my thesis committee. Thank you all for giving me the opportunity in exploring the possibilities into this relatively broad thesis topic. I would like to gratefully thank Bas Jonkman, the chair of this thesis committee, for his valuable feedback, knowledge shared and guidance throughout this thesis duration. I would like to thank Martine Rutten, member of this thesis committee, for her guidance and insightful questions during the meetings. I would like to thank Manuel Diaz Loaiza, member of this thesis committee, for his help, even after working hours, with the model framework used for the simulations crucial to this research. I would like to thank Elisa Ragno, member of this thesis committee, for your much needed guidance during our weekly meetings and your patience. Those weekly meetings always helped me move one step closer to the end.

My greatest appreciation to all my fellow students, whom I now call friends. Thank you for all your help, support and friendships during my university years. To my '*N.L.*' friendgroup, which consists of my closest friends and even roommates, I cannot envision a better friendship than the ones we have, for that I thank you all. I have had a magical time and will cherish that for the rest of my life.

Lastly, I would like to convey special thanks to my dear family and my girlfriend. To my beautiful girlfriend Nathalie, I thank you for your unconditional love and support during the final stage of my study. Many thanks to my brilliant sister Margriet for her help, support and revisions with very useful adaptations. My deepest gratitude to my parents, Philip and Malee, for always creating a safe haven and push me to do better. You have helped me in every way possible to reach my goals, even when unasked for and sometimes unappreciated. You have made me the man I am today.

*Hugo Kim Nota*
*Rotterdam, February 2022*

# Executive Summary

## Introduction

The effects of climate change are felt all around the world. Examples of these include more frequent and intense droughts and storms, melting glaciers, steadily increasing temperatures and, crucially, rising sea levels. An increased sea level goes hand in hand with an increased risk of flooding. In order to combat this, the coastlines must be reinforced to withstand future sea levels. However, repeatedly reinforcing coastlines to keep up with the sea level rise (SLR) could prove extremely costly. An alternative approach would be to shorten the coastline, as the Netherlands did with the Afsluitdijk to enclose the IJsselmeer. Looking at Europe, Groeskamp and Kjellsson (2020) proposed the construction of the Northern European Enclosure Dam (NEED) — a dam that would disconnect the North and Baltic Seas from the Atlantic Ocean. In this way, it would protect fifteen northern European countries against the accelerated global mean SLR (GMSLR), as it simultaneously shortens the coastline that requires reinforcement. This thesis aims to determine whether the NEED (*Adaptation Strategy 2*) would be a financially favourable adaptation strategy over raising the coastal defences on a country-by-country basis (*Adaptation Strategy 1*) around the North Sea to combat future GMSLR, and if so, at which GMSLR. Figure 1 illustrates the concept of this thesis.

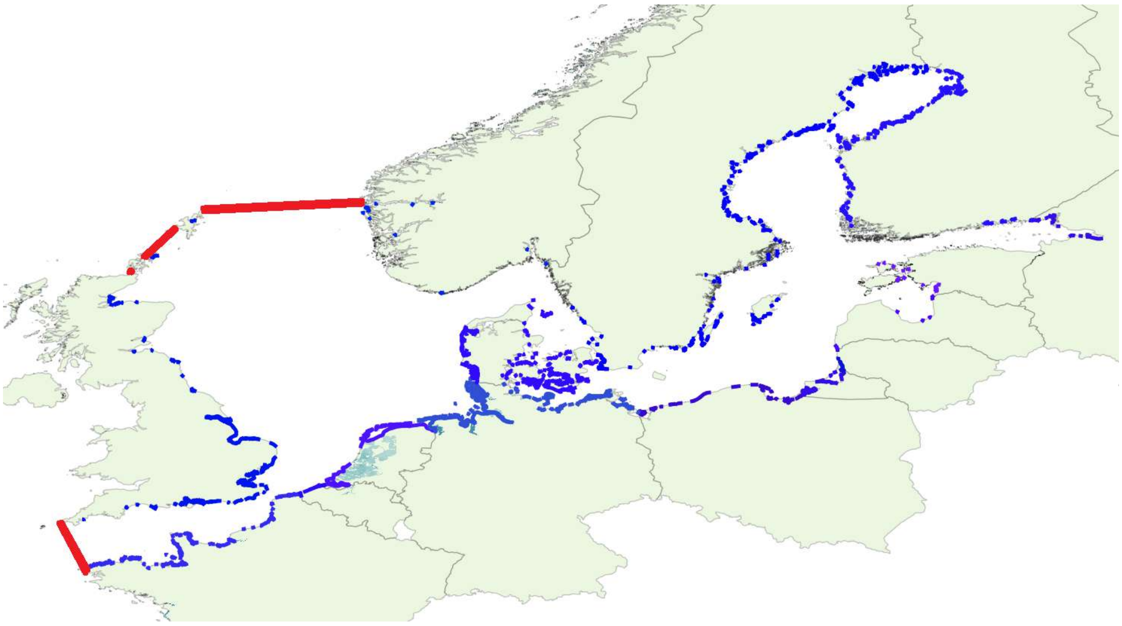

Figure 1: Map of Europe depicting the location of the NEED (red) and the coastline requiring reinforcement (blue) for the countries in question.

## Assessment Flood Exposure Indicators

First, several consequences of future flooding are investigated, then the assessment of the two flood protection strategies are assessed. The consequences, or flood exposure indicators, scrutinised in this research are (i) the size of the exposed (flood-prone) areas, (ii) population affected and (iii) economic damages caused by flooding. These flood exposure indicators are determined up to 2080 using inundation maps retrieved from the GLObal Flood Risk with Image Scenarios (GLOFRIS) model framework. Analysis of various future scenarios that account for variables such as Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP), conclusively yields the estimates for the three flood exposure indicators. For the most extreme scenario that generated the greatest exposure indicator values (i.e. SSP5 with RCP8.5 and a return period of 1000 years), it was estimated that by 2080 a total of 15,000 km$^2$ would be inundated, affecting 9.5 million people and resulting in damages up to 1 trillion € for all countries combined. This is an increase of roughly 200% and 900% for the people affected and economic damages, respectively, when compared to current conditions in 2010 for a 1000 year storm event.

## Flood Protection Strategies

Given the enormous consequences of future flooding, it is evident that adapting flood defences in the region shown in Figure 1 will be vital. This report subsequently analysed two flood protection adaptation strategies and eventually determined which will be financially favourable in the long term.

### Adaptation Strategy 1: Regional Flood Protection

To assess the costs for the necessary regional flood protection reinforcement, the coast length, height and price rate per km/m must be known. These costs are analysed separately for sea dikes and storm surge barriers that fall within the protection range of the NEED. The total length of the coastal defences around the North Sea that requires raising is determined based on the inundation maps and amounted to a total of roughly 6,000 km. For the reinforcement height, it is assumed that this height must be equal to the maximum inundation height found for each country. This assumption will inevitably lead to an overestimation of the reinforcement height. However, this way it can be guaranteed that no future flooding will occur as all countries are protected against the highest projected future inundation retrieved from the GLOFRIS model framework. The price rate per km/m for storm surge barriers is assumed to be fixed, but for sea dikes it varies per country. For the Netherlands, for example, this was found to be 13 million € per km/m and for the storm surge barrier reinforcement it is estimated to be 1000 million € per km/m. With these variables known, the total costs were calculated. Through extrapolation, estimates for the total costs fall in the range of 245 to 335 billion € for a 1-metre GMSLR, with an increase in costs between 170 and 235 million € per metre GMSLR. However, a sensitivity analysis has shown that the total costs highly depend on the assumed relation between SLR and required dike raising. The costs previously mentioned are obtained using the conservative approach of raising the dikes with the maximum inundation height. At the end of this thesis, different relations are tested, such as a more realistic assumption of using the average inundation height instead of the maximum.

### Adaptation Strategy 2: NEED Flood Protection

In this thesis, it is assumed that the NEED is an earth-fill dam design with 1:6 slopes on either sides (see Figure 5.3) on the location suggested in Groeskamp and Kjellsson (2020) (see Figure 5.2). The construction costs of the NEED are assumed to be dictated by five key elements: core material (sand), revetment, geotextile, pumps and sluices. Each element is priced and quantified according to the dimensions of the NEED, which in turn are dependent on the bathymetry. In this thesis, the total costs for the NEED is estimated to be just under 1.1 trillion €, with an increase of approximately 11 billion € per metre GMSLR. Here, the major driver of the costs is the core material in the dam, as it accounts for 95% of the total costs.

## Conclusion

It was found that the regional flood protection has lower initial costs compared to the NEED when comparing the two flood protection strategies. However, the determined cost increase per GMSLR are much greater for the regional costs than for the NEED, causing the regional protection adaptation strategy to eventually become more expensive. In Figure 2, the cost projections for both flood protection strategies are depicted as a function of the GMSLR, revealing the GMSLR at which the NEED becomes financially favourable. For the particular NEED design used, the NEED flood protection adaptation strategy is estimated to be more cost-effective beyond 5.15 metres GMSLR, which is associates with construction costs of roughly 1.15 trillion €. According to the data in Figure 6.2, this GMSLR for scenario SSP5-RCP8.5 is expected to occur between 2280 and 2660, approximately. However, as the total costs are greatly contingent upon the core material, modifying slope angles of the NEED design will lead to a significant reduction in volume and, hence, costs. For the alternative designs with a 1:4 and 1:5 slope, the total costs are reduced by 17% and 34%, respectively. For these designs, the NEED will already become favourable at 3.35 and 4.25 metres GMSLR, respectively.

Several cost distributions have been created based on the four aspects that have been investigated, namely (i) coastline reinforcement length, (ii) size of inundated area, (iii) population exposed and (iv) economic damages caused by flooding. Together with the extrapolated regional costs per country, it is possible to determine which distribution is the most and least financially favourable for each country and whether contributing to the NEED is even favourable at all from the perspective of each country. Figure 6.4 depicts the four aspect-weighted NEED cost distributions (assuming a 1:6 slope design) and the regional protection costs for each country. A similar graph of the cost distribution is made for NEED designs with 1:4 and 1:5 slopes. For the Netherlands, it can be seen that it will have to bear a significant amount of the NEED costs, due to its high exposure risk based on the four aspects.

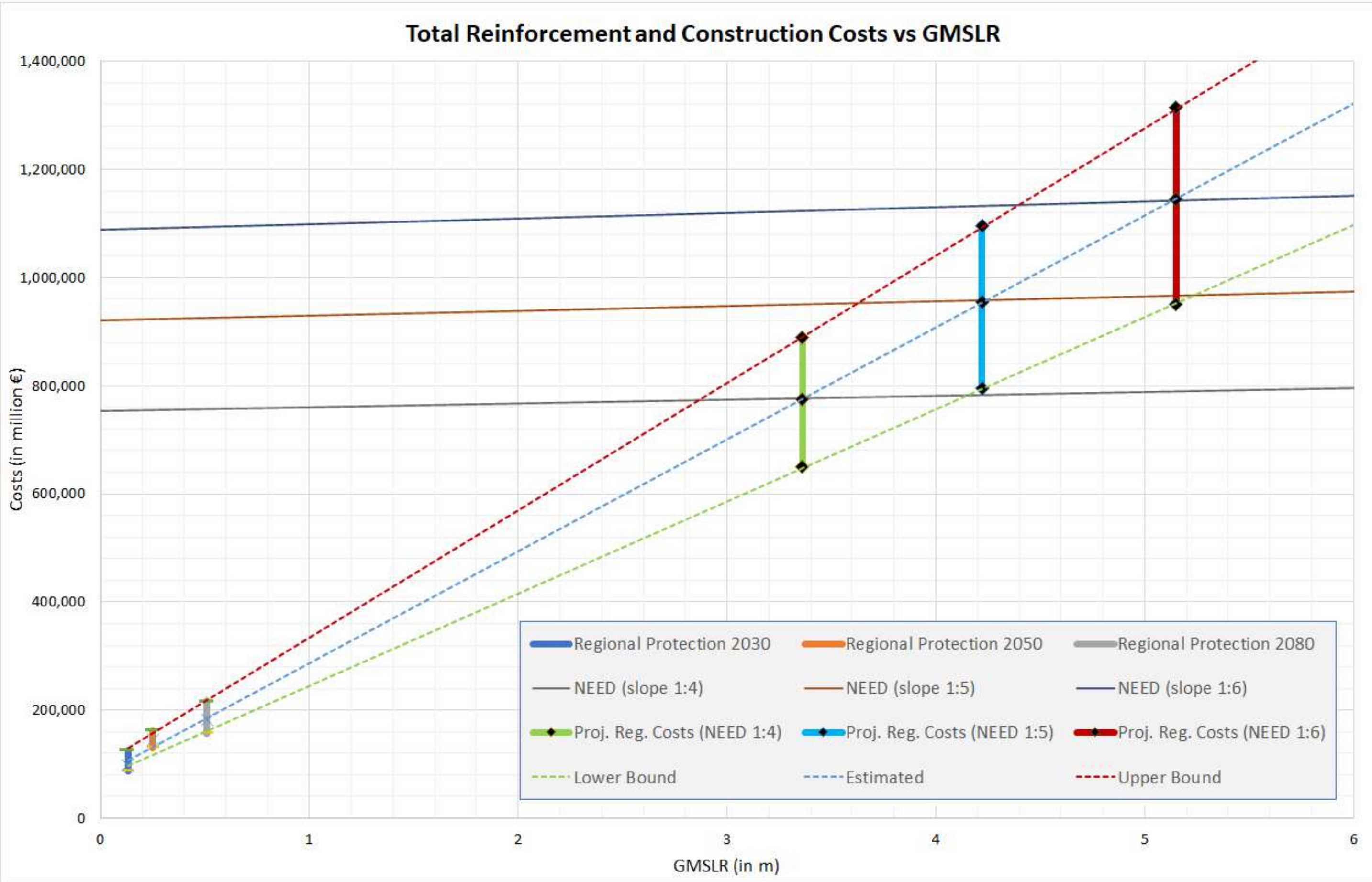


Figure 2: Graph depicting the regional reinforcement and the NEED construction costs as a function of GMSLR.

This research scrutinised the costs, effects and consequences of the most extreme scenario that generated the greatest exposure indicator values (i.e. SSP5-RCP8.5 combined with a return period of 1000 years). Through this assessment, it was possible to estimate the costs associated with both adaptation strategies, and furthermore, to determine at which GMSLR one strategy surpasses the other in financial attractiveness and when this GMSLR can be expected. However, it should be noted that recent studies (the new IPCC report published in 2022 and (KNMI, 2021)) have shown that, in reality, the most extreme scenario might, unfortunately, turn out to be even more extreme than the most extreme scenario assumed in this thesis. And as the consequences strongly dependent on how climate change will unfold in the future, the costs to combat and the timing of such GMSLR occuring will differ.

The results retrieved from this research provide insight into when the NEED flood protection adaptation strategy will become a better alternative to regional flood protection reinforcement. However, it should be borne in mind that it is not a matter of '*either-or*', but rather '*both-and*', as regional dike reinforcement cannot entirely be omitted when deciding to construct the NEED. Instead, a balance must be found in the extent to which regional dike reinforcement is required to protect the countries while the NEED is under construction. So there are plenty of uncertainties and questions that require additional research to fully comprehend all the effects of this massive operation and making it feasible.

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# List of Abbreviations

| | |
|---|---|
| ArcGIS | Aeronautical Reconnaissance Coverage Geographic Information System |
| BE | Belgium |
| DE | Germany |
| DK | Denmark |
| DUT | Delft University of Technology |
| ECO | Economic Damages |
| ES | Estonia |
| FI | Finland |
| FLOPROS | FLOod PROtection Standards |
| FR | France |
| GDP | Gross Domestic Product |
| GEBCO | GEneral Bathymetric Chart of the Oceans |
| GHG | Greenhouse Gas |
| GLOFRIS | GLObal Flood Risk with IMAGE Scenarios |
| GMSLR | Global Mean Sea Level Rise |
| IPCC | Intergovernmental Panel on Climate Change |
| KNMI | Koninklijk Nederlands Meteorologisch Instituut (*Royal Netherlands Meteorological Institute*) |
| LT | Lithuania |
| LV | Latvia |
| MCA | Multi-Criteria Analysis |
| NEED | Northern European Enclosure Dam |
| NL | the Netherlands |
| NO | Norway |
| PO | Poland |
| POP | Population Exposed |
| QGIS | Quantum Geographic Information System |
| RCP | Representative Concentration Pathways |
| RU | Russia |
| SE | Sweden |
| SLR | Sea Level Rise |
| SMB | Surface Mass Balance |
| SSP | Shared Socioeconomic Pathways |
| SWL | Sea Water Level |
| UK | the United Kingdom |

# 1

# INTRODUCTION

*This chapter provides an introduction to this thesis. Section 1.1 gives a concise background on climate change and highlights the importance of flood protection. Subsequently, it introduces the most important flood defences structures and the NEED (Northern European Enclosure Dam) project proposed by Groeskamp and Kjellson to counteract the rising sea level. Sections 1.2 and 1.3 elaborate on the research questions and scope of this thesis. Finally, Section 1.4 shows the general outline of this thesis.*

## 1.1. FLOODING IN A CHANGING CLIMATE

Global warming is a phrase that refers to the effect of human activities on the climate, in particular the burning of fossil fuels in combination with large-scale deforestation. Burning fuels sends large amounts of greenhouse gases emissions into the atmosphere. These gases absorb infrared radiation emitted by the earth's surface and act as a blanket, making it warmer than it otherwise would be. This phenomenon is otherwise known as (global) climate change (Houghton, 2005). This entails many other problems, including a rise in temperature which will subsequently lead to an accelerated sea level rise (SLR) and therefore an increase in the risk of flooding ((Chen *et al.*, 2017) & (Kopp *et al.*, 2014)). Given that a significant part of the world's population is situated in the areas that are prone to flooding, and that, worldwide, flood disasters affect more people than any other disaster type, it emphasises the necessity for proper flood protection (CRED, 2019). Besides the inhabitants, the SLR will also threaten low-lying deltas and their cities, nature, economies and cultural heritage on an enormous scale (Nicholls and Cazenave, 2010).

### 1.1.1. FLOOD RISK SOLUTIONS

There are several solutions to the flood risk problem. Logically, the best solution is to address the problem at the source, which means that our human contribution that exacerbates the climate change problem, must decrease significantly or soon come to a halt altogether. This solution should be seen as the long-term solution. Although it should be noted the sea level rise will not directly come to a halt as the heat capacity of the ocean keeps increasing, it would significantly reduce the climate change process. On the short(er) term, however, there are several strategies for combatting flooding, according to the knowledge institute Deltares (Haasnoot *et al.*, 2019). Four possible strategies, illustrated in Figure 1.1, are listed and briefly explained below.

- **Closed protection**
  Protecting the coast against flooding and erosion by means of hard or soft measures, such as flood defences, sand replenishment or wetlands. In this strategy, river arms will be closed (with dams or storm surge barriers).

- **Open protection**
  Same as closed protection, but the rivers remain in open connection to the sea.

- **Moving seaward**
  Creating new, higher and seaward land to protect the delta against the effects of flooding.

- **Adaptation**
  Reducing vulnerability to the consequences of higher sea level rise by water- or salt-tolerant land use (e.g. buildings on stilts), raising land, spatial planning and/or planned relocation.

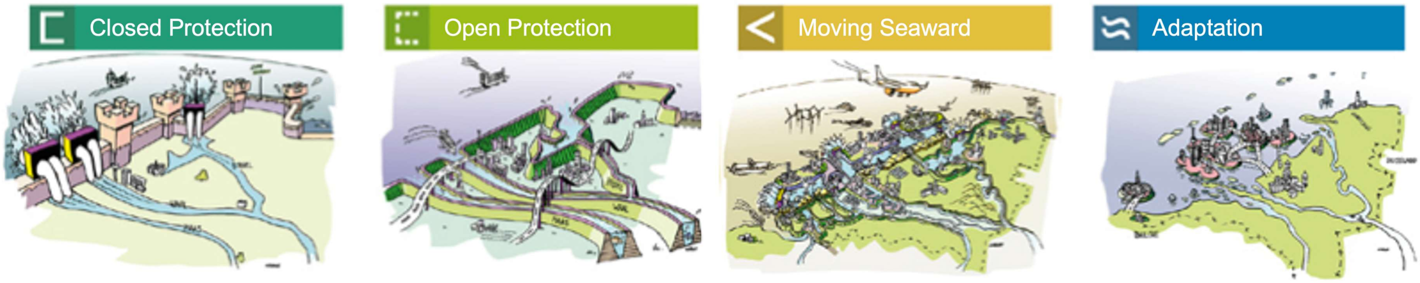



Figure 1.1: Four flood strategies for adaptation to the SLR used for the Dutch Delta (Haasnoot *et al.*, 2019).

It could be argued that taking no action should also be an option. However, as pointed out in the paragraph above, floods are affecting the population more than any other disaster type, which means that no action should not be considered an acceptable option. The current expected annual population exposed to coastal flooding is approximately 100.000 people and is projected to reach up to 3.65 million by the end of year 2100 in Europe alone (Vousdoukas *et al.*, 2018).

Managed retreat, or planned relocation, could potentially be less expensive than protection in certain locations and may theoretically be a good solution when implemented over long periods of time, well before a potential disaster occurs (Diaz, 2015). However, it has a disruptive health, sociocultural and economic impact on communities that relocate (Dannenberg *et al.*, 2019). Managed retreat is not a low-regrets option, nor is it easily reversed. Immaterial costs, such as cultural heritage loss, can be particularly high with retreat and can lead to national and international sociopolitical instability, forcing decision makers to shy away from spurring processes to facilitate managed retreat (Hino *et al.*, 2017). Related mitigation is, therefore, not widely applied and is arguably not a viable solution to timely address the threat of sea level rise.

When considering flood protection, there are three different types of strategies. *Hard* flood strategies involves building artificial structures, such as dikes and dams, that will protect the area behind it from the water. *Soft* flood strategies is a more natural approach to manage flooding, examples of this are beach nourishment and dunes. A *hybrid* flood strategy is a combination of hard and soft strategies. For example, combining a storm-surge barrier and coastal wetland development. According to Du *et al.* (2020), the soft strategies will not be able to substantially reduce the risk of flooding in the year 2100, contrary to the hard strategies. However, the soft strategies can have a vital role in reducing the residual risk resulting from hard strategies.

Besides these hard protections against flooding interventions, other measures can be implemented to reduce the probability and/or the consequences of flooding. For example, in the Netherlands, an integrated and programmed approach referred to as the *Room for the River* programme has been implemented. This programme is a collection of measures aimed at increasing the discharge capacity of the country's main rivers, thus reducing the flood risk at rivers and enhancing the environmental and spatial quality by creating more space for the river ((Zevenbergen *et al.*, 2013) & (HaskoningDHV, 2021)). The measures that are applied in this programme are illustrated in Figure 1.2.

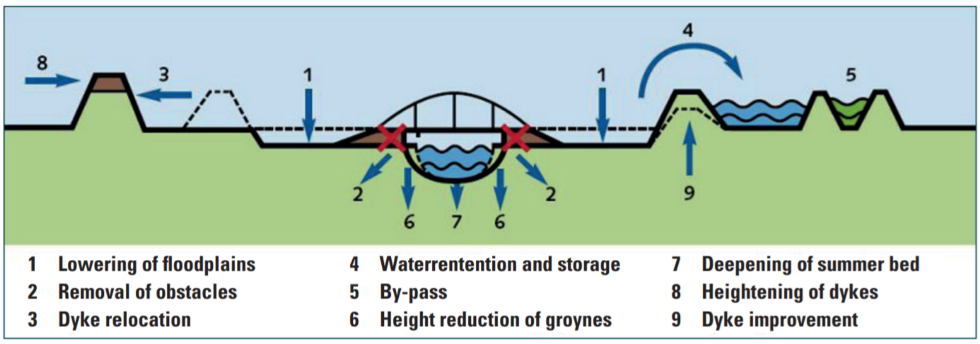



Figure 1.2: Measures that are applied in the Room for the River Program (Zevenbergen *et al.*, 2013).

Flood defences are of great importance to prevent flooding of low-lying areas. A flood defence is a hydraulic structure with the primary objective of combatting flooding along the coast, rivers, lakes and other waterways. Different types of flood defences exist, of which the most important ones are a dikes, dams, storm surge barriers, dunes, flood walls, temporary flood defences, hydraulic structures and multi-functional flood defences (Jonkman *et al.*, 2018). The dike (also referred to as levee) and dam are the most common structures. A dam is a water retaining structure which separates two bodies of water. These structures differ in that, behind a dike, land is located whereas, behind a dam, a body of water is located.

Designing a hydraulic structure that can withstand an uncertain future sea level rise (SLR) is challenging, since it is impossible to predict the exact future anthropogenic greenhouse gas (GHG) emission and other factors that affect climate change and, therefore, SLR. A range of future scenarios was developed as a basis for modelling its effect for the Intergovernmental Panel on Climate Change (IPCC). These scenarios, the so-called Representative Concentration Pathways (RCP), reflect the range of values for annual greenhouse gas radiative forcing, namely from 2.6, 4.5, 6 to 8.5 W/m$^2$ in the year 2100 (Nazarenko *et al.*, 2015). In Figure 1.3(a), the global mean sea level rise from 2006 to 2100 is depicted for various RPC scenarios. Figure 1.3(b) illustrates the new SLR projections made by KNMI up to 2300 combining RCP and SSP Shared Socioeconomic Pathways (SSP) scenarios. SSP scenarios show how socioeconomic factors such as economic growth and population could change in the future. The SSP and RCP scenarios are explained in more detail in Section 2.3.3 Section 2.3.2, respectively. In Figure 1.3(c), the change in average sea level around the world is depicted for the RCP scenarios RCP2.6 (left) and RCP8.5 (right), respectively.

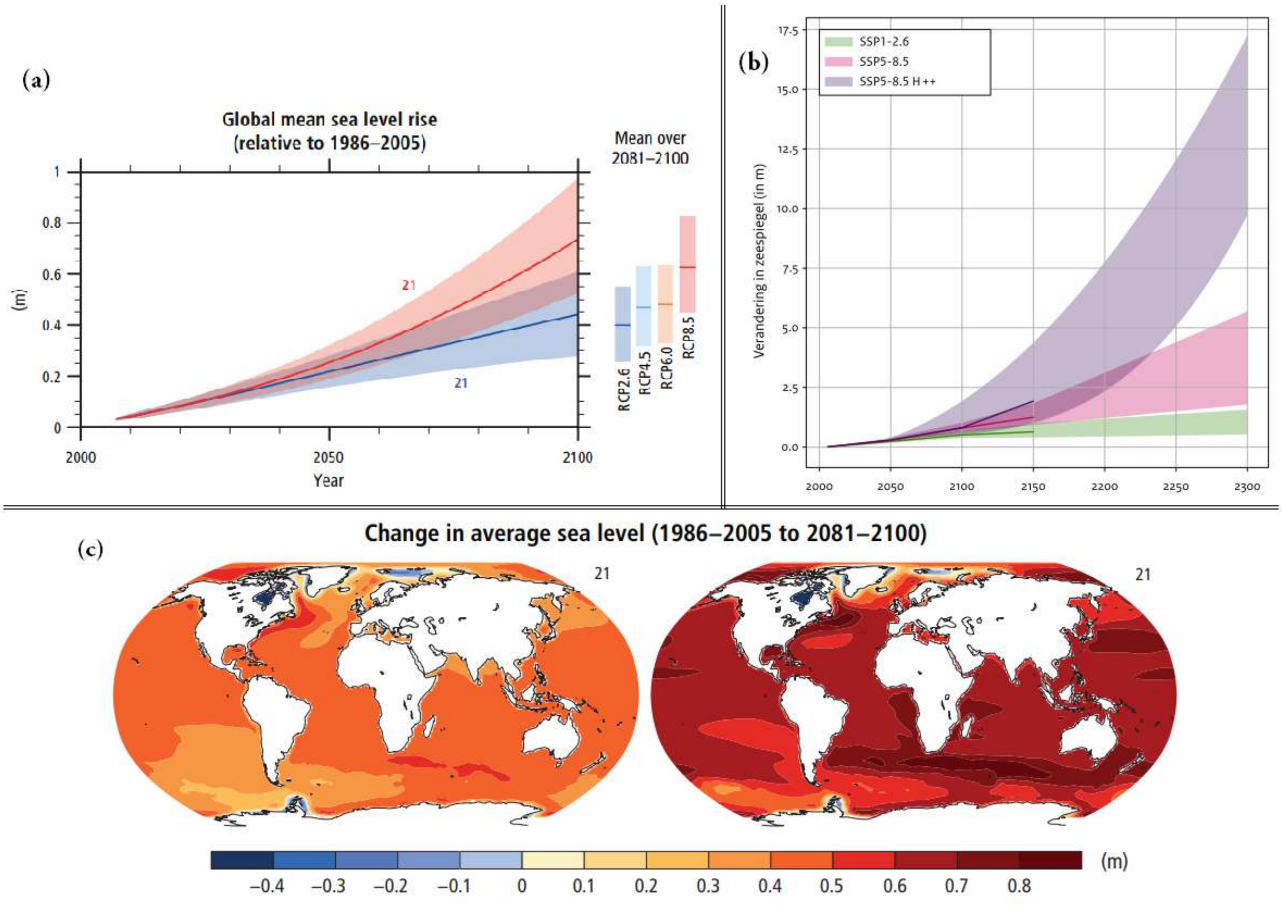



Figure 1.3:
(a) Global mean sea level rise from 2006 to 2100 as determined by multi-model simulations. All changes are relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The number of Couples Model Intercomparison Project 5 (CMIP5) models used to calculate the multi-model mean is indicated (Pachauri and Meyer, 2015).
(b) New SLR scenarios projection made by the KNMI (Koninklijk Nederlands Meteorologisch Instituut) for the Dutch coast until 2030 for SSP1-RCP2.6 (purple), SSP5-RCP8.5 (pink) and SSP5-RCP8.5++ (green). The latter includes the unstable ice-sheet processes on the outskirts of Antarctica. The median lines can only indicate SLR until 2150. The shaded bandwidth corresponds with 67% (KNMI, 2021).
(c) Couple Model Intercomparison Project Phase 5 multi-model mean projections for the 2081-2100 period under the RCP2.6 (left) and RCP8.5 (right) scenarios for change in average sea level (Pachauri and Meyer, 2015).

In Europe, most countries already have plans to counteract SLR. Especially the North Sea countries, who have a high vulnerability and a long history of SLR policies, are planning for long horizons taking into account the highest level of SLR. Nevertheless, there are still a concerning number of European countries with little to no SLR planning (McEvoy *et al.*, 2021). According to an analysis of economically efficient protection scenarios along Europe's coastline of Vousdoukas *et al.* (2020), it is found that roughly 80 percent of the flood damages in Europe could be avoided by improving the dikes in an economically efficient way along approximately 25 percent of Europe's coastline. The stretch of coastline that defends Europe against SLR is significant. Another way to approach the problem, rather than strengthening the large magnitude of coastline that defends Europe against SLR, is to create a shorter coastline that protects the same amount of land, if not more. Shortening the coastline is not a novel concept, as the Netherlands have the Delta Works or the Afsluitdijk to show for it.

### 1.1.2. Introduction NEED

Following the principle of shortening the coastline to better defend Europe against SLR, Groeskamp and Kjellsson (2020) proposed an international cooperation to protect these areas if climate change mitigation fails: the construction of the Northern European Enclosure Dam (NEED). This dam will turn the North Sea into a massive enclosed basin, which would protect coastal communities in fifteen European countries — namely Belgium, Denmark, England, Estonia, Finland, France, Germany, Latvia, Lithuania, Poland, Netherlands, Norway, Russia, Scotland and Sweden — against the accelerated SLR. The dam proposed by Groeskamp and Kjellson consists of three trajectories (see Figure 1.4). The first part (A) stretches over 161 kilometres from Brest (France) to the south coast of the United Kingdom. The second and third part run from Scotland via the Orkneys to the Shetland Islands (B) and from there to Bergen (Norway) (C), stretching over 145 and 331 kilometres, respectively. The total length of the dam thus equals 637 kilometres with a maximum depth of 321 metres in the Norwegian Trench.

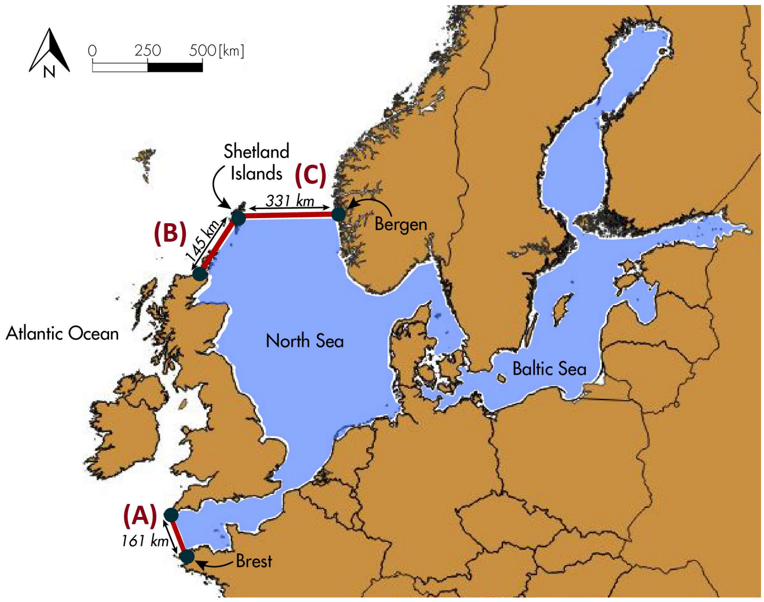



Figure 1.4: The location of the NEED (in red) and the enclosed basin consisting of the North Sea and the Baltic Sea (in blue), as proposed by Groeskamp & Kjellson (2020) (van Strien *et al.*, 2021).

### 1.1.3. Effects and limitations

The proposed enclosure dam will have significant societal, environmental and economic effects. These effects are listed and briefly elaborated on below.

#### Society

- **SLR protection**
  The main purpose of the NEED is to offer protection for the fifteen European countries whose coastline are (partially) protected by the enclosure dam from the rising sea level, hence ameliorating the risk of flooding ((Groeskamp and Kjellsson, 2020) & (van Strien *et al.*, 2021)).

- **Set-up**
  Although the NEED will protect the low-lying European countries against SLR, it does not entirely guarantee protection against flooding. Once the NEED has created an enclosed basin of the North Sea, the sea level can be slightly tilted upwards at the coast due to set-up. This phenomenon is depicted in Figure 1.5, and as is shown on the right, it generates a slightly higher water level, whereas on the left a slight drop in water level (set-down) is created.

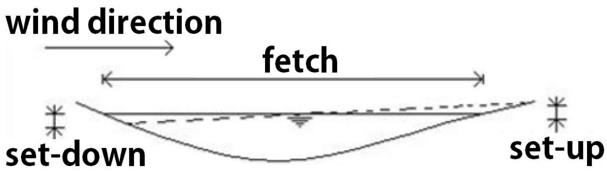



Figure 1.5: Visually depicting all elements related to the set-up process.

- **Coastal landscape**
  The coastal landscapes will change as a result of the NEED due to the changing sediment transport patterns which eventually alter the tidal plains and beaches. This could lead to some coastal regions requiring coastal nourishment and/or management in order to maintain the existing structures (Stronkhorst *et al.*, 2018).

- **(International) Politics**
  The enclosure of the North Sea will have a significant impact on European politics. Firstly, an international cooperation among the impacted countries will be necessary to realise a construction of this magnitude. And once constructed, many regulations regarding international law, transport and other aspects will have to be in place. Also, former EU member, United Kingdom, might not be receptive to this concept. Since the Brexit unequivocally indicated that the UK no longer wants to be part of the European Union, it will be difficult to sell the British on an enclosure dam that will physically reconnect them with the European Union. Let alone any other hindrance that will arise for the UK when proceeding with this plan.

- **Security and terrorism**
  Given that this structure protects millions of people against the rising sea level, it could be seen as a target for terrorists. Although it would probably need a significant amount of force and time to create a breach that would lead to a dangerous rise in water level.

- **Fresh water source**
  Due to the enclosure of the North Sea, the salt seawater slowly becomes more brackish water or even fresh water. This basin could then be useful in periods of extreme drought, which is likely to occur more frequently in the future due to global warming (Cook *et al.*, 2018).

- **Recreation**
  Apart from serving a practical function, the basin could also have recreational purposes.

### Environment

- **Transition of salt water to fresh water (salinity)**
  When constructing the NEED, the salty oceanic water will no longer be able to reach the North Sea basin, as it will be shielded by the dam. Naturally, this will affect the salinity of the basin as it will become fresher. This could have implications for the ecology. The changes in salinity might negatively affect the vegetation, marine life and birds (van Strien *et al.*, 2021).

- **Temperature**
  According to the study performed by the MDP group (van Strien *et al.*, 2021), the temperature fluctuations of the North Sea basin will decrease slightly in amplitude after the completion of the NEED. This could lead to an increase in ice formations due to the lower temperatures of the sea during winters. Furthermore, with the drop in salinity (mostly at the surface level), the ice formations increases. The second implication due

to the temperature change is related to the ecology. There is a possibility that some species are not able to adapt to these increased fluctuations. And also the change in temperature could influence the weather in some coastal regions.

### ECONOMY

- **Maritime transport**
  With the presence of the NEED, the usual course of the vessels will no longer be possible. Obviously, this is not conducive for the maritime transport and economy. Thus, it will be necessary to place sluices or create transshipment ports. Despite these sluices, shipping time will go up since entering and leaving the port within the created North Sea basin might become more challenging.

  Besides the hindrance of big vessels heading towards ports, the smaller fishery ships will be impacted as well. The effects the NEED will have on the environment could negatively influence the fish population, resulting in a economical setback for the fishermen who use the North Sea as their hunting waters.

- **Tourism**
  The dam will attract tourists as this enclosure dam will be (one of) the biggest hydraulic structure built by that time. A downside of the dam, however, is that it would render existing beaches obsolete as these would no longer be connected to the sea. Hence, tourism would suffer as a result.

- **Knowledge**
  Besides being one of the biggest civil engineering projects in history, the NEED will offer an opportunity to study what has never been done before on such a scale: closing off an entire sea. This knowledge can be useful to apply in other places where enclosing an sea might offer a solution to sea level rise as well.

- **Power generation**
  The NEED structure could also be used to our advantage in terms of power generation. The previously mentioned construction of the NEED will create a massive enclosed basin in the North Sea and this result in a transition of salt to fresh water. This difference in salinity can be used to our advantage, since this can be used to generate power. Through the use of membranes and the separation of positively and negatively charged ions, a battery-like situation can be created. This method is an perfect example of an unusual continuous sustainable energy generation method. The company REDstack — where RED stands for Reverse Electro-Dialysis — has installed such a test installation on the Afsluitdijk in the Netherlands and can be considered pioneers in this field (REDstack, 2021).

  Another way to generate power is through wind turbines. The North Sea basin will be an even more favourable location for the installation of wind farms, since the environment will be less rugged and corrosive due to the enclosure ((202, 2020) & Reubens *et al.* (2011)).

  Lastly, power generation through waves and tides can be explored as the created basin can now serve as the ideal experimental/research area.

At first glance, this NEED proposal might appear overwhelming and unrealistic, but in their preliminary study Groeskamp and Kjellson have suggested that it might not only be financially favourable, but also favourable in terms of scale, impacts and challenges, compared to alternative solutions, such as massive migrations and country-by-country protection efforts. Moreover, it also briefly touched on some technical considerations for constructing the NEED. However, its comparison with financial feasibility and ongoing national protection measures has solely been cross-referenced with examples from the Netherlands. The concept of constructing the NEED illustrates the extent of protection efforts that might be required if mitigation efforts fail to limit sea level rise.

An aspect which is absent from the study performed by Groeskamp and Kjellson and could be worth exploring, is the determination of when and for which SLR the NEED becomes more financially attractive, compared to the alternative country-by-country strengthening efforts as a function of the SLR.

## 1.2. Objective and research question

This thesis aims to gain additional insight into the effect of the NEED on the North Sea basin and to perform an analysis on how the NEED will withstand future sea level rises and its corresponding risks of flooding for the European countries. This was, to some extent, briefly studied by Groeskamp and Kjellsson (2020) in their preliminary study. However, the motivation of this thesis is to further investigate this and to determine the magnitude of SLR for which the NEED will become more financially attractive than the conventional country-by-country measures, i.e., dike reinforcement. It also will be determined under which conditions the NEED will become a more attractive alternative for protection of the North Sea basin when compared to the raising of coastal defences along the coasts of the European countries. The main research question of this thesis is therefore formulated as follows:

***At which SLR does the NEED become a more financially favourable strategy than raising coastal defences on a country-by-country basis in the countries around the North Sea?***

To answer this research question, other aspects will be analysed as well and are summarised in the following sub-questions:

- *What are the* ***exposed (flood-prone) areas*** *around the North Sea?*
- *What is the* ***size of the population*** *and* ***economic damages*** *in these exposed areas?*
- *What is the* ***length of coastal defences around the North Sea*** *that would need to be reinforced to combat SLR and at which* ***costs****?*
- *What are the* ***costs estimates*** *of the NEED as a function of SLR?*
- *How do the coastal reinforcement costs* ***compare*** *to the costs of the NEED and* ***at which SLR*** *would the NEED become favourable over reinforcing coastal defences?*

## 1.3. Research approach

It can be concluded from Section 1.1.3 that this enclosure dam will have an enormous impact on many aspects. In order for this project to succeed, these aspects all must be thoroughly analysed and clear agreements and policy proposals must be made. This thesis will not go into further detail on these aspects, but will mainly focus on the flood risk related aspects.

Figure 1.6 visualises the roadmap of this thesis. After an initial introduction, the thesis starts with an analysis of the current situation regarding the fight against the rising sea level, mainly focused on the area, population and economic damages, and concludes with an evaluation of the proposed NEED structure. The framework indicates what is included in the scope of this thesis. Furthermore, it indicates in which way the research will be conducted in order to conclusively answer the research question.

To this end, the study is divided into several parts. Firstly, the exposure area corresponding to different SLR levels must be determined. Subsequently, an estimation of the population affected in these areas can be determined as a function of the SLR. Thereafter, the economic damages can be determined, again as a function of the SLR. All aforementioned assessments make use of the GLOFRIS model framework and using QGIS, a geographic information system, the results found in GLOFRIS can be visualised (Ward *et al.*, 2020). These results will be used for the estimation of the reinforcement or construction costs of both the country-by-country flood protection and the NEED structure. After both adaptation strategies have been researched, a cost overview will be constructed to indicate which of the approaches is more economically attractive.

## 1.4. Readers guide

Figure 1.6 provides an visual overview of the layout of this thesis. Chapter 2 introduces the GLOFRIS model framework. This model framework is used for the assessment of future flood hazards and QGIS and ArcGIS are used for the subsequent visualisation. In Chapter 3, the three flood exposure indicators — inundated area, population exposed and the associated economic damages — are determined for all RCP scenarios and time frames relevant within the scope of this thesis. This gives a better sense of the importance and the magnitude of the project. Chapter 4 evaluates the reinforcing of the regional protection that is needed to withstand the SLR at the coastline that will be in the protection range of the NEED based on the results of Chapter 3. Chapter 5 then provides an assessment of the NEED structure and presents a cost estimation for the construction of this enclosure dam. Chapter 6 compares the regional and the NEED flood protection adaptation strategies in order to determine which strategy will provide greater financial benefit and under which conditions. Finally, Chapter 7, states the conclusion, a discussion and recommendations regarding the research performed in this report.

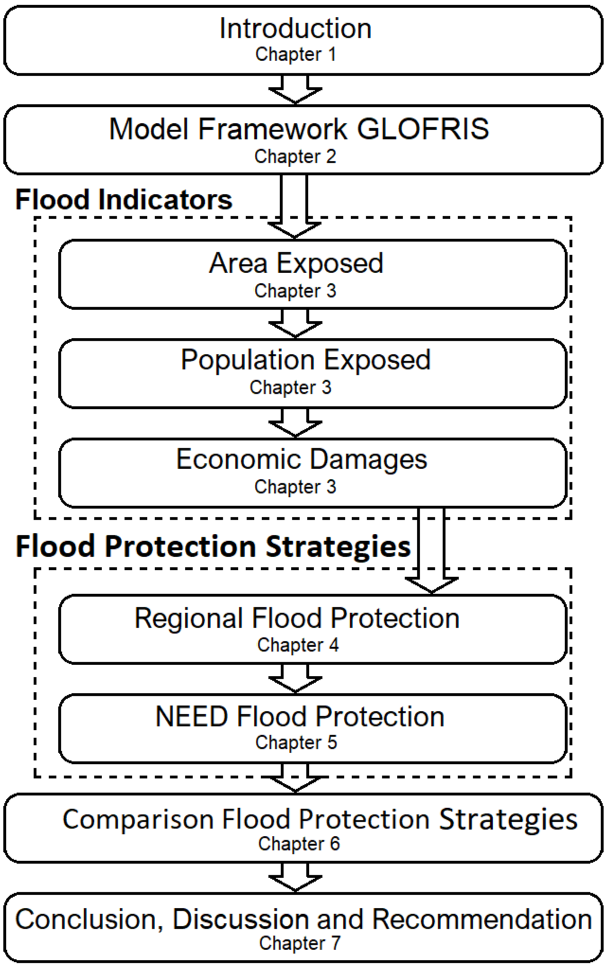



Figure 1.6: A visual overview of this thesis.

# 2

# Model Framework GLOFRIS

*This chapter will provide an extensive overview on the model framework GLOFRIS that is used in this thesis. Firstly, Section 2.1 states the problem at hand and the aspects of interest for this thesis. Section 2.2 will introduce the model framework GLOFRIS and give a guideline of the steps taken regarding this thesis project. Section 2.3 will briefly go through all the input variables used in the model. Lastly, Section 2.4 will state the assumptions made using GLOFRIS.*


## 2.1. Problem statement / Objective

Before designing the NEED, it is important to have a clear picture of the effect of climate change on the flood risk for the countries in question. The determined effects will be used to assess whether the construction of the NEED would be a good adaptation strategy.

The aspects of interest for this thesis are the population exposed, the area exposed and the resulting economic damages. In the following section, the methodology for retrieving information on these aspects is further explained. The model framework, GLOFRIS, enabled the simulation of the future results regarding the aspects of interest.

Before delving into the model, the term "risk" requires some further clarification. According to the Cambridge English Dictionary, risk is defined as "the possibility of something bad happening". As this research will be analysing a disaster risk, this term is according to IPCC a combination of three components: hazard, exposure and vulnerability (Cardona *et al.*, 2012). Hazard being a potential source of harm or adverse health effect on a person. Within the scope of this thesis, natural hazards, and more specifically floods, are of particular interest. Exposure refers to the inventory of elements in an area in which hazard events may occur. Vulnerability is the likelihood that assets will be affected when exposed to a hazard.

## 2.2. Model framework GLOFRIS

The model framework that is used to analyse the flood risk is called **GLOFRIS**, which is short for GLObal Flood Risk with Image Scenarios. This model framework is a tool for assessing all three components of flood risk, where the model distinguished between two hazard categories: riverine and coastal floods. However, since this thesis is solely focused on the coastal inundation caused by SLR, the riverine floods will be disregarded. By creating future climate scenarios through carefully selecting variables of relevance, the model framework can evaluate three flood exposure indicators: the total population exposed, the GDP (Gross Domestic Product) of the exposed area and the building damages. GLOFRIS simulates the flood risk by combining information on hazard, exposure and vulnerability (Ward *et al.*, 2020).

The hazard is presented through inundation maps, showing the flood extent and depth of floods of several return periods (2, 5, 10, 25, 50, 100, 250, 500 and 1.000 years). The return period of floods is the expected time interval between floods of a similar size or intensity. The resolution of these maps is of 30x30 arc seconds (30"x30"), which roughly equates to 1km x 1km at the equator. Unfortunately, the presence of flood protection has not been taken into account in the simulation of hazard layers by the GLOFRIS model framework. However, this does not mean that flood protection should be excluded in the risk computation. In order to still account for some form of flood protection standard in the analysis of this report, the effects of flood protection is incorporated in the risk calculation by assuming zero damage below the assumed standard of protection. This will be discussed in greater detail in the step-by-step guideline of the GLOFRIS model framework as well as in Section 2.4.

The exposure is represented by different input datasets. For the population and the GDP affected, exposure is expressed in gridded maps of population and GDP per cell. For the building damages, exposure is represented with land use maps showing which cells are urban and rural. Urban cells, or built-up cells, are comprised of at least 50 percent man-made structures and are assigned a value of maximum economic damage per square kilometre for each country. This represents the maximum damage (in USD$ purchasing power parity 2005 values per $km^2$) that could occur due to flooding in urban areas per $km^2$ per country.

The vulnerability of the population and the GDP to floods was assessed as a binary condition; either affected or non-affected. In any cell with inundation depths greater than 0, the population and the GDP within that cell were considered 100 percent vulnerable. This model framework did not include a distinction between different levels of vulnerability, such as forced migration, fatalities, etc.

For the building damages exposure indicator, the vulnerability is indicated with depth-damage functions, which show the percentage of the maximum damage that would actually occur for different inundation depths; these depth-damage functions are only applied for the building damage exposure indicator (Diaz Loaiza *et al.*, 2021). These global flood depth-damage functions were adopted from the database developed by Huizinga *et al.* (2017), and consist of normalised global damage curves up to six metres (m), and maximum damage to structures per country. The flood depth-damage function values for Europe is stated in Table 2.1. The model determines the maximum damage per country based on GDP per capita and construction cost surveys.

Table 2.1: Overview of flood depth-damage function values for Europe (Huizinga *et al.*, 2017).

| **Flood depth (m)** | 0 | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Damage (%)** | 0 | 25 | 40 | 50 | 60 | 75 | 85 | 85 | 95 | 100 |

Flood protection measures, such as dikes, can reduce the impact of a potential flood and are, therefore, important to consider when calculating the risk. In the GLOFRIS model, the default protection values are based on the FLOod PROtection Standards (FLOPROS) model methodology obtained from Scussolini *et al.* (2016).

FLOPROS is a database of current protection standards for both riverine and coastal floods, developed specifically for Aqueduct Floods, an online tool for measuring and mapping flood risks worldwide. For the database of FLOPROS an extensive literature review was finalised and rounded off with experts interviews to derive a dataset of flood protection standards around the world. However, as information on this matter is not available for many regions, a modelling approach was also developed. This modelling approach would compare the estimated values with reported values on flood protection standards for several locations. FLOPROS consists of three layers of information, and combines them into one dataset. The *design* layer contains information in the actual standard of existing protection; the *policy* layer contains information on protection standards from policy regulations; and the *model* layer uses a validated modelling approach to calculate protection standards. The policy layer and the model layer can be considered reasonable representatives of actual protection standards included in the design layer, and serve to increase the spatial coverage of the database (Scussolini *et al.*, 2016).

Regrettably, the FLOPROS database contains more detailed information on the riverine protection standards than its coastal counterpart. Coastal flood protection standards are only expressed for the design and policy layer, whereas the riverine flood protection standards also include a model and merged layer.

The coastal countries affected by the NEED are highlighted in FLOPROS and are illustrated in Figures A.1 through A.7 in Appendix A.1. The current coastal protection standard values of FLOPROS for all the states of the countries affected by the NEED can be found in Table A.1, A.2 and A.3. Here, the coastal protection standards are indicated as follows;

- **DL_Min_Co** and **DL_Max_Co**:
  The minimum and maximum return period value of the coastal flood protection standard in the Design Layer expressed in years, respectively.

- **PL_Min_Co** and **PL_Max_Co**:
  The minimum and maximum return period value of the coastal flood protection standard in the Policy Layer expressed in years, respectively.

Land subsidence is an important variable used for calculating future flood risk. In many coastal areas, groundwater extraction is the dominant cause of human-induced land subsidence ((Galloway *et al.*, 2016) & (Erkens and Sutanudjaja, 2015)). Land subsidence was modelled on a global scale using three existing models, namely the hydrological model PCR-GLOBWB, its integrated global Modular Finite-Difference Flow (MODFLOW) groundwater model and a land subsidence model.

Below a step-by-step guideline is stated of the necessary steps within the GLOFRIS model framework in order to attain results of the flood exposure indicators desired.

1. **Select a combination of variables (see Table 2.2) to set its projected scenario of which its flood exposure indicators values (i.e. GDP exposed, population exposed and economic damages) will be generated**

2. **Select Country as the geographical scale for the simulations output**

3. **Run GLOFRIS simulations for all relevant future indicator scenarios. The model framework returns:**
   - Global output of GLOFRIS flood exposure indicator values, at the country scale
   - Global future inundation map

4. **Obtain flood exposure indicator values for all NEED affected countries**

5. **Determine the base value (value in year 2010) for all countries based on each country's coastal flood protection standard**
   *Country's flood protection standard (in return period years) retrieved from FLOPROS, see Table 2.4*

6. **Subtract each country base value from their (projected) simulation outputs to find the approximate flood exposure indicator values**

7. **Determine the most dominant SSP scenario for the selected countries**
   *See Boxplot Figures B.1 through B.42 in Appendix B.1*

8. **Determine per country the dike reinforcement lengths along the coastlines in metres by subtracting the country base inundation map from the projected inundation maps (for RP1000)**

## 2.3. Input

In order to run simulations in GLOFRIS, it is necessary to carefully select the variables corresponding to the desired simulation scenario. This section will briefly elaborate on the applicable input variables for this model and will clarify the motivation for including specific variables. In Table 2.2, an overview of all the input variables used for the simulation within the GLOFRIS model framework is given. It should be noted that the input variables RCP and SSP, later described in more detail, are used for simulating various future scenarios as the other variables (i.e. Year, Return Period and Percentile) are used to simulate a range of severity of the outcome. Table B.2 in Appendix B.3 shows an overview of the specific scenarios simulated in GLOFRIS and indicates the number of runs necessary for a specific scenario per indicator.

Table 2.2: Overview of all input variables included in the GLOFRIS scenarios simulation.

| RCP | SSP | Year | Return Period (RP) (in years) | Percentile |
|---|---|---|---|---|
| 4.5 | 1 | 2010 | 100 | $5^{th}$ |
| 8.5 | 2 | 2030 | 500 | $50^{th}$ |
| | 3 | 2050 | 1000 | $95^{th}$ |
| | 4 | 2080 | | |
| | 5 | | | |

### 2.3.1. Percentiles of inundation

Each scenario has a certain 'bandwidth', or error band, of the flood exposure indicator output by GLOFRIS composed by three values. In the input inundation maps, this bandwidth is indicated by the $5^{th}$, $50^{th}$ and $95^{th}$ percentile. After simulation, GLOFRIS will have generated an output future inundation map associated with its percentile, which subsequently can be translated into a value per country. The $5^{th}$ percentile indicates the value below which 5% of the data falls. Similarly, 50% and 95% of the data fall below the $50^{th}$ (the median) and $95^{th}$ percentile, respectively. However, for interpreting this data, the flood exposure indicator values retrieved from the $50^{th}$ percentile represent scenarios which are derived from its global mean sea level. The minimum and maximum fluctuation generated by tides and surges due to climate variability are the $5^{th}$ and $95^{th}$, respectively. In Figure 2.1, it is illustrated how sea level, tides storm surges interact in normal conditions and in conditions of intensified storms.

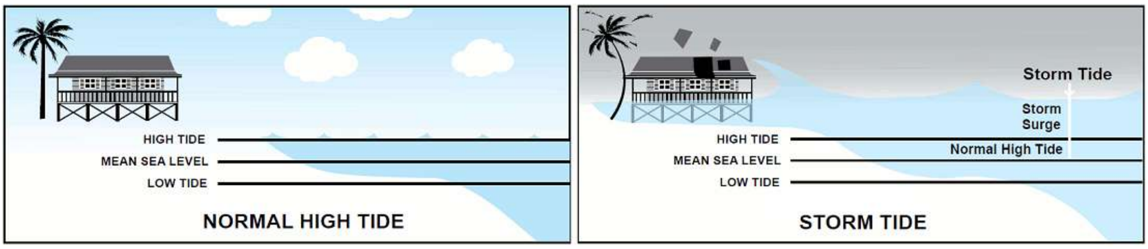



Figure 2.1: Effects of storm surges and tides on the SLR (Cassowary Coast, 2021).

### 2.3.2. Representative Concentration Pathways (RCP)

As briefly described in Section 1.1.1, the Representative Concentration Pathways (RCP) was developed by the researchers and describe different levels of greenhouse gases and other radiative forcing that can potentially occur in the future. The RCP scenarios describe alternative trajectories for carbon dioxide emissions and the resulting atmospheric concentration from the year 2000 up to 2100, which is depicted in Figure 2.2. The four trajectories, or pathways, developed by the IPCC span a broad range of radiative forcing values in 2100 (2.6, 4.5, 6.0 and 8.5 Watts per square metre), but purposefully did not include any socioeconomic 'narrative' to support them.

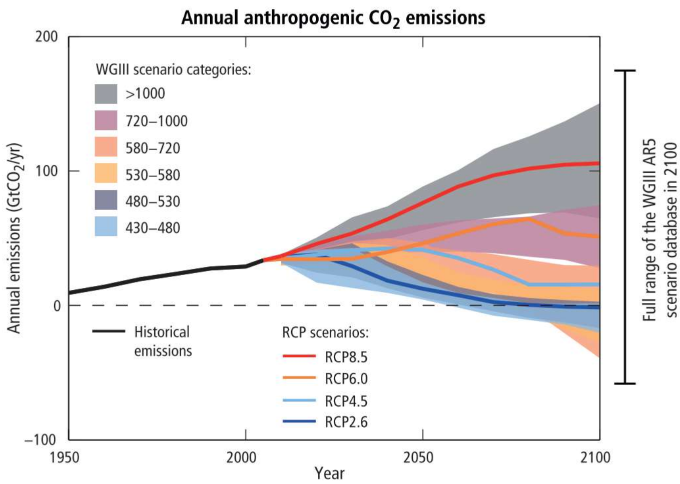



Figure 2.2: Emissions of carbon dioxide in the RPCs from 1950 up to 2100 (Pachauri and Meyer, 2015).

The simulations done for this research with GLOFRIS explored the RCP4.5 and RCP8.5 pathways, which creates two scenarios for the future. As such, this research can make a clear distinction between the effects it will have on the countries in question. The RCP4.5 scenario described by the IPCC is an intermediate scenario. The emissions in this pathway peak around 2040 and start declining around 2045. The RCP8.5, on the other hand, is a trajectory where emissions continue to rise throughout the 21$^{th}$ century. This pathway can be considered to be the worst-case climate change scenario and is based on an overestimation of the projected coal outputs.

### 2.3.3. Shared Socioeconomic Pathways (SSP)

As briefly described in Section 1.1.1, the Shared Socioeconomic Pathways (SSPs) are scenarios which show how socioeconomic factors, such as population, economic growth, education, urbanisation and the rate of technological development, could change up to 2100. These scenarios represent five different ways in which the world might evolve in the absence of climate policy as well as how different levels of climate change mitigation could be achieved when mitigation targets of RCP are combined with the SSPs. The two were designed to be complementary. The RCP set pathways for greenhouse gas concentrations and, effectively, the amount of warming that could occur by the end of the century. Here, the SSPs are the narratives of the future depending on challenges in mitigation and adaptation, however, these are possible outcomes of the future. The SSPs feature multiple baseline scenarios because underlying factors, such as population, technological, and economic growth, could lead to significantly different future emissions and global warming outcomes, even in the absence of climate policies. In Figure 2.3, all five scenarios are depicted in a graph in relation to the socioeconomic challenges for mitigation and adaptation. The SSPs are based on five narratives describing broad socioeconomic trends that could shape future society. These are intended to span a range of plausible futures. A brief explanation of each narrative can be found in Table B.1 of Appendix B.2.

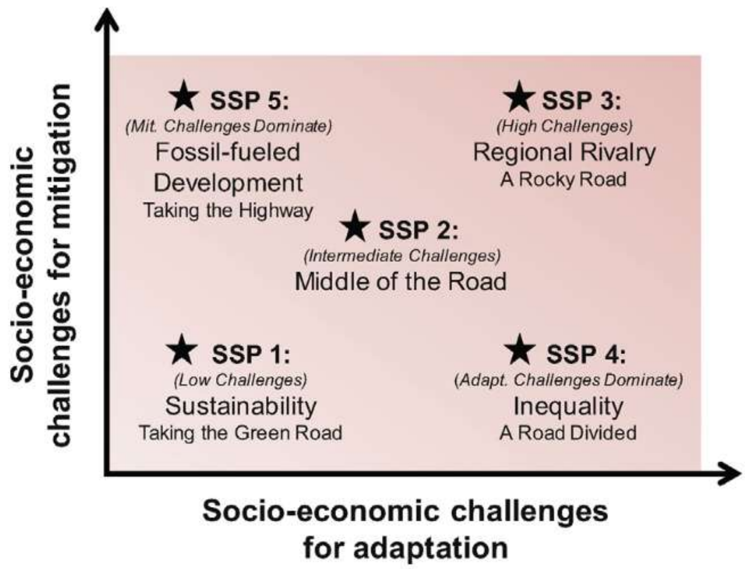



Figure 2.3: The five SSPs representing different combinations of challenges to mitigation and adaptation (O'Neill *et al.*, 2017).

Contrary to the RCP, it cannot immediately be assumed that SSP1 and SSP5 will have the best and worst outcome in terms of the exposure indicators, respectively. As the SSPs are dependent on multiple factors that each have an impact on its scenario, the outcome will not be as clear-cut. Additionally, the exposure maps required as an input map for the GLOFRIS model are contingent on the SSPs scenario and the year. For that reason, all five SSPs have been included in the GLOFRIS simulations as input to analyse its effect on the flood exposure indicators.

### 2.3.4. Years

The model is able to return inundation maps which show the inundated area, people exposed and damages generated for the years 2010, 2030, 2050 and 2080. For the future scenarios, i.e. all except 2010, a 'bandwidth' of the results is determined by three percentiles, namely 5$^{th}$, 50$^{th}$ and 95$^{th}$. The flood risk simulation of 2010 is assumed as the base scenario. In this study, the simulation using GLOFRIS was conducted for all possible model years. By doing so, it is possible to closely analyse the future development of the flood exposure indicators.

### 2.3.5. Return periods (RP)

The model calculates the indicator values through inundation maps showing the flood extent and depth for floods of several return periods. Coastal inundation maps with the following return periods are available: 1.5, 2, 5, 10, 25, 50, 100, 250, 500 and 1.000 years. For this research, it is opted to limit the return periods to 100, 500 and 1000 years. This is because the largest return periods correspond with the biggest impact on the indicators, which is most relevant for this research and also offers the practical benefit of limiting the amount of simulations necessary.

### 2.3.6. Subsidence

Besides the return period specified for an inundation map, these maps can also include land subsidence. For this research, it is chosen to include this effect, as it should in theory provide a more accurate simulation output. In addition to greater accuracy, it will also provide the biggest differential with a future simulation, therefore giving the greatest possible value of the effect on the exposure indicator.

### 2.3.7. Global Mean Sea Level Rise (GMSLR)

The inundation maps created through the determination of the sea water level (SWL). These inundation maps are derived by combining information on projections of the tide, (storm) surge, land elevation and GMSLR. The GMSLR used in the GLOFRIS model is retrieved from the Intergovernmental Panel on Climate Change (IPCC) report (Stocker *et al.*, 2013). The GMSLR values for scenarios RCP4.5 and RCP8.5 are stated in Table 2.3. As mentioned in Section 2.3.1, the value corresponding with the 50$^{th}$ percentile derived from GLOFRIS represents the GMSLR for a given year and scenario, whereas the 5$^{th}$ and 95$^{th}$ represent the minimal and maximal fluctuation in GMSLR caused by surges and tides due to climate variability. The traditional approach for projecting sea level rise is based on simulation of individual sea level components — contributions from ocean thermal expansion and melting/dynamics of glaciers and the ice sheets — which are then added up (Jevrejeva *et al.*, 2014). These components are listed below.

- Thermal expansion
- Glacier surface mass balance (SMB)
- Greenland SMB and dynamical changes
- Antarctica SMB and dynamical changes
- Changes in land water storage

Table 2.3: Overview of GMSLR (in metres) for different RCPs up to 2100 used in GLOFRIS (Stocker *et al.*, 2013).

| | RCP 4.5 | | | RCP 8.5 | | |
|---|---|---|---|---|---|---|
| **Year** | **5$^{th}$ percentile (Lower bound)** | **50$^{th}$ percentile (Estimated GMSLR)** | **95$^{th}$ percentile (Upper bound)** | **5$^{th}$ percentile (Lower bound)** | **50$^{th}$ percentile (Estimated GMSLR)** | **95$^{th}$ percentile (Upper bound)** |
| 2010 | 0.03 | 0.04 | 0.05 | 0.03 | 0.04 | 0.05 |
| 2030 | 0.09 | 0.13 | 0.16 | 0.10 | 0.13 | 0.17 |
| 2050 | 0.17 | 0.23 | 0.29 | 0.19 | 0.25 | 0.32 |
| 2080 | 0.28 | 0.41 | 0.54 | 0.37 | 0.51 | 0.67 |
| 2100 | 0.36 | 0.53 | 0.71 | 0.53 | 0.74 | 0.98 |

## 2.4. Assumptions

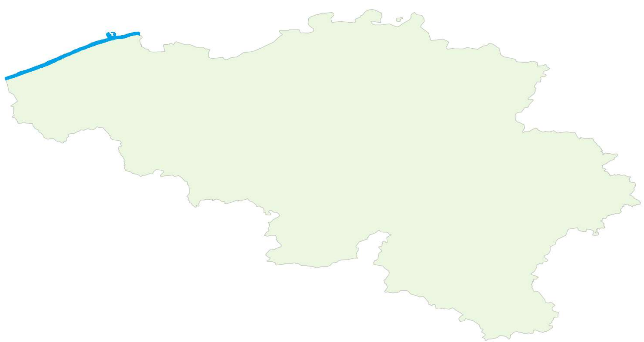
Although the GLOFRIS model framework generates predictions of the flood exposure indicator calculated for the future scenarios, these values might not reach the desired precision aligned with this research. This is due to the fact that there are some inconsistencies and limitations that have to be considered in the assessment when using this model framework. For this reason and to avoid overcomplicating this thesis, the following assumptions within this research were necessary:

1. The countries England and Scotland are combined in the GLOFRIS model framework as the UK (United Kingdom). Therefore, this thesis will assess a total of fourteen countries.

2. Flood exposure indicator values retrieved through GLOFRIS are country-based and are the indicator value for the entire coast of that country. When assuming that this indicator value will be avoided with the presence of the NEED, the full extent of the coast for each country should be protected by this dam. However, some countries (England, Scotland, Norway, Russia, France, e.g.) will not entirely be protected by this structure. Meaning

that the value retrieved from this model for these particular countries does not, in fact, have the correct magnitude of the indicator value that will be avoided. However, for the sake of this thesis research, this is assumed to be the case. To clarify, Figure 2.4(a) and Figure 2.4(b) illustrate this, taking France and Belgium as examples. Here the coastlines in blue fall within the protection range of the NEED, where the coastlines in red do not, indicating that the country-based flood exposure indicator values would, in reality, not hold true in this example.

(a) France



(b) Belgium

Figure 2.4: Indication of the protection range of the NEED for France (a) and Belgium (b), where blue coasts are protected and red are not.

3. GLOFRIS model does not take flood protections into account. Hence, the effects of flood protection is included by assuming zero damage below the assumed standard of flood protection in 2010, i.e. the base scenario. Naturally, this flood protection standard is different for each region of a country, as can be seen in Tables A.1, A.2 and A.3 in Appendix A.2. By means of the FLOPROS database, it is possible to assume the country's flood protection standard (FPS). However, due to the absence of some countries' coastal flood protection standards information, an assumption had to be made. An overview of the flood protection standards for the countries can be found in Table 2.4. The 'x' stated either in the *Design Layer* or *Policy Layer* indicates that the FLOPROS database did not have data on the return period for the country in question. With the countries' flood protection standards either defined or assumed, the base scenario value associated with the correct return period can be determined. Thus, the estimated base scenario value per country can be used to subtract from the value found for a future simulation in order to obtain the approximated flood exposure indicator value, as per Equation 2.1.

$$Flood\ exposure\ indicator\ value = Future\ simulation\ value - FPS\ Base\ simulation\ value\ (FLOPROS) \tag{2.1}$$

Table 2.4: Overview of flood protections for the countries according to FLOPROS (see Tables A.1, A.2 and A.3).

| Country | Country Code | Return Period FLOPROS | | Return Period Used |
|---|---|---|---|---|
| | | Design Layer (min. / max.) | Policy Layer (min. / max.) | |
| Belgium | BE | 1000 | 1000 | 1000 (max) |
| Denmark | DK | x | 50 / 1000 | 500 |
| Estonia | ES | x | x | 100 |
| Finland | FI | x | 100 | 100 |
| France | FR | x | x | 100 |
| Germany | DE | x | 100 | 100 |
| Latvia | LV | x | x | 100 |
| Lithuania | LT | x | x | 100 |
| Netherlands, the | NL | 4000 / 10.000 | 300 / 1000 | 1000 (max) |
| Norway | NO | x | x | 100 |
| Poland | PO | x | 100 / 200 | 100 |
| Russia | RU | x - 1000 / 10.0000 | x | 500 |
| Sweden | SE | x | x | 100 |
| United Kingdom, the | UK | x | 100 / 200 | 500 |

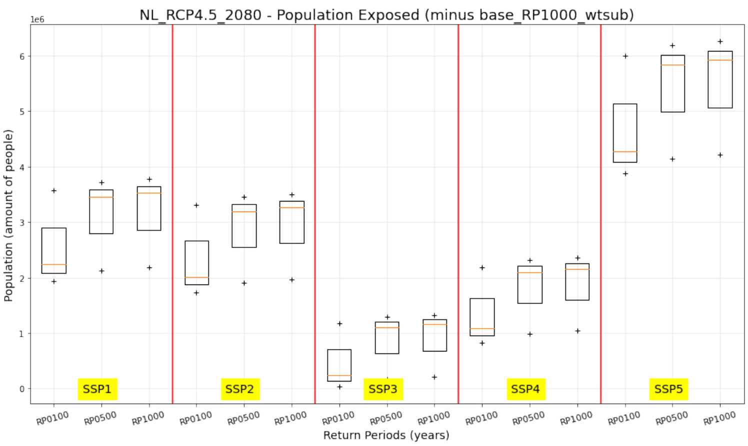
# 3

# Flood Exposure Indicator Results

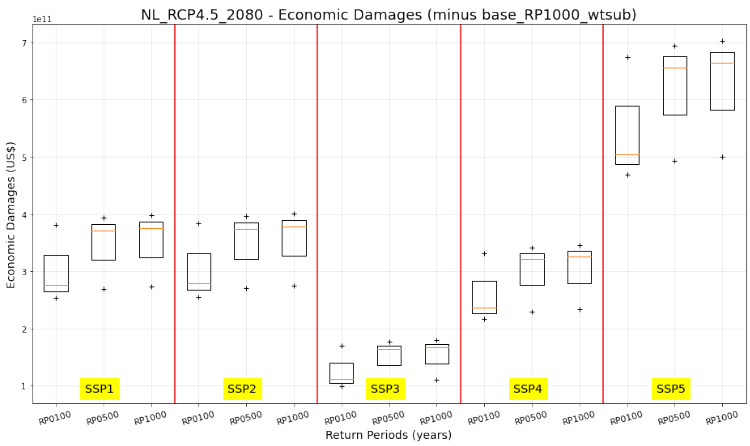
*This chapter delivers the results from the model framework GLOFRIS described in Chapter 2. Firstly, Section 3.1 briefly analyses the results regarding all SSPs and narrow these down to two SSPs, the most and least dominant scenarios, for subsequent calculation. Section 3.2 provides an overview of the area inundated for all European countries in question. Lastly, the results of the population exposed and economic damages obtained from the simulations run with GLOFRIS are given and analysed in Section 3.3 and Section 3.4, respectively.*


## 3.1. Scenario Determination

With the GLOFRIS model framework, it was possible to determine the flood risk in terms of population exposed and economic damage for all the countries affected by the NEED. This is done for all SSP scenarios for both RCP4.5 and RCP8.5 regarding the three return periods chosen for the analysis. These results regarding all SSP scenarios are depicted in boxplots and can be found in Section B.1 in Appendix B. In Figure 3.1(a) and Figure 3.1(b) the scenario RCP4.5 boxplots with return periods 100, 500 and 1000 years of both the increase in population exposed and economic damages for the Netherlands are depicted as an example. In the boxplots, the red lines represent the medians ($50^{th}$ percentile; median), the box represents the range of the interquartile ($Q_3$-$Q_1$; the distance between the upper ($Q_3$=$75^{th}$ percentile) and lower ($Q_1$=$25^{th}$ percentile) quartiles) and the plus signs in this case represent the $5^{th}$ (lower sign) and the $95^{th}$ (upper sign) percentile, respectively.




(a) Population exposed




(b) Economic damage

Figure 3.1: Increase in population exposed and economic damage for all five SSPs of the RCP4.5 scenario for the Netherlands.

From these boxplots, it is clearly visible which SSP scenarios are the least and most dominant in the future. In other words, which SSP scenario generated the lowest and the highest values for the flood exposure indicators. The least dominate and the most dominant SSP scenario per country per flood exposure indicator from all boxplots are summarised in Table 3.1 and Table 3.2, respectively. In these tables the SSP scenarios which derogate from the rest for both the population exposed and economic damage are indicated in bold.

Table 3.1: The SSP's (Shared Socioeconomic Pathway) per country which generated the **lowest** value in the year 2080 for RCP4.5 and RCP8.5.

| | | RCP 4.5 - 2080 - RP1000 | | RCP 8.5 - 2080 - RP1000 | |
|---|---|---|---|---|---|
| **Country** | **Country Code** | **POP Exposed** | **Economic Damage** | **POP Exposed** | **Economic Damage** |
| Belgium | BE | SSP3 | SSP3 | SSP3 | SSP3 |
| Denmark | DK | SSP3 | SSP3 | SSP3 | SSP3 |
| Estonia | ES | SSP3 | SSP3 | SSP3 | SSP3 |
| Finland | FI | SSP3 | SSP3 | SSP3 | SSP3 |
| France | FR | SSP3 | SSP3 | SSP3 | SSP3 |
| Germany | DE | SSP3 | SSP3 | SSP3 | SSP3 |
| Latvia | LV | **SSP5** | SSP3 | **SSP5** | SSP3 |
| Lithuania | LT | **SSP4** | SSP3 | **SSP4** | SSP3 |
| Netherlands, the | NL | SSP3 | SSP3 | SSP3 | SSP3 |
| Norway | NO | SSP3 | SSP3 | SSP3 | SSP3 |
| Poland | PO | SSP3 | SSP3 | SSP3 | SSP3 |
| Russia | RU | **SSP4** | SSP3 | **SSP4** | SSP3 |
| Sweden | SE | SSP3 | SSP3 | SSP3 | SSP3 |
| United Kingdom, the | UK | SSP3 | SSP3 | SSP3 | SSP3 |

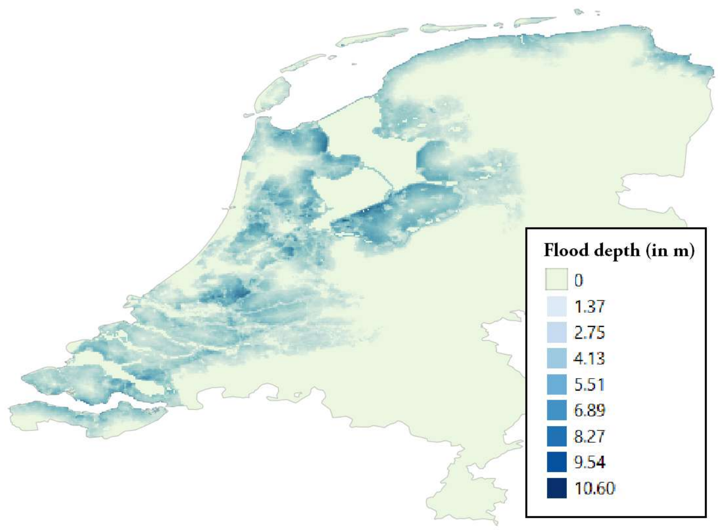
Table 3.2: The SSP's (Shared Socioeconomic Pathway) per country which generated the **greatest** value in the year 2080 for RCP4.5 and RCP8.5.

| | | RCP 4.5 - 2080 - RP1000 | | RCP 8.5 - 2080 - RP1000 | |
|---|---|---|---|---|---|
| **Country** | **Country Code** | **POP Exposed** | **Economic Damage** | **POP Exposed** | **Economic Damage** |
| Belgium | BE | SSP5 | SSP5 | SSP5 | SSP5 |
| Denmark | DK | SSP5 | SSP5 | SSP5 | SSP5 |
| Estonia | ES | SSP5 | SSP5 | SSP5 | SSP5 |
| Finland | FI | SSP5 | SSP5 | SSP5 | SSP5 |
| France | FR | SSP5 | SSP5 | SSP5 | SSP5 |
| Germany | DE | SSP5 | SSP5 | SSP5 | SSP5 |
| Latvia | LV | **SSP3** | SSP5 | **SSP3** | SSP5 |
| Lithuania | LT | **SSP3** | SSP5 | **SSP3** | SSP5 |
| Netherlands, the | NL | SSP5 | SSP5 | SSP5 | SSP5 |
| Norway | NO | SSP5 | SSP5 | SSP5 | SSP5 |
| Poland | PO | SSP5 | SSP5 | SSP5 | SSP5 |
| Russia | RU | **SSP3** | SSP5 | **SSP3** | SSP5 |
| Sweden | SE | SSP5 | SSP5 | SSP5 | SSP5 |
| United Kingdom, the | UK | SSP5 | SSP5 | SSP5 | SSP5 |

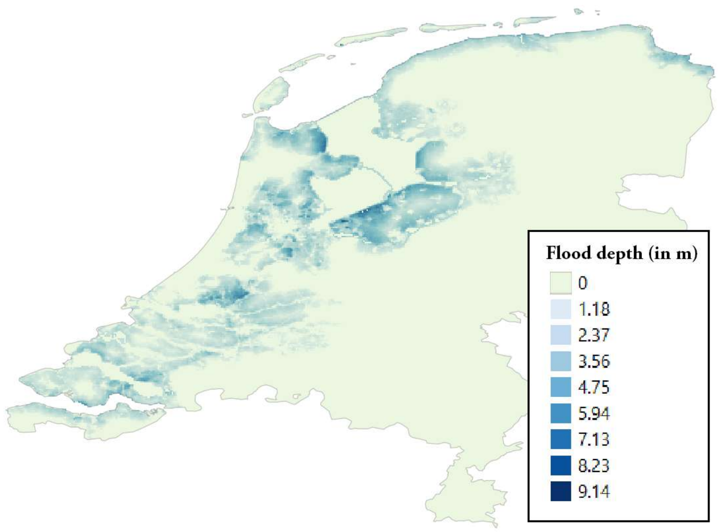
From Tables 3.1 and 3.2, it can be concluded that nearly all countries have the same dominant SSP scenarios which generated the highest and lowest value for the flood exposure indicators. With Latvia, Lithuania and Russia as the only exceptions regarding the population indicator, it is determined that **SSP3** (*Regional Rivalry - high challenges to mitigation and adaptation*) and **SSP5** (*Fossil-fueled Development - high challenges to mitigation, low challenges to adaptation*) are the least and most dominant SSP scenarios, respectively, and are therefore assumed as such in further calculations/modulations. It does not come as a surprise that scenario SSP5 generates the most dominant values as, like the name suggest, it is founded on fossil-fueled development.

## 3.2. Area exposed

In order to determine the area exposed through the inundation maps, it is paramount to analyse the inundation maps used as an input for the GLOFRIS model framework. A similar approach is used for determining the inundated area, but it requires the base scenario to be subtracted from the future scenario for every individual cell on the maps, rather than the summarised values of each country. By doing so, the increment of inundation per cell is determined, making it possible to exactly assess the inundated area for all countries. As an example, both inundation maps of the Netherlands are depicted in Figure 3.2(a) and (b), where 3.2(a) is the map of the future scenario (RCP8.5 in 2080 for the 50$^{th}$ percentile) and 3.2(b) is the base scenario (2010), corresponding to the flood protection standard of 1000 years for the Netherlands. The subtracted inundation map for this example of the Netherlands is depicted in Figure 3.3. All inundation maps (the subtractions from future and base scenarios) can be found in Section D.1 in Appendix D.




(a) Inundation map of the Netherlands for RCP8.5 with RP1000 years in 2080 for the 50$^{th}$ percentile.




(b) Inundation map of the Netherlands for the year 2010 (base scenario).

Figure 3.2: Inundation maps of the Netherlands for the years 2080 (a) and 2010 (b).

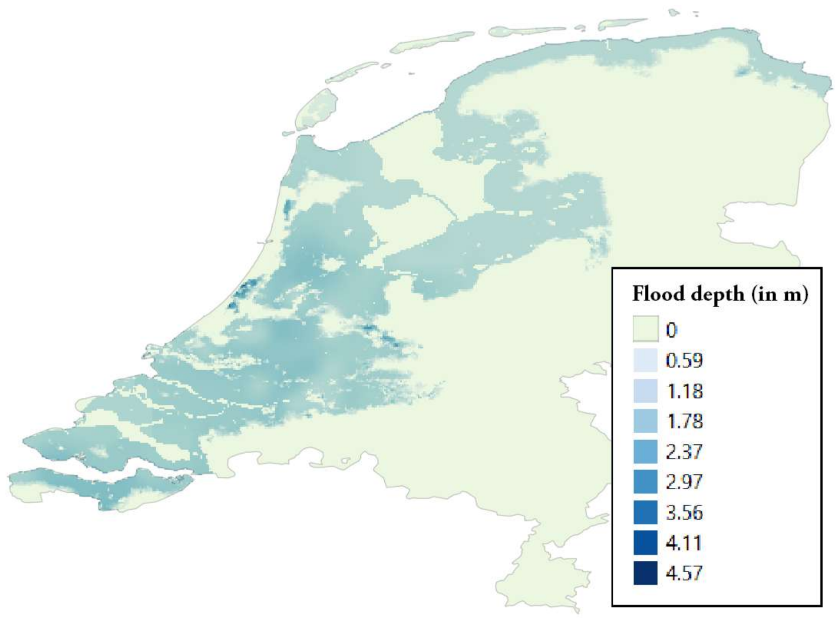



Figure 3.3:
The inundation map of the Netherlands for RCP8.5 with RP1000 years in 2080 for the 50$^{th}$ percentile after subtraction of the base scenario.

In Table 3.3, an overview is given of the total area and the inundated area per country (based on the shapefiles from QGIS). From this table it can be concluded that the Netherlands, Germany, France and Russia are the countries that will be inundated the most. These numbers are related to the results obtained in QGIS and are pixel-based. This means that the inundated area is determined based on the amount of pixels containing an inundation value divided by the total number of pixels per country times the amount of area (in $km^2$) the total pixels represent. The approach for the determination of the inundated area per country is expressed in Equation 3.1.

$$Inundated\ area = \frac{Number\ of\ pixels\ inundated\ per\ country}{Total\ number\ of\ pixels\ per\ country} \cdot Area\ country \tag{3.1}$$

Table 3.3: Overview of area inundated per country for scenario RCP8.5 with a return period of 1000 years compared to the base scenario in 2010.

| Country | Total Area ($km^2$) | Percentage inundation (pixel-based) | Area inundated ($km^2$) |
|---|---|---|---|
| Belgium | 30,480 | 1.531 % | 467 |
| Denmark | 42,671 | 0.006 % | 2.5 |
| Estonia | 45,545 | 0.010 % | 4.5 |
| Finland | 333,797 | 0.027 % | 90 |
| France | 546,729 | 0.261 % | 1,428 |
| Germany | 356,109 | 1.073 % | 3,821 |
| Latvia | 64,299 | 0.032 % | 21 |
| Lithuania | 64,849 | 0.063 % | 41 |
| Netherlands, the | 35,493 | 16.55 % | 5,876 |
| Norway | 316,962 | 0.028 % | 90 |
| Poland | 310,715 | 0.134 % | 418 |
| Russia | 16,851,940 | 0.012 % | 2,059 |
| Sweden | 443,780 | 0.013 % | 58 |
| United Kingdom, the | 243,137 | 0.230 % | 560 |

The inundated area of the respective countries is indicated with a light green colour in the figures. It should be noted, however, that the area does not solely contain land, but also lakes and rivers. Looking at the Netherlands for example, in Figure 3.2 and Figure 3.3, it is clearly visible that the IJsselmeer is included in the total area of the country. Thus, when determining the total area of inundation through pixels, it should be noted that the percentage found in Table 3.3 are (slightly) greater in reality.

## 3.3. Population exposed

Using the GLOFRIS model framework, the total population exposed is determined until 2080 for all the countries in question for both the RCP4.5 and 8.5 scenario. Since the years are associated with a specific GMSLR level, a graph is constructed for each country indicating the increase in population exposed versus the GMSLR level. The RCP4.5 graphs for all countries are given in Figure C.1 through Figure C.14 in Appendix C.2 and for RCP8.5 in Figure C.17 through Figure C.30 in Appendix C.3. In Figure 3.4, the RCP8.5 scenario graph of the increase in population exposed for the Netherlands is depicted as an example.

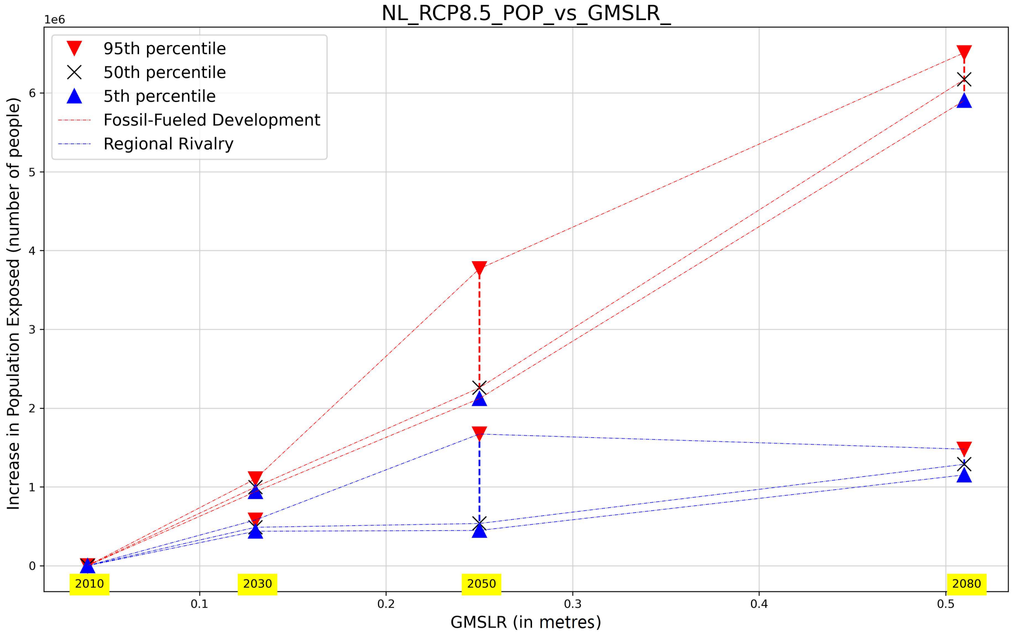



Figure 3.4: Graph of Population in NL for scenario RCP8.5 with RP1000 as a function of GMSLR.

It is not feasible to determine a specific value for a future scenario as there are too many uncertainties. Therefore, a value range is defined using the $5^{th}$, $50^{th}$ and $95^{th}$ percentile in the graphs. However, Table 3.4 has been added to help put all the countries into perspective, which includes the values of the medians ($50^{th}$ percentile, P50) and its relative increase compared to the base value of the country. In this table, an overview of the increase in exposed population is given in percentages compared to the base value (from 2010) per country for all countries in 2080. Keep in mind that all values at 2010 are set to base scenario and thus equal to values of zero, as also can be seen in the graphs. To provide some clarity on Table 3.4, according to GLOFRIS the Netherlands will roughly have 3.3 million people exposed to inundation in 2010 (base value). Considering scenario RCP4.5 with SSP3, the Netherlands is expected to have an increase in people affected by roughly 1.2 million in 2080, thus having a total of approximately 4.5 million affected by inundation. While for scenario RCP4.5 with SSP5, the Netherlands has an increase of 5.9 million in 2080 giving a total of approximately 9.2 million affected. In the case of Estonia, the percentage increase relative to the base scenario cannot be given as there are no people exposed to inundation at its base level.

Table 3.4: Overview of the increase in population exposed (in people) relative to the base scenario for SSP3 & SSP5 for all the countries in 2080 regarding RCP4.5 & 8.5.

| | | RCP4.5 - 2080 - P50 | | | | RCP8.5 - 2080 - P50 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Country** | **Base Values** | **SSP3** | | **SSP5** | | **SSP3** | | **SSP5** | |
| Belgium | 56,719 | 150,927 | + 266 % | 498,970 | + 880 % | 161,951 | + 286 % | 520,525 | + 918 % |
| Denmark | 16,039 | 8,096 | + 50 % | 56,810 | + 354 % | 12,037 | + 75 % | 72,125 | + 450 % |
| Estonia | 0 | 203 | [203] | 424 | [424] | 207 | [207] | 431 | [431] |
| Finland | 1,934 | 3,028 | + 157 % | 9,822 | + 508 % | 4,408 | + 228 % | 12,988 | + 672 % |
| France | 222,530 | 129,051 | + 58 % | 623,506 | + 280 % | 172,104 | + 77 % | 706,929 | + 318 % |
| Germany | 422,385 | -136,452 | - 32 % | 388,518 | + 92 % | -112,970 | - 27 % | 414,814 | + 98 % |
| Latvia | 20 | 236 | + 1,180 % | 174 | + 870 % | 781 | + 3,905 % | 589 | + 2,945 % |
| Lithuania | 634 | 369 | + 58 % | -87 | - 14 % | 961 | + 152 % | 235 | + 37 % |
| Netherlands, the | 3,294,912 | 1,161,556 | + 35 % | 5,920,312 | + 180 % | 1,287,378 | + 39 % | 6,171,640 | + 187 % |
| Norway | 18,107 | 3,850 | + 21 % | 37,751 | + 208 % | 4,553 | + 25 % | 39,655 | + 219 % |
| Poland | 18,790 | -977 | - 5 % | 13,108 | + 70 % | 3,258 | + 17 % | 22,941 | + 122 % |
| Russia | 10,790 | 8,436 | + 78 % | 1,488 | + 14 % | 13,022 | + 121 % | 4,420 | + 41 % |
| Sweden | 4,073 | 5,065 | + 124 % | 25,181 | + 618 % | 7,935 | + 195 % | 34,935 | + 858 % |
| United Kingdom, the | 428,090 | 178,162 | + 42 % | 1,271,468 | + 297 % | 233,551 | + 55 % | 1,405,090 | + 328 % |
| **Total** | 4,495,023 | 1,511,550 | - | 8,847,445 | - | 1,789,176 | - | 9,407,317 | - |

In addition to this table, Figures 3.5 and 3.6 visualise the increase in exposed population (expressed in number of people) per country for the RCP scenarios 4.5 and 8.5, respectively. In the barchart, the blue bars represent the Regional Rivalry (SSP3) and the red represent the Fossil-Fueled Development (SSP5) SSP scenario. Note that the charts are logarithmically scaled, as a linear scale is unable to meaningfully depict the data for countries such as Estonia, Latvia and Lithuania, that have relatively small indicator values. The values corresponding to the 5th, 50th and 95th percentile for each country corresponding to the years can be found in the tables below the graph for each country in Appendix C.2 and Appendix C.3 for RCP scenario 4.5 and 8.5, respectively.

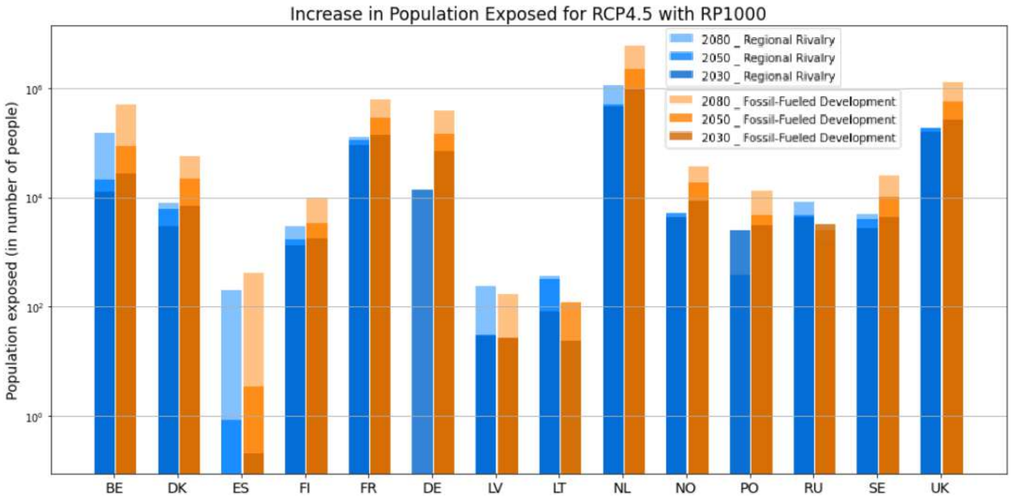



Figure 3.5: Barcharts of increase in population exposed for all 14 countries for RCP4.5 scenario.

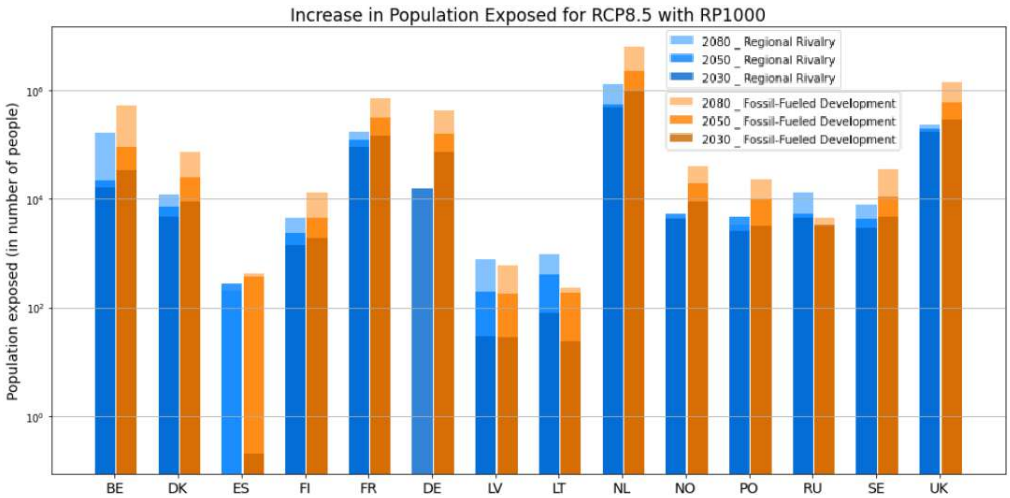



Figure 3.6: Barcharts of increase in population exposed for all 14 countries for RCP8.5 scenario.

Analysing the results from Table 3.4, there are several interesting findings from the results. First of all, Estonia did not have any people exposed to the inundation at 2010, giving a value of zero as base value. This made it impossible to express the growth of future exposed population in Estonia relative to the base value. For this reason, the total population exposed to inundation in Estonia is expressed in Table 3.4 in number of people, indicated in brackets.

Another noteworthy finding from Table 3.4 is that certain countries experience a decrease rather than an increase in population exposure value comparing the Regional Rivalry with the Fossil-Fueled Development SSP scenarios. This is the case for Latvia, Lithuania and Russia. This did not come as an surprise, as Table 3.1 and Table 3.2 already alluded to this. This has to do with the individual societal development from the SSP scenario regarding the challenges to mitigation and adaptation within a country or coastal cities.

Furthermore, the countries Germany and Poland had striking results with regard to the values for the Regional Rivalry scenario, as its negative percentages imply an exposed population that is smaller than the base values from 2010. Besides this relating to the country's challenges to mitigation and adaptation, it is also strongly correlated with the total change of the country's population. Meaning that for these countries it is apparent that an decrease in total population will occur in the future. In other words, the negative percentages reflect a reduction in population exposed due to an expected overall decrease in total population in the country analysed.

Comparing the increase in population exposed to the base values per country, Latvia and Belgium have the highest percentual increase. However, in terms of the number of people exposed, it is clear that the Netherlands is the evident loser, whereas Germany and Lithuania seem to be impacted the least. The values corresponding to the three aforementioned countries expressed in the number of people exposed are listed in Table 3.5.

Table 3.5: Overview of the countries most and least impacted with regards to the increase in population exposed (in number of people).

| | **RCP4.5 - 2080 - P50** | | **RCP8.5 - 2080 - P50** | |
|---|---|---|---|---|
| **Country** | **SSP3** | **SSP5** | **SSP3** | **SSP5** |
| Netherlands, the | 1,161,556 | 5,920,312 | 1,287,378 | 6,171,640 |
| Germany | -136452 | - | -112970 | - |
| Lithuania | - | -87 | - | 235 |

In the bottom row of Table 3.4, the overall exposed population to the future inundation is expressed in number of people. It is readily apparent that the Fossil-Fueled Development SSP scenario has roughly a 5.5 times larger population exposed to the rising SLR than Regional Rivalry and thus generates a more disastrous outcome for the future. Also, it can be recognised that the country with the greatest population exposed is the Netherlands, as it accounts for roughly 70% of the total population exposed for both considered RCP and SSP scenarios.

## 3.4. Economic damages

For the increase in economic damages exposed to future inundation heights, a similar approach is taken as with the increase in population exposed. The RCP4.5 graphs for all countries are depicted in Figure C.33 through Figure C.46 in Appendix C.5 and for RCP8.5 in Figure C.54 through Figure C.62 in Appendix C.6. In Figure 3.7, the scenario RCP8.5 graph of the increase in population exposed for the Netherlands is depicted as an example.

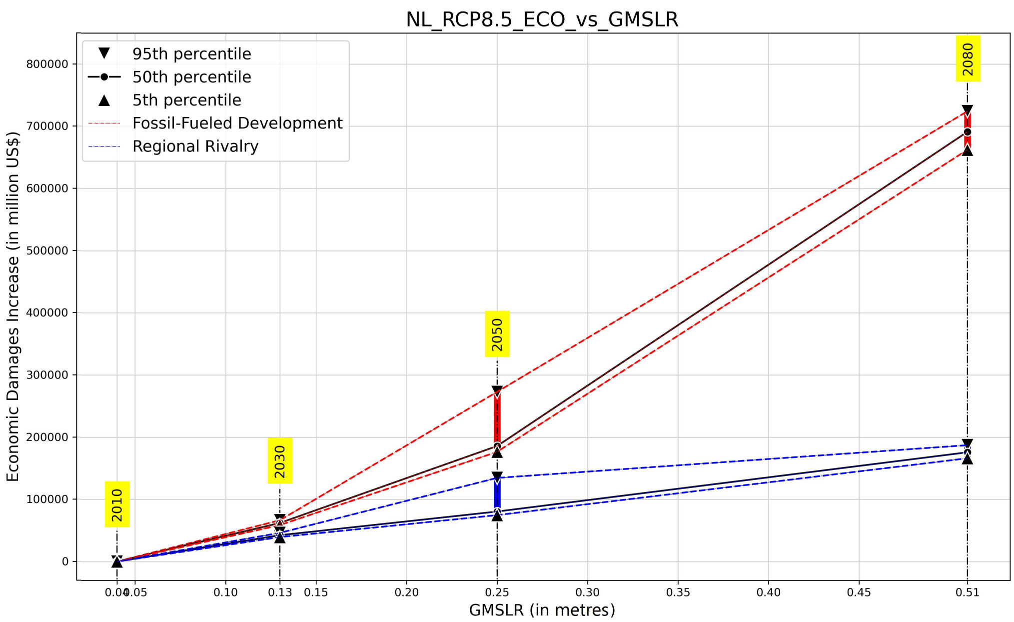



Figure 3.7: Graph of Economic Damages in NL for scenario RCP8.5 with RP1000 as a function of GMSLR.

In Table 3.6, all values of the median (50th percentile) of each country are shown. This table provides an overview of the increase in economic damages exposed as well as the percentual change relative to the base value per country for all countries in 2080. Keep in mind that all values at 2010 are set to base scenario and thus equal to zero, as can be seen in the graphs. To provide some clarity on Table 3.6, according to GLOFRIS, the Netherlands has roughly 77 billion € in economic damages that is caused by inundation in 2010 (base value). Considering scenario RCP4.5 with SSP3, the Netherlands is expected to have an increase in economic damage by roughly 144 billion € in 2080 and thus having a total of approximately 221 billion € in damages. While for scenario RCP4.5 with SSP5, the Netherlands has an increase of 574 billion € in 2080 giving a total of approximately 651 billion € in damages.

Table 3.6: Overview of the increase in economic damages (in million €) relative to the base scenario for SSP3 & SSP5 for all the countries in 2080 regarding RCP4.5 & 8.5.

| | | RCP4.5 - 2080 - P50 | | | | RCP8.5 - 2080 - P50 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Country** | **Base Values** | **SSP3** | | **SSP5** | | **SSP3** | | **SSP5** | |
| Belgium | 2,976 | 23,509 | + 790 % | 80,421 | + 2,702 % | 25,140 | + 845 % | 85,352 | + 2,868 % |
| Denmark | 1,097 | 2,186 | + 199 % | 9,099 | + 830 % | 2,637 | + 240 % | 10,484 | + 956 % |
| Estonia | 11 | 65 | + 572 % | 278 | + 2,463 % | 76 | + 677 % | 313 | + 2,773 % |
| Finland | 39 | 188 | + 485 % | 734 | + 1,893 % | 273 | + 704 % | 1,023 | + 2,638 % |
| France | 3,914 | 7,607 | + 194 % | 37,111 | + 948 % | 8,381 | + 214 % | 39,827 | + 1,018 % |
| Germany | 14,393 | 15,350 | + 107 % | 106,533 | + 740 % | 16,740 | + 116 % | 111,995 | + 778 % |
| Latvia | 1.4 | 7 | + 464 % | 21 | + 1,495 % | 11 | + 772 % | 34 | + 2,345 % |
| Lithuania | 7.1 | 48 | + 678 % | 93 | + 1,311 % | 62 | + 869 % | 119 | + 1,672 % |
| Netherlands, the | 76,963 | 144,062 | + 187 % | 573,790 | + 746 % | 151,870 | + 197 % | 597,265 | + 776 % |
| Norway | 210 | 251 | + 119 % | 1,480 | + 704 % | 290 | + 138 % | 1,626 | + 774 % |
| Poland | 532 | 901 | + 169 % | 5,182 | + 974 % | 1,196 | + 225 % | 6,354 | + 1,194 % |
| Russia | 280 | 1,125 | + 402 % | 3,238 | + 1,158 % | 1,300 | + 465 % | 3,675 | + 1,314 % |
| Sweden | 167 | 591 | + 354 % | 2,177 | + 1,303 % | 770 | + 461 % | 2,733 | + 1,636 % |
| United Kingdom, the | 9,823 | 17,316 | + 176 % | 98,575 | + 1,004 % | 19,717 | + 201 % | 107,941 | + 1,099 % |
| **Total** | 110,413.5 | 213,205 | - | 918,732 | - | 228,462 | - | 968,740 | - |

In addition to this table, Figures 3.8 and 3.9 visualise the increase in economic damages (in million €) per country for the RCP scenarios 4.5 and 8.5, respectively. In the barchart, the blue bars represent the Regional Rivalry (SSP3) and the red represent the Fossil-Fueled Development (SSP5) SSP scenario. Note that the charts are logarithmically scaled, as a linear scale is unable to meaningfully depict data for countries such as Estonia, Latvia and Lithuania, that have relatively small indicator values. The values corresponding to the 5th, 50th and 95th percentile for each country corresponding to the years can be found in the tables below the graph for each country in Appendix C.5 and Appendix C.6 for RCP scenario 4.5 and 8.5, respectively.

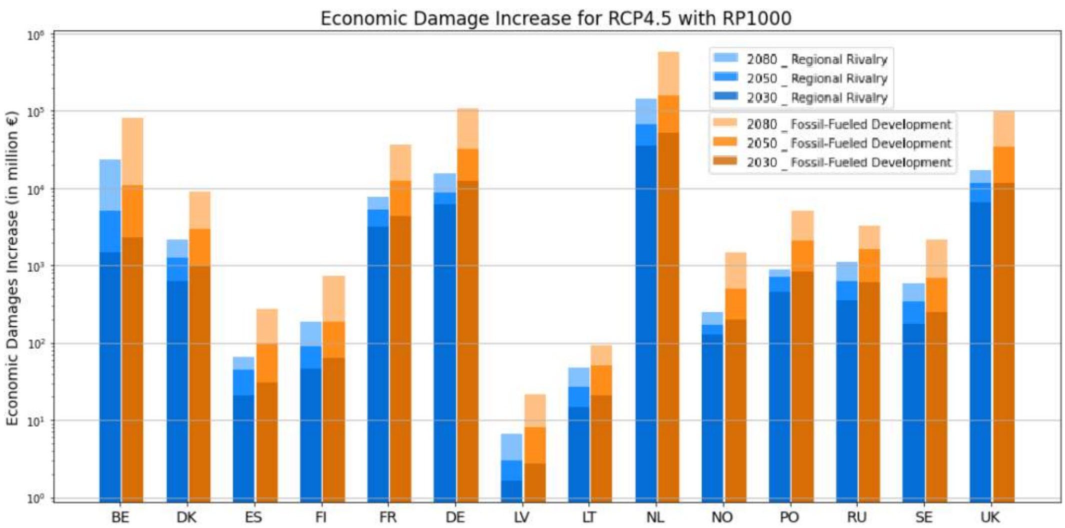



Figure 3.8: Barcharts of increase in economic damages for all 14 countries for RCP4.5 scenario.

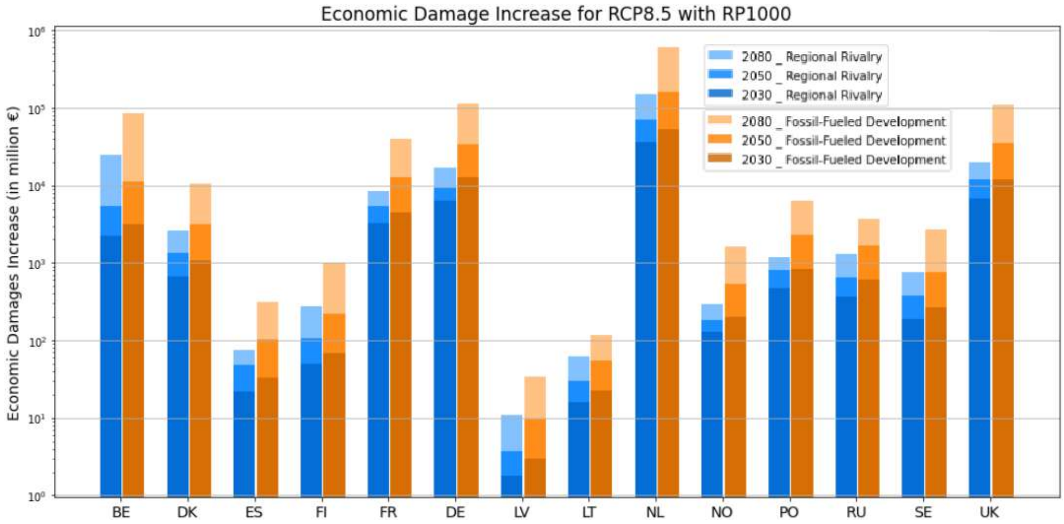



Figure 3.9: Barcharts of increase in economic damages for all 14 countries for RCP8.5 scenario.

All countries experience an increase in economic damages relative to the base scenario of 2010, which is self-evident since the water level around the world rises as well. Also, the greater economic damages for the Fossil-Fueled Development SSP scenario compared to the Regional Rivalry scenario is observed for all countries. This was to be expected, given the data in Table 3.1 and Table 3.2. However, naturally the rate of increment varies for all countries.

Analysing the increase in economic damages relative to the base values per country, it was found that Belgium and Lithuania have the highest percentual increase. However, in terms of the costs in million €, it is clear that Latvia and the Netherlands are the least and most impacted countries, respectively. The values corresponding to the Netherlands and Latvia expressed in millions € of economic damage are listed in Table 3.7.

Table 3.7: Overview of the countries most and least impacted with regards to the increase in economic damages (in million €).

| | **RCP4.5 - 2080 - P50** | | **RCP8.5 - 2080 - P50** | |
|---|---|---|---|---|
| **Country** | **SSP3** | **SSP5** | **SSP3** | **SSP5** |
| Netherlands, the | 144,062 | 573,790 | 151,870 | 597,265 |
| Latvia | 7 | 21 | 11 | 34 |

In the bottom row of Table 3.6, the overall economic damage caused by the future inundation is stated in million €. It is readily apparent that the Fossil-Fueled Development SSP scenario estimates a roughly 4.25 times greater population unprotected against to the rising SLR than the Regional Rivalry scenario and thus generates a more disastrous outcome for the future. Also, it can be recognised that the greatest economic damages are suffered by the Netherlands as it accounts for roughly 65% of the total damages for both considered RCP and SSP scenarios.

# 4

# Regional Flood Protection

*This chapter provides a detailed look into the regional flood protection adaptation strategy, which is the first of two solution adaptation strategies analysed in this thesis. Firstly, Section 4.1 provides background information on dike reinforcement in general and introduces the important factors that will be analysed later in this chapter. Section 4.2 provides the length assessment and overview of the coast reinforcement for all countries in question. Section 4.3 gives the price rate for reinforcement for both sea dikes and storm surge barriers based on literature. This section also states the cost conversion regarding the sea dike reinforcement for all countries in question based on the GDP per capita. Section 4.4 provides the heights required for reinforcement to withstand future water levels for all countries. Lastly, Section 4.5 provides an overview of the total estimated reinforcement costs.*


## 4.1. Dike reinforcement

The construction or reinforcement of a dike has some implications for the landscape in flood-prone and flat countries, but these are not necessarily negative. When it comes to the Netherlands, hardly any new dikes are constructed, but dike reinforcements have to be executed regularly (Jonkman *et al.*, 2018). In densely populated areas that are nearby the flood defences sometimes even buildings are constructed in the dike profile. These structures, known as multifunctional flood defences, tend to protect the land against the water while also serving another purpose. An example of this is illustrated in Figure 4.1, where a parking garage is combined with a quay.

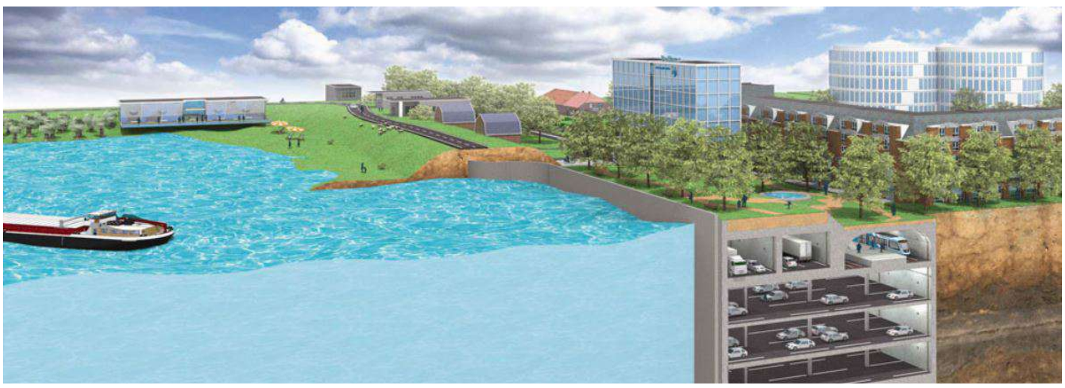


Figure 4.1: Visualisation of a multifunctional flood defence which combines a quay with a parking garage (from Deltares.nl).

The land use in the surrounding areas should be taken into account when planning for dike reinforcement, as it is often instrumental for the chosen reinforcement. Dike reinforcement usually consists of heightening and widening a dike. In the reinforcement process it is key to preserve a similar slope for the dike, as this ensures stability. This means that when a dike is heightened, the width of the dike needs to increase as well, as illustrated in Figure 4.2.

Occasionally buildings and other structures need to be torn down and inhabitants have to relocate in order to implement the reinforcement programme. In the design of dike reinforcement several aspects need to be taken into account (Jonkman *et al.*, 2018):

- The required heightening and widening to comply with safety standards.
- The effects on the surroundings (e.g. nearby structures, etc.)
- The costs (construction method, materials and equipment, additional measures in the surroundings, etc.)

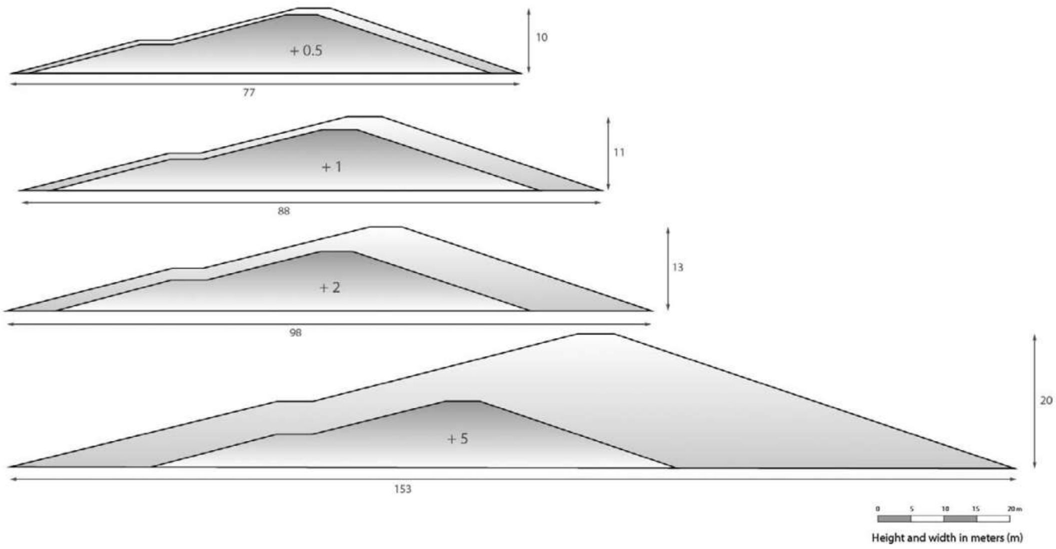



Figure 4.2: Effects of dike soil reinforcement on the sea dike cross-section (Jonkman *et al.*, 2013).

The necessary extra space for reinforcement can be found either on the inside or the outside of the dike. However, as the inside will generally conflict with already present structures, the outside is often a better option. Although, this could lead to an unwanted reduction in flow area in riverine areas. Here, the placement of sheet piles or diaphragm walls could be a solution if no extra space can be created, but in general these costs are significantly greater than soil reinforcements (Jonkman *et al.*, 2018).

Before determining the costs of the flood defences that can withstand the future rising sea level rise at the fourteen European countries, it is important to take some factors into consideration. First of all, it is difficult to differentiate between all flood defence types such as dikes, dunes, hydraulic structures (i.e. storm surge barriers) from the entire coastline that the NEED will impact. This in turn makes it hard to precisely estimate the expenditure that will be needed for the strengthening of the flood defences. However, in order to still make a cost estimate it has been assumed to generalise all necessary reinforced coastline as a (sea) dike reinforcement, except for the storm surge barriers. As storm surge barriers are larger and more costly compared to dikes, these are assessed separately. Moreover, it is assumed that the locations which require necessary reinforcement already have a sea dike in place, albeit not sufficient in height. This assumption will prevent the cost assessment of regional flood protection to be an overestimation, as the construction of a new dike would be more costly and is, as previously mentioned, hardly done.

In Figure 4.3, a schematic cross section of a typical Dutch sea dike is illustrated. The core of the dike generally consists of sand and provides support for the cover layer and gives the structure sufficient volume and weight to resist the water pressures. The cover layer, not indicated in Figure 4.3, is an impermeable layer. This layer is often composed of clay, but sometimes supplemented by asphalt and lies on top of the sand as it serves to protect the (sand) core. The slope on the seaside has a gradient between 1:3 and 1:6 in order to reduce wave loading, and the landside slope has a gradient between 1:2 and 1:3 in order to minimise land use and maximise stability (CTCN (Climate Technology Centre & Network) *et al.*, 2017). The revetment is always placed on the sloping seaward part of the dike and are very often constructed as permeable structures using natural stones or concrete blocks. This allows it to absorb wave energy and minimise reflection and wave run-up.

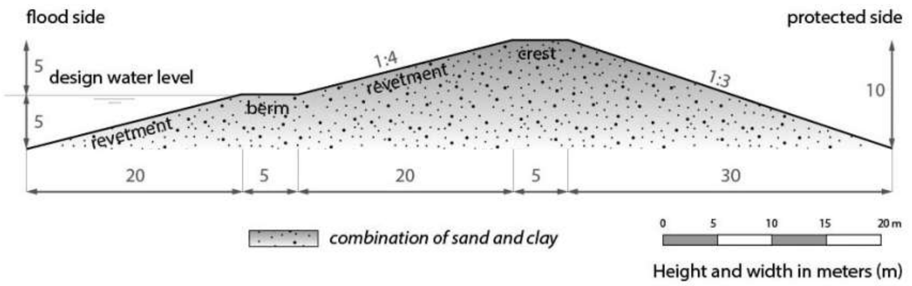



Figure 4.3: Cross section of typical sea dike in the Netherlands (Jonkman *et al.*, 2013).

The total costs of the reinforcement for the flood defences depend on the three factors listed below. This chapter is thus sectioned according to these factors.

- The coast length that needs to be reinforced
- The costs for such a reinforcement for each country
- The height of the reinforcement

## 4.2. Length assessment

Using the geographic information programme QGIS, it was possible to determine where along the coastline reinforcement is necessary. The maps with the coastal reinforcement indication for all countries are depicted in Figure D.2(b) through D.15(b) in Appendix D.1 for the RCP8.5 scenario with a return period of 1000 years. The map of the Netherlands in Figure 4.4, indicates the coastline needing reinforcement in blue. The determination of this, however, had to be done manually, because each location (cell) needed to be assessed independently. This resulted in an assessment that solely focused on the coastline in the protection range of the NEED. By doing so, a clear and one-to-one comparison can be made between the costs of the NEED and the costs of this specific coast reinforcements necessary for each country in question. Considering the Netherlands in Figure 4.4, the sandy coast/dune areas were not intentionally avoided for the fact it consisted of natural flood protections. The length assessment was based purely on coastal locations that encounter a inundation height according to the GLOFRIS inundation maps. In conformity with this assessment, the dune areas in the Netherlands did not encounter inundated coastal cells, therefore did not require any reinforcement length.

Figure 4.4: The coast reinforcement map of the Netherlands for RCP8.5 with RP1000 years in 2080 for the 50$^{th}$ percentile.

In Table 4.1, an overview is given of the coastline reinforcement needed. Also, with knowledge of the total coastline per country, the percentage of coast reinforcement could be calculated. From the table it is evident that roughly 6,000 km of the coast has to be reinforced. In Figure 4.5, a map of all coast reinforcement is illustrated for all the fourteen countries that have been analysed. Here, the blue lines display the locations along the coast that need to be reinforced and the red lines represent location of the NEED, to clearly define the domain with regard to the coast reinforcement.

Table 4.1: Overview of coastline length based on The World Factbook (CIA.gov) and the required dike raising length for all countries in 2080 for scenario RCP8.5.

| Country | Total Coastline length (km) | Coastline reinforcement necessary (km) | Percentage |
|---|---|---|---|
| Belgium | 67 | 58 | 87 % |
| Denmark | 7,314 | 1,067 | 14.6 % |
| Estonia | 3,794 | 30 | 0.8 % |
| Finland | 1,250 | 334 | 26.7 % |
| France | 3,427 | 510 | 14.9 % |
| Germany | 2,389 | 1,815 | 76 % |
| Lavia | 498 | 19 | 3.8 % |
| Lithuania | 258 | 80 | 30.9 % |
| Netherlands, the | 451 | 355 | 78.6 % |
| Norway | 53,133 | 32 | 0.05 % |
| Poland | 440 | 196 | 44.6 % |
| Russia | 37,652 | 211 | 0.6 % |
| Sweden | 3,218 | 395 | 12.3 % |
| United Kingdom, the | 12,429 | 923 | 7.4 % |
| **Total** | | 6,025 | |

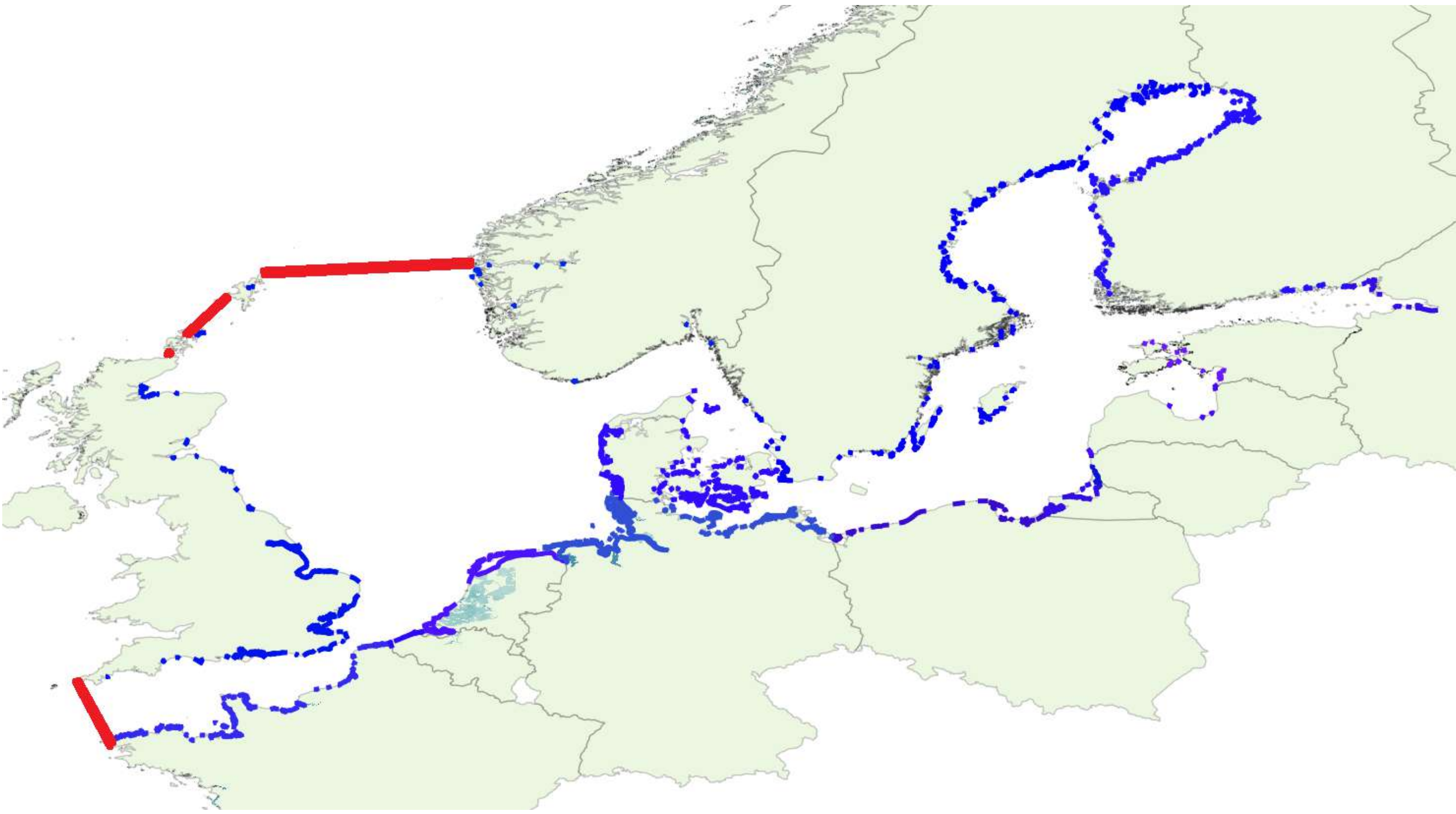


Figure 4.5: The coast reinforcement map of the affected area by the NEED for RCP8.5 with RP1000 years in 2080 for the 50$^{th}$ percentile.

## 4.3. Reinforcement pricing

This section will define the price rate for the coastal reinforcement types, assuming it is only necessary to determine its pricing for sea dikes and storm surge barriers. In the following subsections a more detailed analysis is given for each type of coastal reinforcement.

### 4.3.1. Sea dikes

With regard to dike reinforcement, the price rate per 1-metre increase in crest level has to be estimated in order to make an assessment of the total costs. In Table 4.2, multiple historical price rates for both rural and urban dike reinforcement have been stated along with its source. Dike construction costs vary considerably between rural and urban areas. Naturally, due to the greater land availability, the rural areas are less costly. However, in further analysis and calculations in this thesis it has been chosen to use the same dike reinforcement price rate for both rural and urban areas within the range of the ones stated in Table 4.2. A detailed study on the length assessment of a rural and urban coast for the majority of the European coastline seemed too labour-intensive and error-prone. With this generalisation, no discrepancy is assumed between the length of rural and urban coast. Now that the entire necessary reinforced coast (apart from the storm surge barriers) will be generalised as one specific dike reinforcement, a cost estimate can be made. The average of the price rates listed in Table 4.2 is found to be roughly 13.5 million € per kilometre per metre. For further analysis and calculation in this thesis it has chosen to proceed using a price of 13 million € per kilometre for an increase of 1 metre in crest level.

Table 4.2: Overview of the sea dike reinforcement costs in the Netherlands.

| Adaptation Measure | Country | Year Price Level | Costs (mil. €/km per m) | Source |
|---|---|---|---|---|
| Raising sea dikes 1 m (rural) | NL | 2009 | 9.4 - 11.2 | Kok *et al.* (2008) |
| Raising sea dikes 1 m (rural) | NL | 2009 | 4.5 - 12.4 | Eijgenraam (2006) |
| Raising sea dikes 1 m (rural) | NL | 2009 | 7.8 | Arcadis *et al.* (2006) |
| Raising sea dikes 1 m (rural) | NL | 2009 | 9 | Stijnen *et al.* (2014) |
| Raising sea dikes 1 m (urban) | NL | 2009 | 18.7 - 22.4 | Kok *et al.* (2008) |
| Raising sea dikes 1 m (urban) | NL | 2009 | 15.5 | Arcadis *et al.* (2006) |
| Raising sea dikes 1 m (urban) | EU | 2012 | 18.6 - 26.7 | Prahl *et al.* (2012) |

### 4.3.2. Storm surge barriers

Table 4.3 gives an overview of the costs for storm surges barriers found in the literature along with its source. As reported by Stijnen *et al.* (2014), the reinforcement of the storm surge barriers according to the SLR can cost several billions over many years. However, in order to determine the costs for the storm surge barriers it is necessary to identify the storm surge barriers in the countries which will be affected by the NEED.

Table 4.3: Overview of the storm surge barrier reinforcement costs.

| Adaptation Measure | Country | Year Price Level | Costs (mil. € per km) | Source |
|---|---|---|---|---|
| Storm surge barriers | Global | 2009 | 500 - 2,700 | Hillen *et al.* (2010) |
| Storm surge barriers | US | 2012 | 450 - 3,600 (in US$) | Aerts *et al.* (2013) |
| Storm surge barriers | Global | 2016 | 320 - 4,200 (in US$) | Aerts (2018) |
| Storm surge barriers | Global | 2017 | 2,200 | Mooyaart and Jonkman (2017) |

In Table 4.4 an overview of existing storm surge barriers with their characteristics and costs are stated. After analysis of these barriers, it can be concluded that the Hollandse IJssel Barrier, Ramspol and Cardiff Bay do not need to be included in further calculation, as Cardiff Bay is located in the western part of the United Kingdom and the other two barriers are already protected by the Maeslant barrier and Afsluitdijk, respectively. The total length of the barriers that possibly need to be reinforced in this region is 29,220 metres, roughly 29 kilometres. For further analysis and calculation in this thesis it has been chosen to use a price roughly in line of the listed ranges; therefore a price of **1,000** million €/km per raised metre is assumed for the storm surges.

Table 4.4: An overview of storm surge barriers and their characteristics in the countries affected by the NEED (Aerts *et al.*, 2013).

| **Name & Location** | **Type** | **Width (m)** | **Height (m)** | **Head (m)** | **Construction costs 2012 price levels (mil. $ )** |
|---|---|---|---|---|---|
| Hollandse IJssel Barrier, NL | Vertical lifting gates | 110 | 11.5 | 3.5 | 127 |
| Maeslant barrier, NL | Floating sector gate | 360 | 22 | 5 | 852 |
| Hartel barrier, NL | Vertical lifting gates | 170 | 9.3 | 5.5 | 185 |
| Eastern Scheldt Barrier, NL | Vertical lifting gates | 2400 | 14 | 5 | 5227 |
| Ramspol, NL | Bellow barrier | 240 | 8.2 | 4.4 | 171 |
| Ems, DE | Sector gates | 360 | 8.5 | 3.8 | 376 |
| Cardiff Bay, UK | Sluice/lifting | 1100 | 7.5 | 3.5 | 340 |
| Thames, UK | Sector gates | 530 | 17 | 7.2 | 1883 |
| St. Petersburg, RU | Floating sector/vertical lifting | 25400 | 23.5 | 5 | 6953 |

### 4.3.3. Cost conversion

As the costs for raising a dike's crest height with 1 metre has already been set at 13 million € per kilometre, it should be noted that this is a price indication that solely applies for the Netherlands. In order to make a fair and realistic estimate of the total expenditure, the reinforcement price for all other countries has to be determined. The variation in these costs per country is strongly dependent on its national net wealth, expressed in GDP per capita. Using the fixed Dutch cost over GDP per capita ratio, the costs per metre increase in crest height per kilometre for all countries are determined with Equation 4.1 and stated in Table 4.5.

$$Dike\ Reinforcement\ Costs\ of\ Country = GDP\ per\ Capita\ of\ Country \cdot \frac{13{,}000{,}000}{58{,}003} \tag{4.1}$$

Table 4.5: Overview of the sea dike reinforcement costs (in million €) per km/m based on GDP/capita (International Monetary Fund, 2021).

| **Country** | **GDP per capita** | **Cost per km / m** |
|---|---|---|
| Belgium | 50,103 | 11.2 |
| Denmark | 67,218 | 15.1 |
| Estonia | 26,525 | 5.9 |
| Finland | 54,330 | 12.2 |
| France | 44,995 | 10.1 |
| Germany | 51,860 | 11.6 |
| Latvia | 19,831 | 4.4 |
| Lithuania | 22,253 | 5.0 |
| Netherlands, the | 58,003 | 13.0 |
| Norway | 81,995 | 18.4 |
| Poland | 16,930 | 3.8 |
| Russia | 11,654 | 2.6 |
| Sweden | 58,977 | 13.2 |
| United Kingdom, the | 46,344 | 10.4 |

## 4.4. Reinforcement height

With the lengths and the costs ratio per country determined for the dike reinforcements, the only missing variable is the height. There are two ways to assess the reinforcement heights necessary. The first approach would be by assuming the wave run-up height. It is assumed that the waves are depth limited and break at half the water depth. When applied to the wave run-up equation, Equation 4.2, the $h_{run-up}$ is the run-up height, $H_s$ is the significant wave height and $\tan(\alpha)$ is the outer slope of the dike. The increase in crest level ($\Delta h_{crest}$, see Equation 4.3) is the sum of SLR and the increase in wave run-up. For a dike with a slope of 1:4 this yields the following for the wave run-up height (Stijnen *et al.*, 2014).

$$\Delta h_{run-up} = 8 \cdot H_s \cdot \tan(\alpha) \approx 8 \cdot 0.5 \cdot SLR \cdot 1/4 = SLR \tag{4.2}$$

$$\Delta h_{crest} \approx \Delta h_{run-up} + SLR = 2 \cdot SLR \tag{4.3}$$

Besides the linear relation found for the dike raising in Equation 4.3, there is also an relation between the dike widening and surface area increase and this is stated in the Table 4.6 and previously illustrated in Figure 4.2. However, in further analysis of this research, it has been assumed that all countries have enough space available in the coastal areas to cope with the increase in dike widening when raising its sea dikes. No detailed study is done on the available dike widening space for all determined reinforcement locations as this seemed too labour-intensive. Although, as briefly described in Section 4.1, dike widening does has a big impact on the reinforcement of the dikes and can be accompanied with e.g. significant additional costs, loss of cultural heritage and political resistance.

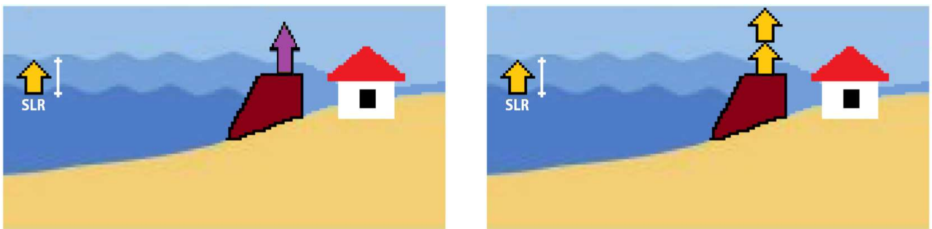
Table 4.6: Relation of dike dimensions with SLR (Kok *et al.*, 2008).

| | | |
|---|---|---|
| Dike raising | $\approx 2 \cdot SLR$ | Linear |
| Dike widening | $\approx 7 \cdot SLR$ | Linear |
| Dike surface area increase | $\approx 12 \cdot SLR^2 + 140 \cdot SLR$ | Quadratic |

The second approach, being the one applied in this research, is by assuming the maximum inundation height. Using GLOFRIS model framework, the maximum inundation heights for all the countries have been assessed along the length of the coast that the NEED will protect instead of the entire country's coastline, see Equation 4.4. This is illustrated in Figure 4.6(a), where the purple arrow is the maximum inundation height found along the coast for a given country. By using the maximum inundation height found to reinforce the entire coastal length assessed, it can be guaranteed that the countries are protected for future scenarios.

$$\Delta h_{crest} = h_{max\ coast\ inundation} - h_{existing\ crest} \tag{4.4}$$

Alternatively, according to the first approach it could be argued that twice the GMSLR should be the reinforcement height, as illustrated in Figure 4.6(b). However, the second approach which uses the maximum inundation heights found in GLOFRIS also account for the future tides and surges in addition to the GMSLR, therefore giving a more accurate prediction on the future water level than solely focusing on GMSLR. Also, it offers a more detailed analysis of the inundation height along the coastline. The heights of inundation along the coastlines notably differ per country and are not always greater than the GMSLR corresponding to its scenario.




(a) Maximum inundation height along coast (b) SLR

Figure 4.6: Visualisation of the determination of reinforcement heights.

In Table 4.7, an overview is given of the maximum inundation height measured in the coastal protection range of the NEED per country for all three percentiles until 2080 for scenario RCP8.5 with a return period of a 1000 years. The same has been done for the storm surge barrier, as the maximum inundation heights at the locations of the storm surge barriers was again obtained through GLOFRIS and are stated in Table 4.8. Noticeable is that the maximum inundation heights measured at the barrier (Table 4.8) do not have to correspond to the maximum inundation heights found along the coast of the entire country (Table 4.7). As the maximum inundation height per country and barrier is very dependent on the location, striking differences between Table 4.7 and Table 4.8 should not be alarming. This is also the justification why there is a significant difference in maximum inundation heights within and between countries. When analysing Poland for instance, there is a clear turning point (year 2050, 50$^{th}$ percentile) where the maximum inundation height jumps up. This is due to the fact that from this scenario onwards a new location is flooded that is associated with the new maximum inundation height.

Table 4.7: Overview of the change in maximum inundation heights (in m) in the coastal range of the NEED for all countries per year per percentile for RCP8.5 with a return period of a 1000 years.

| Years | Percentile | BE | DK | ES | FI | FR | DE | LV | LT | NL | NO | PO | RU | SE | UK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 05 | 0.09 | 1.31 | 0.07 | 0.30 | 2.30 | 1.10 | 0.12 | 0.40 | 1.30 | 0.13 | 0.12 | 0.28 | 0.13 | 2.08 |
| 2030 | 50 | 0.44 | 1.65 | 0.14 | 0.37 | 2.34 | 1.18 | 0.19 | 0.48 | 1.35 | 0.19 | 0.20 | 0.81 | 0.20 | 2.14 |
| | 95 | 0.53 | 1.76 | 0.23 | 0.47 | 2.39 | 2.07 | 0.30 | 0.58 | 1.43 | 0.27 | 1.79 | 0.91 | 0.31 | 2.22 |
| | 05 | 0.53 | 1.70 | 0.15 | 0.41 | 2.37 | 2.54 | 0.24 | 0.53 | 1.39 | 0.23 | 0.28 | 0.86 | 0.25 | 2.14 |
| 2050 | 50 | 0.63 | 2.06 | 0.24 | 0.50 | 2.45 | 2.64 | 0.35 | 0.63 | 1.49 | 0.33 | 2.12 | 0.96 | 0.36 | 2.24 |
| | 95 | 1.42 | 2.19 | 0.37 | 0.64 | 2.55 | 2.78 | 0.48 | 0.76 | 1.67 | 0.46 | 2.25 | 1.09 | 0.49 | 2.37 |
| | 05 | 1.54 | 2.06 | 0.31 | 0.55 | 2.53 | 2.73 | 0.43 | 0.72 | 2.17 | 0.39 | 2.21 | 1.05 | 0.45 | 2.24 |
| 2080 | 50 | 1.68 | 2.15 | 0.54 | 1.14 | 2.67 | 2.94 | 0.64 | 0.93 | 2.31 | 0.59 | 2.70 | 1.25 | 0.65 | 3.03 |
| | 95 | 1.88 | 2.74 | 0.79 | 1.81 | 2.87 | 3.24 | 0.94 | 1.23 | 2.50 | 0.88 | 3.01 | 1.82 | 0.96 | 3.28 |

Table 4.8: Overview of the change in maximum inundation heights (in m) at the barrier per year per percentile for RCP8.5 with a return period of a 1000 years.

| Years | Percentile | Measlant (NL) | Hartel (NL) | Easter Scheldt (NL) | Ems (DE) | Thames (UK) | St. Petersburg (RU) |
|---|---|---|---|---|---|---|---|
| | 05 | 0.27 | 0.13 | 0.27 | 0.26 | 0.14 | 0.07 |
| 2030 | 50 | 0.34 | 0.19 | 0.34 | 0.32 | 0.18 | 0.16 |
| | 95 | 0.42 | 0.27 | 0.42 | 0.41 | 0.23 | 0.27 |
| | 05 | 0.50 | 0.42 | 0.39 | 0.37 | 0.20 | 0.18 |
| 2050 | 50 | 0.60 | 0.52 | 0.49 | 0.47 | 0.28 | 0.30 |
| | 95 | 1.49 | 1.45 | 1.43 | 1.40 | 0.38 | 0.45 |
| | 05 | 1.76 | 1.76 | 1.47 | 1.44 | 0.35 | 0.32 |
| 2080 | 50 | 1.89 | 1.90 | 1.61 | 1.58 | 0.49 | 0.56 |
| | 95 | 2.09 | 2.10 | 1.81 | 1.78 | 0.69 | 0.90 |

## 4.5. Reinforcement costs

In this section the reinforcement costs for both sea dikes and storm surge barriers has been assessed for possible future scenario for all fourteen countries.

### 4.5.1. Sea dikes

With all parameters needed for the calculation determined, the total costs of dike reinforcement per country can be calculated with Equation 4.5. The results of all countries per year and percentile are stated in Tabel 4.9.

$$Total\,Dike\,Reinforcement\,Costs\,per\,Country = Coastlength\,Length \cdot Max.\,Inun.\,Height \cdot Costs\,per\,Country \tag{4.5}$$

Table 4.9: Overview of the sea dike reinforcement costs (in million €) per country per year per percentile for coasts in the range of NEED for RCP8.5 with a return period of a 1000 years.

| Years | Percentile | BE | DK | ES | FI | FR | DE | LV | LT | NL | NO | PO | RU | SE | UK | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 05 | 61 | 21,003 | 12 | 1,234 | 11,812 | 23,260 | 10 | 160 | 5,982 | 76 | 88 | 155 | 656 | 19,956 | 84,463 |
| 2030 | 50 | 286 | 26,532 | 24 | 1,514 | 12,019 | 24,882 | 16 | 191 | 6,239 | 111 | 145 | 444 | 1,058 | 20,509 | 93,970 |
| | 95 | 344 | 28,213 | 41 | 1,904 | 12,303 | 43,568 | 25 | 232 | 6,592 | 158 | 1,335 | 502 | 1,629 | 21,271 | 118,117 |
| | 05 | 344 | 27,292 | 27 | 1,646 | 12,199 | 53,604 | 20 | 210 | 6,427 | 132 | 212 | 470 | 1,305 | 20,514 | 124,402 |
| 2050 | 50 | 407 | 33,094 | 44 | 2,050 | 12,596 | 55,790 | 29 | 251 | 6,864 | 190 | 1,578 | 527 | 1,871 | 21,422 | 136,734 |
| | 95 | 921 | 35,255 | 66 | 2,591 | 13,131 | 58,626 | 40 | 304 | 7,693 | 267 | 1,678 | 601 | 2,573 | 22,691 | 146,438 |
| | 05 | 1,002 | 33,094 | 55 | 2,216 | 13,016 | 57,655 | 36 | 286 | 10,002 | 226 | 1,644 | 576 | 2,333 | 21,495 | 143,637 |
| 2080 | 50 | 1,091 | 34,515 | 96 | 4,627 | 13,737 | 62,004 | 53 | 368 | 10,633 | 342 | 2,013 | 689 | 3,410 | 29,064 | 162,642 |
| | 95 | 1,219 | 44,070 | 140 | 7,345 | 14,770 | 68,445 | 79 | 488 | 11,537 | 511 | 2,240 | 1,000 | 5,006 | 31,420 | 188,269 |

### 4.5.2. Storm surge barriers

The cost estimation for the storm surge barrier reinforcement requires a slightly different formula than Equation 4.5. Since the storm surge barrier reinforcement costs determined from Table 4.3 were applicable globally, no cost conversion for each country was necessary. With GLOFRIS, given the locations of the storm surge barriers, the maximum inundation height is determined and the costs were calculated with Equation 4.6 and stated in Table 4.10.

$$Total\ SSB\ Reinforcement\ Costs = Total\ SSB\ Length \cdot Max.\ Inun\ Height \cdot SSB\ Costs\ per\ raised\ metre \tag{4.6}$$

Table 4.10: Overview of the SSB reinforcement costs (in million €) per barrier per year per percentile for RCP8.5 with a return period of a 1000 years.

| Years | Percentile | Measlant (NL) | Hartel (NL) | Easter Scheldt (NL) | Ems (DE) | Thames (UK) | St. Petersburg (RU) | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 2030 | 05 | 98 | 21 | 654 | 93 | 75 | 1,848 | 2,790 |
| | 50 | 120 | 32 | 803 | 115 | 94 | 3,977 | 5,142 |
| | 95 | 151 | 46 | 1,007 | 146 | 121 | 6,880 | 8,351 |
| 2050 | 05 | 180 | 71 | 935 | 133 | 108 | 4,612 | 6,039 |
| | 50 | 215 | 88 | 1,169 | 168 | 148 | 7,497 | 9,285 |
| | 95 | 537 | 247 | 3,419 | 505 | 202 | 11,417 | 16,327 |
| 2080 | 05 | 633 | 300 | 3,536 | 519 | 183 | 8,206 | 13,376 |
| | 50 | 682 | 323 | 3,864 | 568 | 258 | 14,244 | 19,938 |
| | 95 | 753 | 356 | 4,335 | 639 | 366 | 22,969 | 29,417 |

### 4.5.3. Total costs

The total reinforcement costs are determined and stated in Table 4.11, where storm surge barrier is abbreviated to SSB and dike reinforcement to DR. Looking back at the prediction from Stijnen *et al.* (2014) that the SSB reinforcement could cost several billions over many years, this has been confirmed with the found results in Table 4.10, as the assumption made for the calculation seem to be in line with that prediction.

Table 4.11: Overview of total reinforcements costs (in million €) for coasts in the range of NEED.

| Years | Percentile | SSB Costs | DR Costs | Total Costs |
|---|---|---|---|---|
| 2030 | 05 | 2,790 | 84,463 | 87,253 |
| | 50 | 5,142 | 93,970 | 99,112 |
| | 95 | 8,351 | 118,117 | 126,468 |
| 2050 | 05 | 6,039 | 124,402 | 130,441 |
| | 50 | 9,285 | 136,734 | 146,019 |
| | 95 | 16,327 | 146,438 | 162,765 |
| 2080 | 05 | 13,376 | 143,637 | 157,013 |
| | 50 | 19,938 | 162,642 | 182,581 |
| | 95 | 29,417 | 188,269 | 217,686 |

In the last column of Table 4.11, costs of the countries are summed up per year and percentile, resulting in a total cost per scenario for the respective years. In Figure 4.7, the courses of the three percentiles are graphically displayed. Through linear regression, a trendline was found for the percentiles, which serve as an upper and lower bound line. By extrapolating these trends, an estimation of the range for the costs associated with a 1-metre GMSLR could be made. The values found for the $5^{th}$, $50^{th}$ and $95^{th}$ are approximately 245, 280 and 335 billion € with an increase of 170, 210 and 235 billion € per metre, respectively.

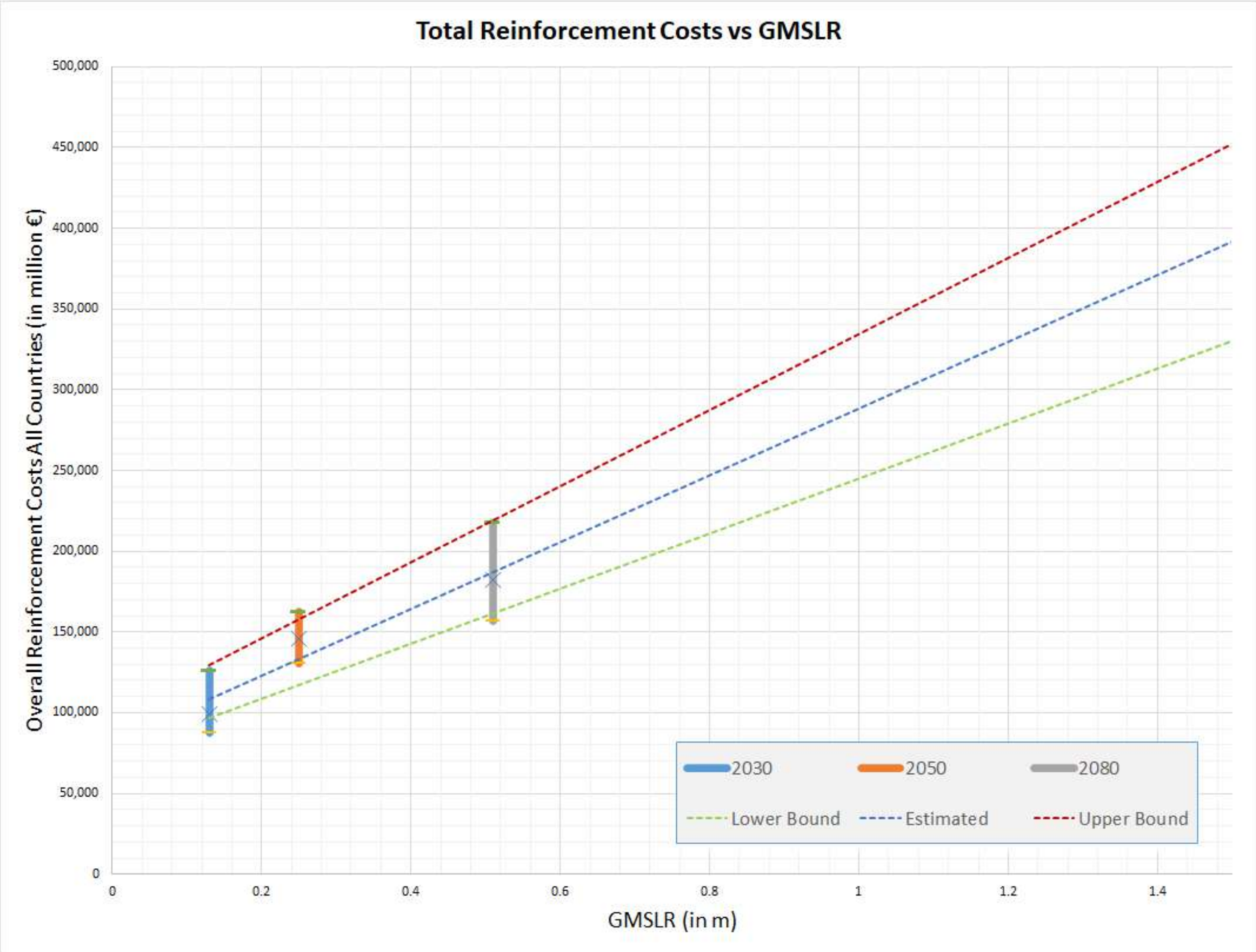



Figure 4.7: Graph of the total reinforcement costs using maximum inundation height as reinforcement height vs the GMSLR.

In Figure 4.8 and 4.9, the total costs per country are depicted. Figure 4.8 shows eight of the fourteen countries which have a significantly lower reinforcement costs, while Figure 4.9 depicts the other six countries with significantly higher costs with regards to its total reinforcement. Unsurprisingly, the countries that require SSB reinforcement are included in the latter figure, as this reinforcement is rather costly.

Both figures depict the regional cost range for each country (indicated with solid lines) for 2030, 2050 and 2080, which each correspond to a specific GMSLR. Based on the regional cost of a country, an extrapolation can be created to be able to analyse the continuation of the regional protection costs for larger future GMSLRs. These extrapolations per country are indicated with dashed lines in both figures.

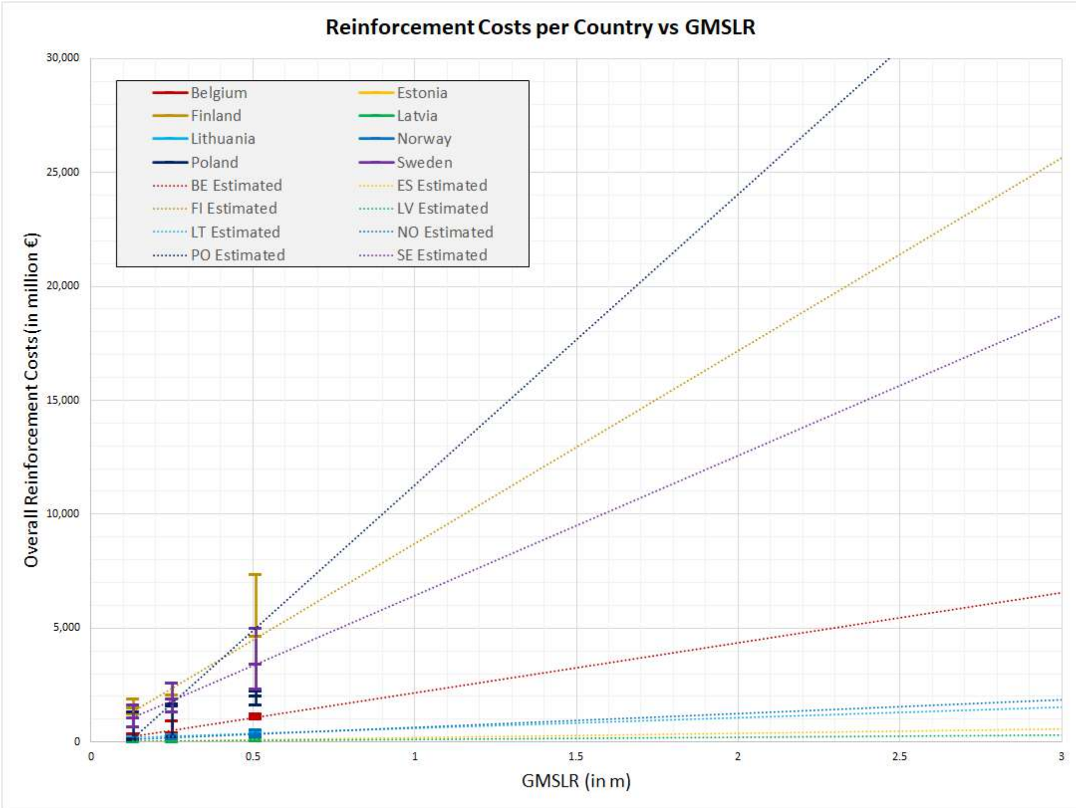



Figure 4.8: Graph of total reinforcement costs for countries on the lower spectrum using average inundation height as reinforcement height.

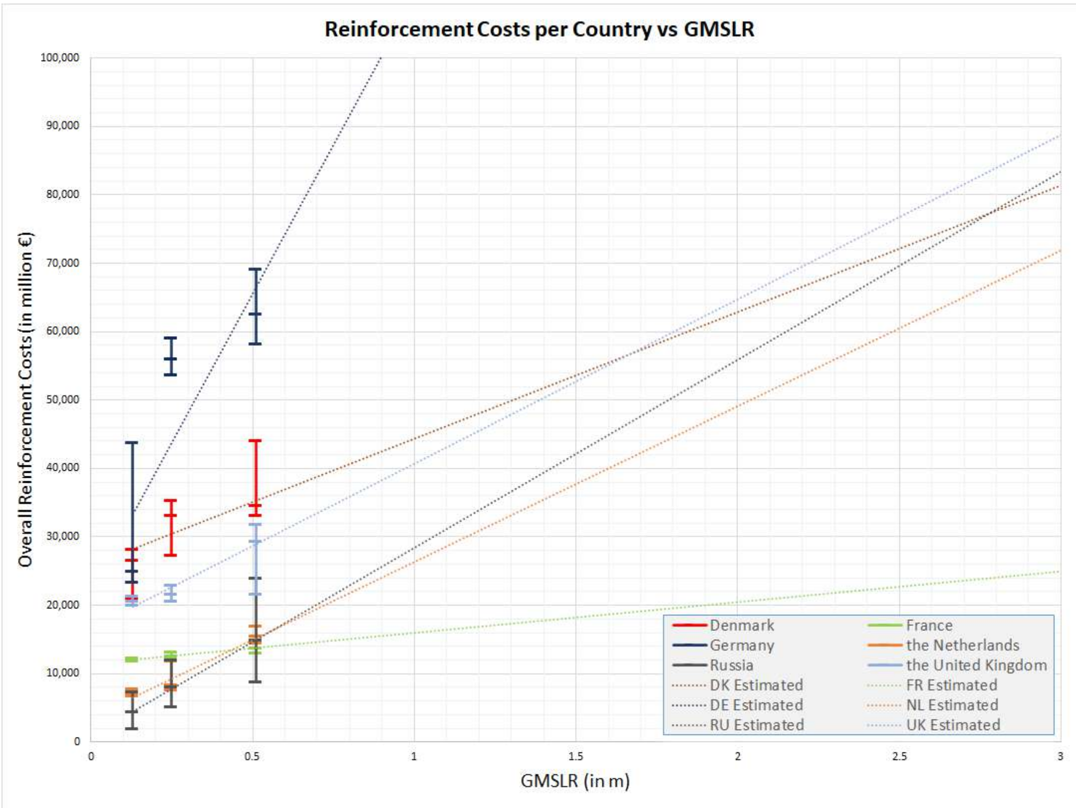



Figure 4.9: Graph of total reinforcement costs for countries on the higher spectrum using average inundation height as reinforcement height.

# 5

# NEED Flood Protection

*This chapter provides a detailed look into the NEED flood protection adaptation strategy, which is the second and last solution adaptation strategies analysed in this thesis. Firstly, Section 5.1 analyses the location and bathymetry of the NEED in order to devise the dimensions for this structure. Section 5.2 explores two possible design options (earth-fill and caisson dam) for the NEED and briefly discuss their failure mechanisms. Section 5.3 provides the total construction costs of the NEED as a function of the GMSLR. In this section, all components of the dam that are expected to have an impact on the total costs are analysed individually and later added to determine the NEEDs total construction costs. Lastly, Section 5.4 provides a brief comparison of the total costs found in this thesis with the estimates put forward by Groeskamp and Kjellsson (2020).*


## 5.1. Bathymetry

The location of the NEED is a key factor in determining the construction costs. Any modification to the location of the NEED will not only impact the length, but also the depth of this huge hydraulic structure, and therefore the construction costs. Moreover, the choice for a given closure location also brings about a trade-off between the cost-efficiency and number of people protected that must be considered. With this in mind, this research will be adopting the same suggested location as in the analysis by Groeskamp and Kjellsson (2020), as this will give a fair one-to-one comparison at the end of this assessment. Here, the southern part of the NEED runs from Ploudalmézeau, France, to the Lizard Heritage Coast in England. The northern part of the NEED runs from John o'Groats up in northern Scotland via the Orkney Islands to the Isle of Noss from where it crosses the North Sea to Bergen in Norway.

Having set the location of the NEED, an analysis on the bathymetry is in order. A bathymetry map is a type of isarithmic map that depicts the submerged topography and physiographic features of oceans and sea bottoms with its primary purpose of providing a depth contour of the area. Figure 5.1 shows the bathymetry map of the area where the NEED would be constructed. In order to create an appropriate bathymetry map it is adjusted to showing only depth values between -500 and +50 metres, since the depths of the area lie between in these values. Here, it can be seen that the depths in certain areas differ significantly. The exact location of the NEED is indicated with colour-coded lines, where yellow indicates a relatively shallow part of its section, red a relatively deep part and orange the transition from shallow to deep.

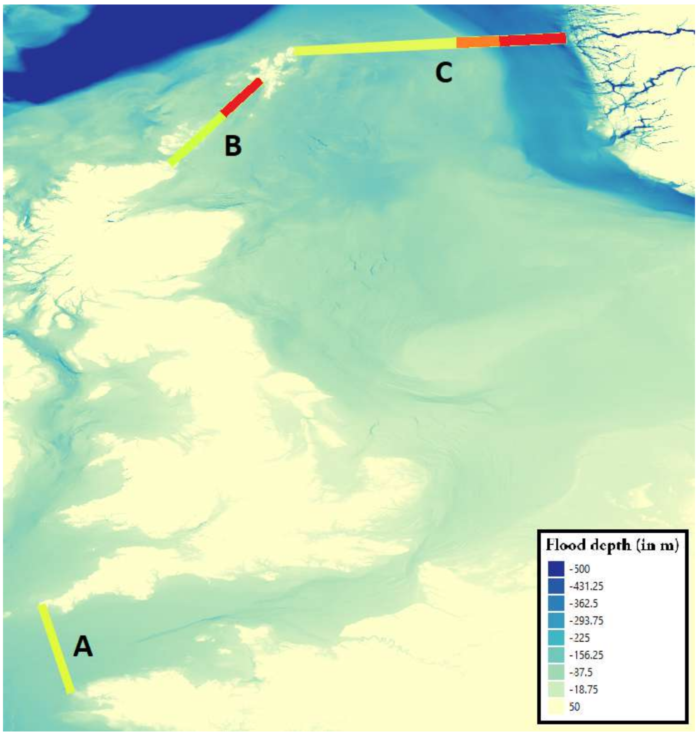
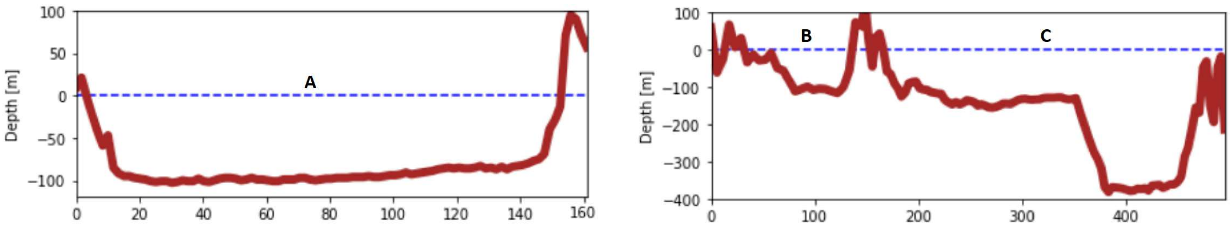



Figure 5.1: Bathymetry map from GEBCO (General Bathymetric Chart of the Oceans), with the NEED structure indicated in coloured lines.

The study by Groeskamp and Kjellsson (2020) provided little insight into the bathymetry. However, since these dimensions play a decisive role in the design of the NEED and therefore the construction costs, a more detailed analysis on the bathymetry is performed in this thesis. With the use of Figure 5.1 and the bathymetry graph in Figure 5.2 it was possible to make a more precise estimation. Table E.1 shows the lengths and depths of each section and the values retrieved from Groeskamp and Kjellsson (2020).

Table 5.1: Overview of the lengths and depths of the NEED based on the bathymetry map from GEBCO and from Groeskamp and Kjellsson (2020) (indicated with an asterisk (*)).

| Section | Part | Length (km) | Depth Interval (m) | Depth Average (m) | Length* (km) | Depth Average* (m) | Depth Maximum* (m) |
|---|---|---|---|---|---|---|---|
| **A** | Total | **150** | 60 - 120 | 90 | **161** | 85 | 102 |
| **B** | Shallow | 75 | 30 - 90 | 60 | - | - | - |
| | Deep | 70 | 90 - 110 | 100 | - | - | - |
| | Total | **145** | 30 - 110 | - | **145** | 49 | - |
| **C** | Shallow | 180 | 90 - 140 | 130 | - | - | - |
| | Transition | 50 | 140 - 350 | 240 | - | - | - |
| | Deep | 70 | 340 - 390 | 350 | - | - | - |
| | Total | **300** | 90 - 390 | - | **331** | 161 | 321 |




(a) Bathymetry graph from GEBCO of the southern part of the NEED.

(b) Bathymetry graph from GEBCO of the northern part of the NEED.

Figure 5.2: Bathmetry graphs of the NEED.

## 5.2. Design

Several design options can be considered for the construction of the NEED, with the most common and straightforward option being an earth-fill dam. Another promising alternative would be a caisson dam. Both will be discussed in the sections below.

### 5.2.1. Earth-fill dam

An earth-fill dam is constructed from several layers, which creates a barrier that holds back the water, tide and waves. The mild slopes of the dam, ranging between 1:3 and 1:6, ensure that the energy from the incoming waves dissipates on the slopes, minimising the impact on the structure. An earth-fill dam can be designed to be solid all the way through or it can consist of materials structured in a laminar fashion. The layered materials can create an avenue for drainage and as such relieve pressure. However, the weight of the dam as a whole creates a tight seal which secures the bottom and sides of the dam. The pressure of the water behind the dam can act to seal the dam in place.

A cross-section akin to that of the NEED is illustrated in Figure 5.3. In this design, the main elements of a (sea) dike are taken into consideration, such as the use of revetment and geotextile. Contrary to Figure 5.3, this simplified version of the NEED will not include the necessary toe protection and subsoil beneath foundation.

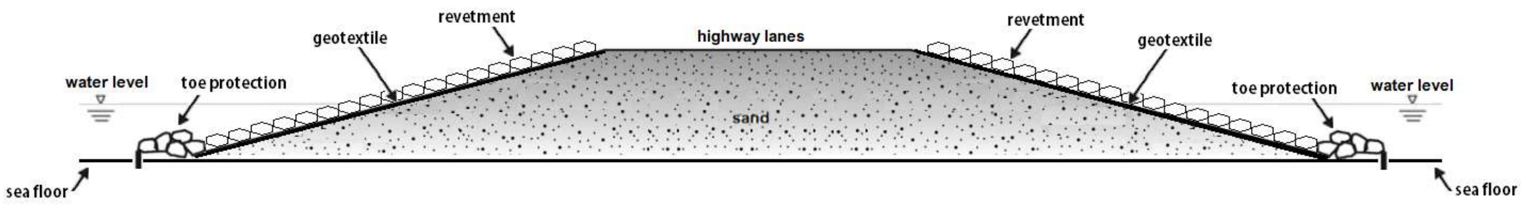



Figure 5.3: Cross-sectional design akin to that of the NEED.

Revetment is a structure situated on slopes which is often constructed as permeable structures using natural stones or concrete blocks. It provides a direct form of erosion protection to a dike caused by wave action, storm surge and currents. Besides absorbing the wave energy, it also minimises the reflection and wave run-up. Generally, revetment is placed on the areas of the slopes where it absorb the waves. However, in this simplified NEED design it is assumed that revetment will be placed along the entire sloped side, as it will also function as a weight to keep the geotextile filter layer in place. Revetment and a geotextile filter layer on a sloped side of a sea dike is illustrated in Figure 5.4.

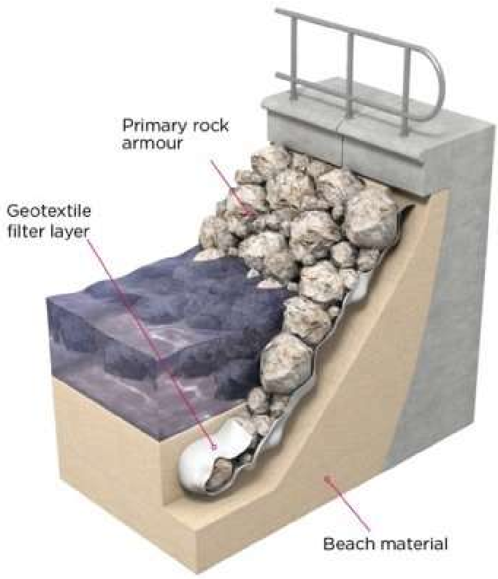



Figure 5.4: Cross-section of sloped side of sea dike (TERRAM, 2020).

Geotextile is a permeable textile material that is used to enhance the soil characteristics by functioning as a fabric structure for soil retention. It invokes strength at the interface with a soil through mobilisation of shear resistance that is largely controlled by friction. It prevents piping below dikes and it increases the dike's external stability. Also it reduces the potential impact of differential settlement in the body. There are two different types of geotextiles; woven and non-woven. Woven geotextiles are made of polypropylene strips that are interlocked/weaved together. The non-woven geotextiles are manufacture by binding materials together through needle punching, thermally or chemically. Due to its interlocking feature, the woven geotextiles are much stronger than the non-woven textiles.

Besides its protective function, the NEED could also serve as a highway connecting the United Kingdom with Norway and France. For this, the width on top of this dam should at least be the width of the highway geometric design. Figure 5.5 depicts a geometric design for a two-way highway. Assuming the dimensions of Figure 5.5 and setting the width of the median to 4 metres, the width of the NEED should be at least 24.8 metres.

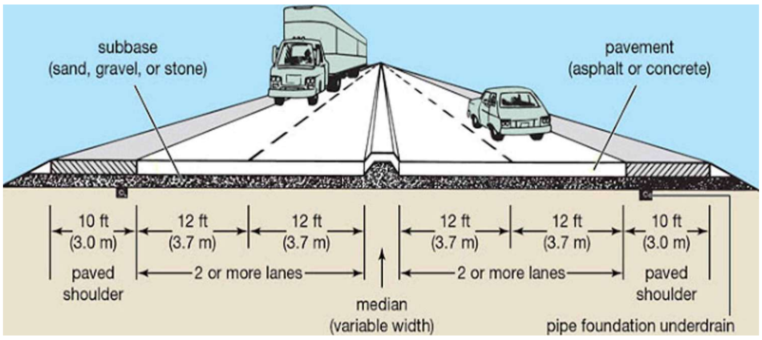



Figure 5.5: Highway geometric design (Steffen, 2021).

This earth-fill dam requires a tremendous amount of material since it will be constructed in deep water. The large amount of material is also due to the gradual slope, as steeping the slope will reduce the stability of the dam which could lead to failure. Other processes that could potentially cause an earth-fill dam to fail are in Figure 5.6.

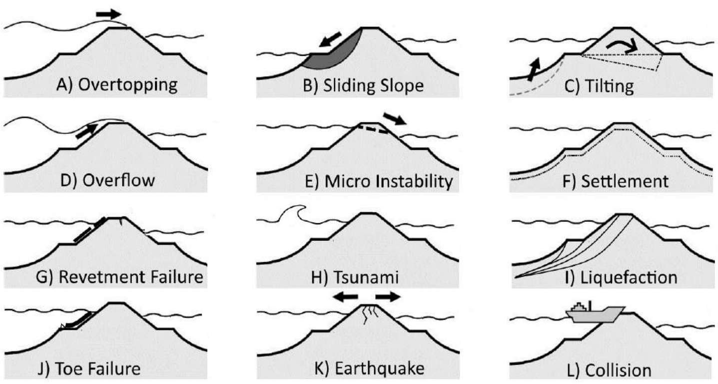



Figure 5.6: Illustrations of failure mechanisms of an earth-fill dam (Jonkman *et al.*, 2018).

### 5.2.2. Caisson dam

Alternatively, a caisson construction could be considered for the NEED. A caisson consists of large concrete boxes which can be transported to the final location and subsequently flooded with water or sunk with ballast to permanently fix it in place, as illustrated in Figure 5.7. This method is very quick and effective when constructing in deep water. A drawback, however, is that the height of one caisson is limited to roughly 80 metres, but when stacked it can overcome large depths. Stacking caisson boxes is a complicated process as divers will have to connect the caissons to each other. However, the usage of these caissons could be useful in the final stage; closing the gap of the structure. During this process, extreme flow velocities and turbulence take place in the gap which makes this process quite difficult to handle (Verhagen, 2016). However, the final gap closing process will not be taken into account as it is not within the scope of this research.

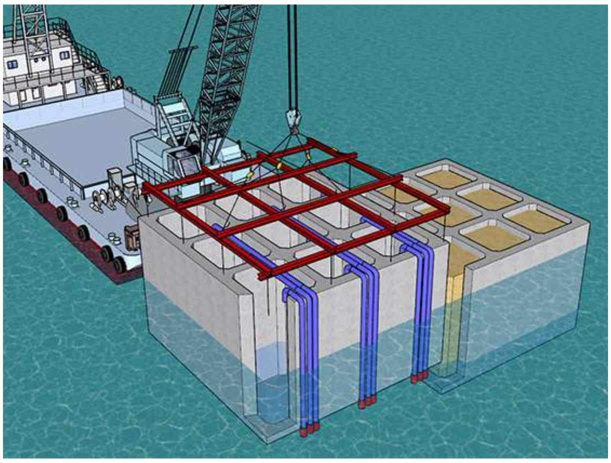


Figure 5.7: Illustration of installation of caisson (AOMI).

As with the earth-fill dam, there are several processes that could lead to failure of a caisson dam. These failure mechanisms are depicted in Figure 5.8. Even though the earth-fill and caisson dams are two completely different structures, they share several failure mechanisms. Besides failure related with revetment, failure mechanisms of the caisson dam and the earth-fill dam mainly differ in the slipping (circular and planar), sliding and turning mechanisms.

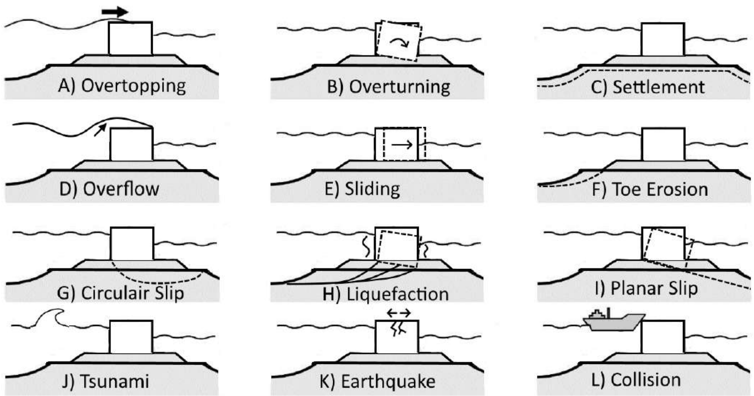



Figure 5.8: Illustrations of failure mechanisms of a caisson dam (Goda, 2000).

Although opting for the caisson dam option will have advantages in terms of construction feasibility and costs, this thesis research will omit the caissons and only focus on the earth-fill dam. It will considerably simplify the construction costs determination, since the volume is the main expenditure for the earth-fill dam. Furthermore, it will be significantly easier to compare the costs assessed with the estimates from Groeskamp and Kjellsson (2020) as this paper also used an earth-fill design for the NEED.

## 5.3. Construction costs

In this section, the construction costs of the NEED will be determined. To this end, the enclosure dam is dissected into the several components. Each component, listed below, will be briefly be assessed in the following subsections. Subsequently, an estimation of the total costs is made dependent on the GMSLR.

- Core material
- Revetment
- Geotextile
- Pumps
- Sluices

### 5.3.1. Core material

As depicted in Figure 5.3, the core material is assumed to exclusively consist of sand. To simplify the analysis, the addition of clay, which is in reality usually present in the design of dikes, is not taken into account. In order to make an approximation of the total amount of core material, all dimensions of the structure must be known. Besides the lengths and depths found in Table E.1, the slope angle and the width on top of the enclosure dam still are yet to be determined. The minimal width for a potential two-way highway connection was estimated in Section 5.2 to be 24.7 metres. In terms of the slope, it has been opted for the slope that generates the most volume, which is **1:6**.

The price per cubic metre of sand is roughly €3 according to Kok *et al.* (2008) and Arcadis *et al.* (2006). However, this price has increased rapidly over the years as it is partly contingent on oil prices and a market characterised by a limited number of large contractors (Jonkman *et al.*, 2013). In Jonkman *et al.* (2013), a range of €5-10/m$^3$ was applied for its calculation. Using the same reasoning as the slope angle, the maximum price for sand is used in the design of the NEED, namely **€10/m$^3$**. The total volume of sand needed for the construction of the NEED as a function of the GMSLR can be found in Table 5.3 in Section 5.3.6. In Appendix E, a more detailed calculation of the volume can be found.

Remarkably, Groeskamp and Kjellsson (2020) has chosen to design the NEED with two sloping sides with a 1:2 ratio. Their analysis estimated that a project of this magnitude will need a volume of approximately 51 billion tons of sand (with a density of 1400 kg/m3), which is equal to about one year of global sand use (Peduzzi, 2014).

### 5.3.2. Revetment

For the revetment, it has been opted for a rock revetment type, as is offers long-term protection with basically an unlimited structure life, making it an efficient and effective option. Permeable surface absorbs wave energy and encourages upper beach stability. The costs however are quite large, but on the other hand, there are with relative low maintenance. Scottish Natural Heritage (2000) predicts the rock revetment to be around 1,000 to 3,000 £ per metre length of the coast, whereas Hudson *et al.* (2015) estimates the price to be around 650 to 2,850 £/m. However, the costs for rock armour lie between 1,350 and 6,000 £ per metre length (Scottish Natural Heritage, 2000).

Considering the design of this enclosure dam, the price of the revetment is set at 6,000 £/m length, or roughly **7,000 €/m length** (using a conversion rate of 1 GBP = 1.17 EUR). It should be noted that both sides of this structure will be needing revetment, since both sides will be retaining water. The total amount of revetment needed for the construction of the NEED as a function of the GMSLR can be found in Table 5.3. In Appendix E, a more detailed calculation of its amount can be found.

### 5.3.3. Geotextile

For the geotextile of the enclosure dam, it is opted for woven rather than non-woven geotextile, as it has superior strength. Even though it stronger, caution is required when placing the revetment, as the geotextile can be punctured by the rocks.

From literature, it can be concluded that the price per squared metre of woven geotextile varies substantially. This variation is dependent on the quality and on the country of production. The quality of a geotextile is expressed in terms of strength (KN/m) and porosity (l/m$^2$/sec). Van Walraven shows that the costs for woven geotextile can vary between €1.25 and 5.25 per m$^2$. For further cost calculation for the construction of the NEED, a cost of **€5/m$^2$** is used. The total amount of woven geotextile needed for the construction of the NEED as a function of the GMSLR can be found in Table 5.3. In Appendix E, a more detailed calculation of its surface area can be found.

### 5.3.4. Pumps

When closing off the North Sea and the Baltic Sea, the water of the river discharge will be contained in the newly created basin. Over time, this will lead to an undesired increase in water level within the basin. According to

Groeskamp and Kjellsson (2020), enclosing the North and Baltic Seas will yield a net freshwater river discharge of roughly 40,000 $m^3/s$ into the basin, which translates to a SLR of 0.9 m/year within the enclosure basin and must therefore be pumped out into the Atlantic Ocean when assuming that the water level in the North Sea is below that of the Atlantic Ocean. Unfortunately, a single pump does not have the capacity to meet this river discharge, denoting that multiple pumps have to be installed in order to prevent the water level in the basin from rising.

In New Orleans, USA, the pumping station has pumps with a capacity of 550 $m^3/s$ was taken in operation (Groeskamp and Kjellsson, 2020). In the Netherlands the Afsluitdijk will have two new pumping stations with a capacity of 400 $m^3/s$ each (Groeskamp and Kjellsson, 2020). When considering the total discharge scaled with the cost and capacity of the pumps of either the Afsluitdijk (200 million €) or New Orleans (500 million €), this would add an additional 20 to 36.5 billion € to the construction costs of the NEED. For further cost calculation of the pumps necessary for the NEED a total cost of **€40 billion** is used.

### 5.3.5. Sluices

When installed, the NEED will be disrupting major shipping lines running to the large ports of Europe, such as Rotterdam, Antwerp and Hamburg. The shipping routes in the North Sea and their intensity are illustrated in Figure 5.9. With roughly 7,500 ships passing through the hotspots areas of the North Sea region daily, it is the busiest shipping grounds in the world (Nilsson *et al.*, 2018). Here, the seaway between England and France, which features the English Channel and Dover Strait, is considered to be particularly busy.

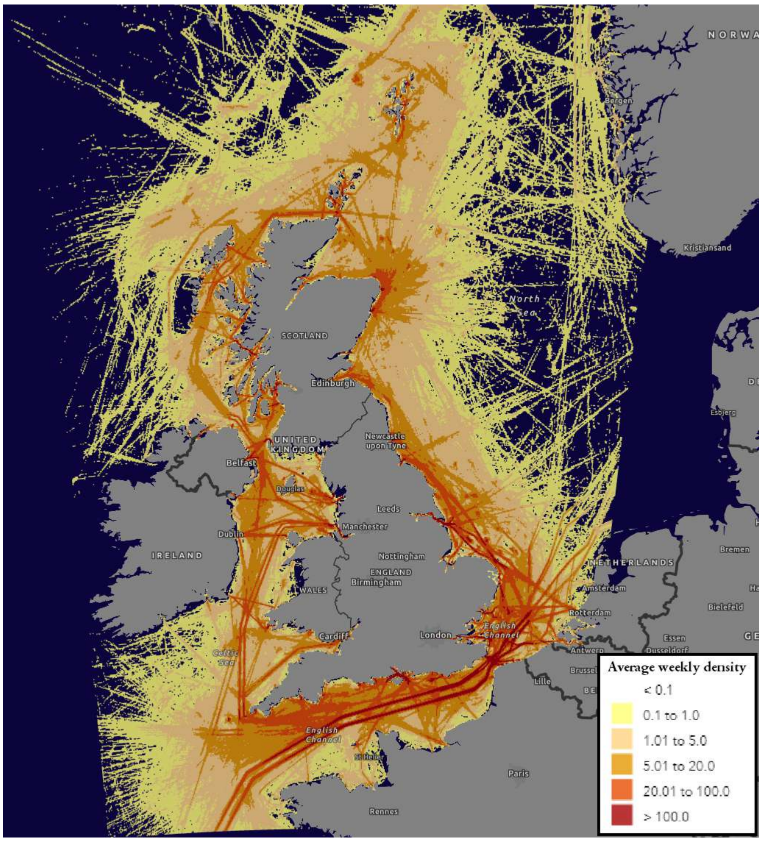



Figure 5.9: Shipping routes and its intensity of 2017 in the North Sea indicated with colour-coded lines from ABPmer's GIS data (ABPmer, 2020).

A solution which allows big container ships to still enter the European ports is the installation of sluices. As the biggest container ship have dimensions of 400 metres in length, 62 metres in width and a draft of 16 metres, the sluices that will need to be present in the NEED should exceed these measurements (202, 2021). At present, Zeesluis IJmuiden, the largest (sea) sluice ever to be created, is being built. This massive sea sluice will be 500 metres in length, 70 metres in width and 18 metres in draft (IJm). The construction cost for this project is expected to be roughly 850 million € (Zee). Assuming that the installation of 15 sluices with the same magnitude as the one in IJmuiden will be needed to maintain desirable marine traffic to the otherwise closed off ports, this adds a total cost of **€12.75 billion** to the NEED's construction costs.

### 5.3.6. Total costs

With the aforementioned insights of the cost elements associated with the construction of the NEED, also listed in Table 5.2, the concrete amounts per element can now be determined. Please note that although the design of the NEED would potentially allow for a highway structure to be built on top of it, the cost for constructing such a highway are not included in the total costs of the NEED.

Table 5.2: Overview of fixed variables determined in Section 5.3.1 through 5.3.5.

| Fixed Variables | Value | Unit |
|---|---|---|
| Slope | 1:6 | - |
| Width on top | 25 | m |
| Costs sand | 10 | €/$m^3$ |
| Costs geotextile | 5 | €/$m^2$ |
| Costs revetment | 6000 | €/m (length) |
| Costs per sluice | $850 * 10^6$ | € |
| Costs of pumps | $40 * 10^9$ | € |

Based on the information gathered from Table 5.2 and the dimensions of the structure from Table E.1, an assessment was made for the volume of sand, surface area for the geotextile and the amount of revetment needed for the NEED. In Table 5.3, an overview is given of the exact amounts as a function of the GMSLR. The substantial volume of sand needed immediately stands out. Realising this design of the NEED would require roughly 150 billion tons of sand when using a density of 1400 kg/$m^3$. For context, 150 billion tons is roughly three years worth of global sand use (Peduzzi, 2014). For the calculation for the amount of revetment, it is assumed that both sloped sides will entirely contain a woven geotextile layer. The costs of the rock revetment is not dependent on the depth, and therefore nor on the GMSLR, but rather on the length of the structure. Hence, the revetment length in the table below stays constant, as the length of the structure does not change as a function of GMSLR. The length of revetment is twice the length of the NEED, as both sloped sides will need to have rock armour revetment.

Table 5.3: Overview of the amount of sand, geotextile and revetment necessary as a function of the GMSLR.

| GMSLR (m) | Volume Sand (mil. $m^3$) | Area Geotextile (mil. $m^2$) | Length Revetment (km) |
|---|---|---|---|
| 0 | 102,215 | 1,033 | 1,190 |
| 1 | 103,252 | 1,033 | 1,190 |
| 2 | 104,296 | 1,033 | 1,190 |
| 3 | 105,348 | 1,033 | 1,190 |
| 4 | 106,406 | 1,034 | 1,190 |
| 5 | 107,472 | 1,034 | 1,190 |
| 6 | 108,545 | 1,034 | 1,190 |
| 7 | 109,625 | 1,034 | 1,190 |
| 8 | 110,712 | 1,034 | 1,190 |
| 9 | 111,807 | 1,035 | 1,190 |
| 10 | 112,908 | 1,035 | 1,190 |

With the quantities for each cost element determined and having defined their cost per unit, the total cost as a function of the GMSLR can be calculated. The costs per elements and the total costs for the NEED are stated in Table 5.4 and visually depicted in Figure 5.10.

Table 5.4: Overview of all the costs per element as a function of the GMSLR.

| GMSLR (m) | Costs Sand (mil. €) | Costs Geotextile (mil. €) | Costs Revetment (mil. €) | Costs Pumps (mil. €) | Costs Sluices (mil. €) | Total Costs (mil. €) |
|---|---|---|---|---|---|---|
| 0 | 1,022,145 | 5,164 | 8,330 | 40,000 | 12,750 | 1,088,389 |
| 1 | 1,032,517 | 5,165 | 8,330 | 40,000 | 12,750 | 1,098,763 |
| 2 | 1,042,961 | 5,166 | 8,330 | 40,000 | 12,750 | 1,109,208 |
| 3 | 1,053,477 | 5,167 | 8,330 | 40,000 | 12,750 | 1,119,724 |
| 4 | 1,064,063 | 5,168 | 8,330 | 40,000 | 12,750 | 1,130,311 |
| 5 | 1,074,721 | 5,169 | 8,330 | 40,000 | 12,750 | 1,140,971 |
| 6 | 1,085,451 | 5,170 | 8,330 | 40,000 | 12,750 | 1,151,701 |
| 7 | 1,096,252 | 5,171 | 8,330 | 40,000 | 12,750 | 1,162,503 |
| 8 | 1,107,124 | 5,172 | 8,330 | 40,000 | 12,750 | 1,173,376 |
| 9 | 1,118,067 | 5,173 | 8,330 | 40,000 | 12,750 | 1,184,321 |
| 10 | 1,129,083 | 5,174 | 8,330 | 40,000 | 12,750 | 1,195,337 |

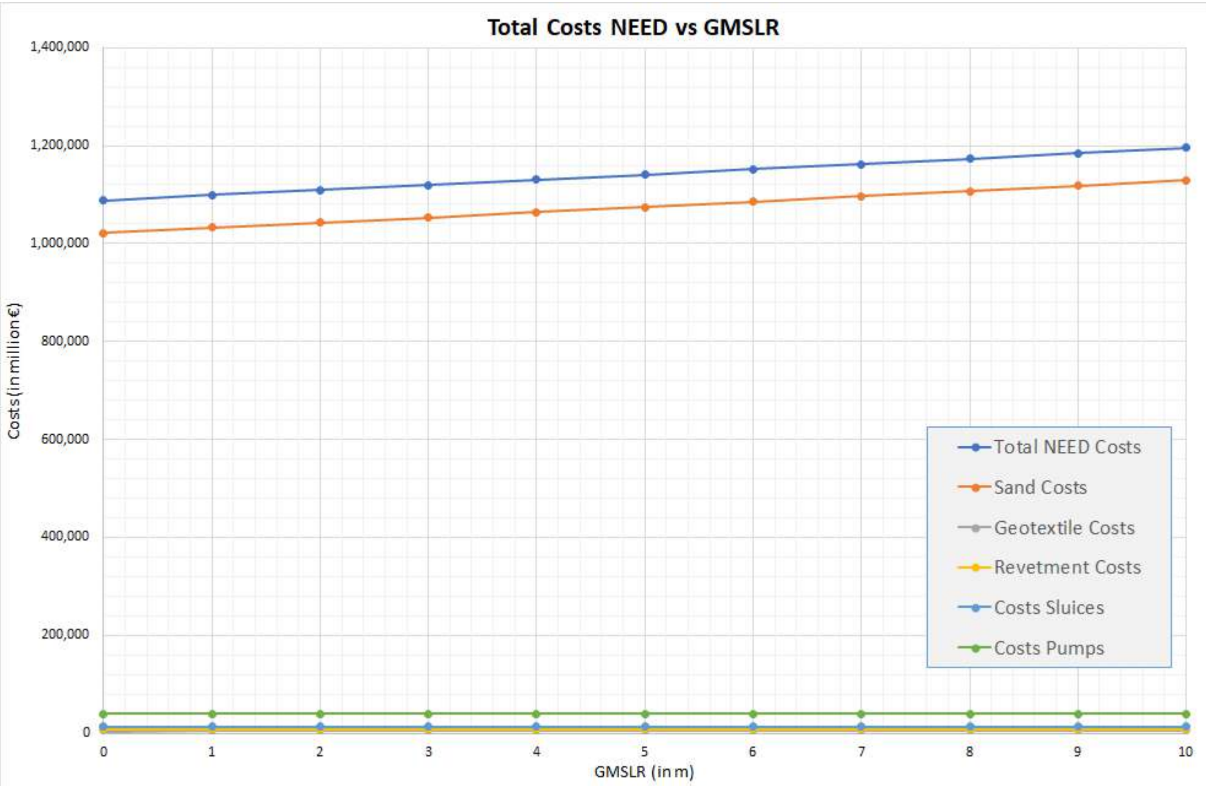



Figure 5.10: Graph showing costs (in million €) for all components of the NEED and total costs over GMSLR.

As can be seen from both the table and the figure, it is clear that costs for the sand are the most dominant costs for the NEED structure. The assessment of the total construction costs used an angle for the slopes of 1:6. In the next chapter this is explored in more detail, as modification in the slope angle could possible lead to significant cost savings.

## 5.4. Comparison with cost estimates by Groeskamp

With the determination of the costs for the NEED finalised, it might be interesting to cross-reference this with the estimates by Groeskamp. In Groeskamp's analysis on financial feasibility of the NEED, they consider it to be to be a "back-of-the-envelope" estimate of the costs of constructing the NEED. Groeskamp made three cost estimates of the construction costs for the NEED based on the methods listed below. Each method will be briefly discussed.

- Upscaling volume - Saemangeum Seawall
- Upscaling volume - Maasvlakte 2
- Linearity between height and costs

### 5.4.1. Method 1: Upscaling volume - Saemangeum Seawall

The first estimate Groeskamp made was done by putting the NEED project side by side with another large hydraulic structure, the 33.9 km long Saemangeum Seawall in South-Korea, depicted in Figure 5.11. By solely comparing the volume of the Saemangeum Seawall (0.34 $km^3$) to the volume needed for the NEED according to Groeskamp (36.1 $km^3$), he multiplied the costs of the Seawall (1.83 billion €) with the same ratio as the volumes and estimated a cost of 192 billion € for the NEED.

Since this thesis research did not find a volume of 36.1 $km^3$, but rather roughly 100 $km^3$ to be required for the NEED, this would instead equate to a total cost of approximately 540 billion €. The main reason for this big difference in volume and subsequently the total costs, is because Groeskamp assumed the NEED to have sloping sides with a 1:2 ratio.

Figure 5.11: Aerial picture of the Saemangeum Seawall in South-Korea.

### 5.4.2. Method 2: Upscaling volume - Maasvlakte 2

Groeskamp used the same approach as the one from the Seamangeum Seawall and applied this to Maasvlakte 2, which is an extension of the Rotterdam harbour that includes hard and soft flood protection and basic infrastructure, depicted in Figure 5.11. Land had to be reclaimed from a depth of 17 metres all the way up to 5 metres above sea level. With a volume of 0.24 $km^3$ and cost of 3.38 billion € for Maasvlakte 2, Groeskamp estimated the total cost (including infrastructure) for the NEED to be 508 billion €.

Using the volume this thesis has found to be needed for the construction of the NEED, i.e. roughly 100 $km^3$, the NEED is estimated to have a total cost of approximately 1,400 billion €.

Figure 5.12: Aerial picture of Maasvlakte 2 in the Netherlands.

### 5.4.3. Method 3: Linearity height/costs

Lastly, Groeskamp made a rough estimate assuming the relation between height and the construction costs of a dike to be linear. He found in multiple sources an upper limit of 42 million € per kilometre for an enclosure dam with a depth of 10 metres. When applying this linear relationship to the dimensions of the NEED he used, this resulted in 311 billion €.

Since in this research the dimensions of the NEED differ from that of Groeskamp's, the price estimate will not be the same. In Table 5.5, the costs per section of the NEED, calculated based on the linearity between length, depth and costs, are stated. Here, both the dimensions and prices of this research as well as those from Groeskamp are listed. From this table it can be concluded that the total cost of the NEED, following this method and using the findings of this thesis, is approximately 360 billion €.

Table 5.5: Overview of the costs assuming linearity between length, depth and costs from this thesis' findings and from Groeskamp and Kjellsson (2020) (indicated with an asterisk (*)).

| Section | Part | Length (km) | Depths Average (m) | Price (bil. €) | Length* (km) | Depths Average* (m) | Price* (bil. €) |
|---|---|---|---|---|---|---|---|
| **A** | Total | 150 | 90 | 56.7 | 161 | 85 | 57.5 |
| **B** | Shallow | 75 | 60 | 18.9 | - | - | - |
| | Deep | 70 | 100 | 29.4 | - | - | - |
| | Total | - | - | - | 145 | 49 | 29.8 |
| **C** | Shallow | 180 | 130 | 98.3 | - | - | - |
| | Transition | 50 | 240 | 50.4 | - | - | - |
| | Deep | 70 | 350 | 102.9 | - | - | - |
| | Total | - | - | - | 331 | 161 | 223.8 |
| | | | **Total** | 356.6 | | **Total** | 311.1 |

Combining all the above, Groeskamp estimated the total costs to be roughly in the vicinity of **250 and 550 billion €**. This includes the costs of the pumps necessary, which would cost an additional 20 - 36.5 billion €. However, it did not account for the construction of sluices. Using the same methods but applying the findings of this thesis, the total costs of the NEED is estimated to range between **400 and 1,450 billion €**.

This significant estimation difference in total costs for the NEED is due to the divergence in volume caused by the change in slopes of the sides. In this assessment a 1:6 slope is used opposed to the 1:2 slope used in Groeskamp and Kjellsson (2020). Although this is a wide range, the calculated costs (roughly 1.1 trillion €) in Section 5.3.6 do fall within that range.

# 6

# Cost Comparison Flood Protection Adaptation Strategies

*In this chapter, the two alternative adaptation strategies analysed in this thesis will be compared. Firstly, Section 6.1 analyses the comparison of the two adaptation strategies. In this section, GMSLR, cost and dike raising estimations are made for when the NEED solution becomes more financially favourable. Section 6.2 provides several ways to (fairly) distribute the total costs for the NEED over the countries involved. Lastly, Section 6.3 provides brief sensitivity analyses of several assumptions made in the assessment of the regional flood protection.*


## 6.1. Comparison of North Sea Adaptation Strategies

Having analysed both flood protection adaptation strategies for the north of Europe, it is now possible to determined which adaptation strategies will be more financially favourable and whether this changes over time and as a function of GMSLR. Naturally, and as confirmed by Figure 5.10, the initial costs for the construction of the NEED are going to be much greater than the regional reinforcement costs for lower values of GMSLR. By combining the information from Figures 4.7 and 5.10, it is possible to find the GMSLR where both adaptation strategies are equal on costs.

It can be noted from Figure 5.10 that the costs for sand are the biggest expense in the total costs before this combination is made. Knowing that the key driver in the total construction costs of the NEED are the costs for the core material, by modifying the design to a slightly steeper slope the costs will reduce significantly. These considerable reductions in costs are depicted in Figure 6.1. When looking at the difference in a slope of 1:4 up to 1:6, the difference in cost and thus at which GMSLR the NEED becomes more financially attractive compared to the country-by-country reinforcements, will thus drastically change. In Figure 6.1 the regional protection costs, its projected costs and the costs for three NEED designs, varying in slope, are depicted.

In Figure 6.1, the intersection between the regional reinforcement costs and the three different NEED designs are visualised by means of linear extrapolation. The intersection points are on the extrapolated estimated regional protection costs (indicated in legend as '*Estimated*') that intersect with all three NEED designs. In Table 6.1 the GMSLR for each NEED design can be found, which essentially is the turning point under which GMSLR conditions the NEED will become more financially favourable than reinforcing all fourteen countries. Having assessed the conditions, the lower and upper bounds in costs for the three different NEED designs can be found as well. The estimated costs as well as the upper and lower bounds for the NEED designs (indicated in legend as '*Proj. Reg. Costs (NEED 1:4 to 1:6)*') are also listed in Table 6.1. Here, it can be concluded that for a NEED structure designed with a slope of 1:4, 1:5 or 1:6, both solution strategies (i.e. Regional flood protection and NEED flood protection) would be equal on costs at a GMSLR of 3.35, 4.25 and 5.15, respectively. At greater GMSLRs the NEED would be financially favourable over regional flood protection.

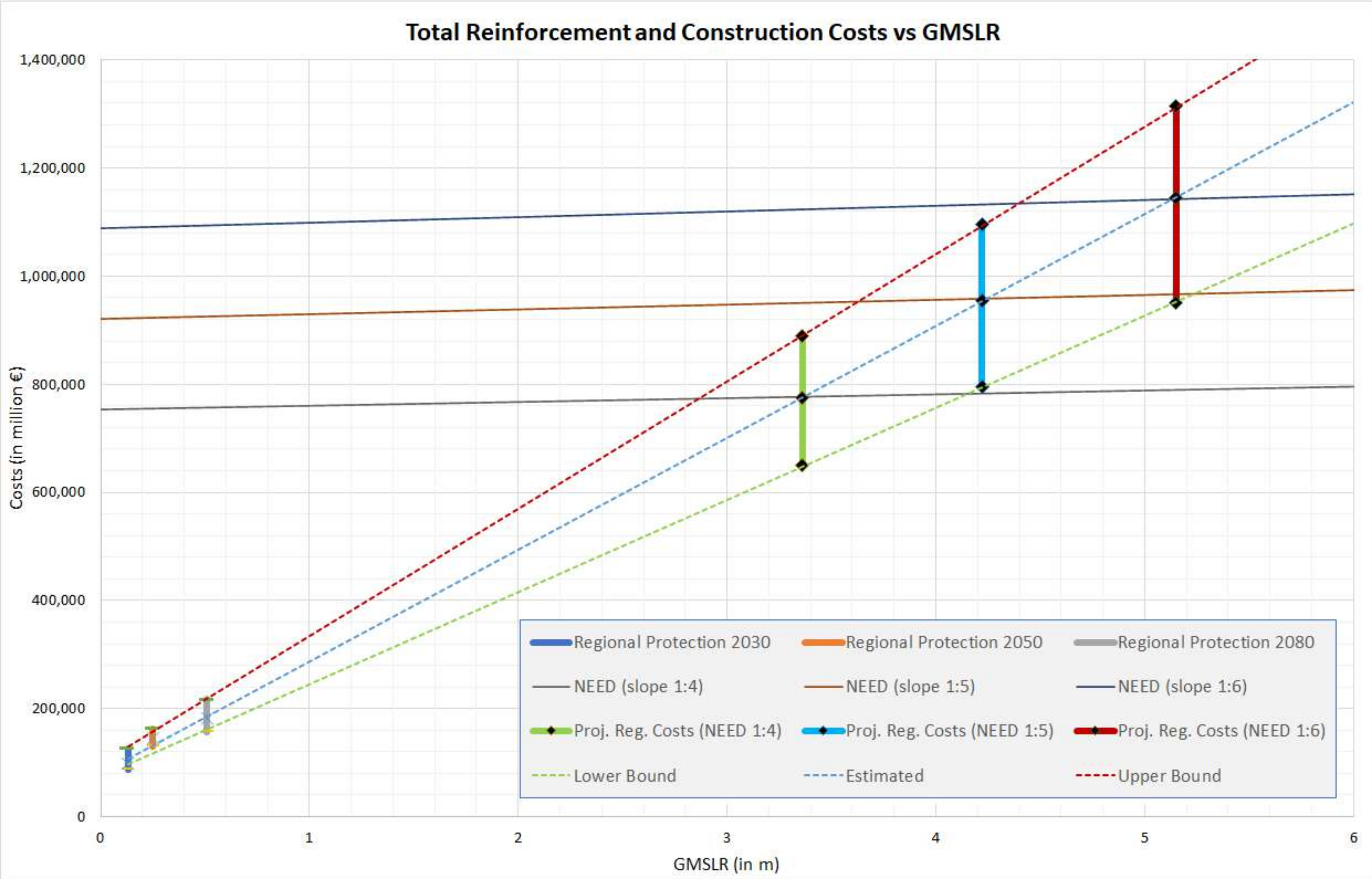



Figure 6.1: Graph depicting the regional reinforcement and the NEED construction costs as a function of GMSLR.

Table 6.1: Overview of the projected regional costs and the intersecting GMSLR for the different NEED designs, based on Figure 6.1.

| | GMSLR (metres) | Lower bound (mil. €) | Estimated (mil. €) | Upper bound (mil. €) |
|---|---|---|---|---|
| NEED (slope 1:4) | 3.35 | 650,000 | 775,000 | 890,000 |
| NEED (slope 1:5) | 4.25 | 795,000 | 955,000 | 1,095,000 |
| NEED (slope 1:6) | 5.15 | 950,000 | 1,145,000 | 1,315,000 |

With the assessment of the GMSLR intersections, it can be predicted when in the future this GMSLR will occur. Using the latest projection of KNMI (2021), depicted in Figure 1.3, an time span indication can be made. In Figure 6.2, the found GMSLR at which the costs for the two solution adaptation strategies intersect are pointed out for the SSP5-RCP8.5 H++, i.e. the most extreme scenario, which also includes the unstable ice-sheet processes in Antarctica. Here, it can be seen that the GMSLRs of 3.35, 4.25 and 5.15 are projected to be reached at roughly 2175, 2195 and 2210, respectively. However, as these are futuristic projections, it should be noted that, according to KNMI (2021), there is an uncertainty range of roughly 100 years.

Figure 6.2 shows that the GMSLRs for SSP5-RCP8.5 are projected to be reached after 2300. Although the original KNMI graph is cut off at the year 2300, an expected trajectory is intuitively extrapolated to still be able to indicate the time span for the scenario used in this report. It should be borne in mind that the indications found for this scenario are thus by no means conclusive projected time spans. In Table 6.2, an overview is given of these projected time spans within which the given GMSLRs are projected to become reality for both scenario SSP5-RCP8.5 and SSP5-RCP8.5 H++.

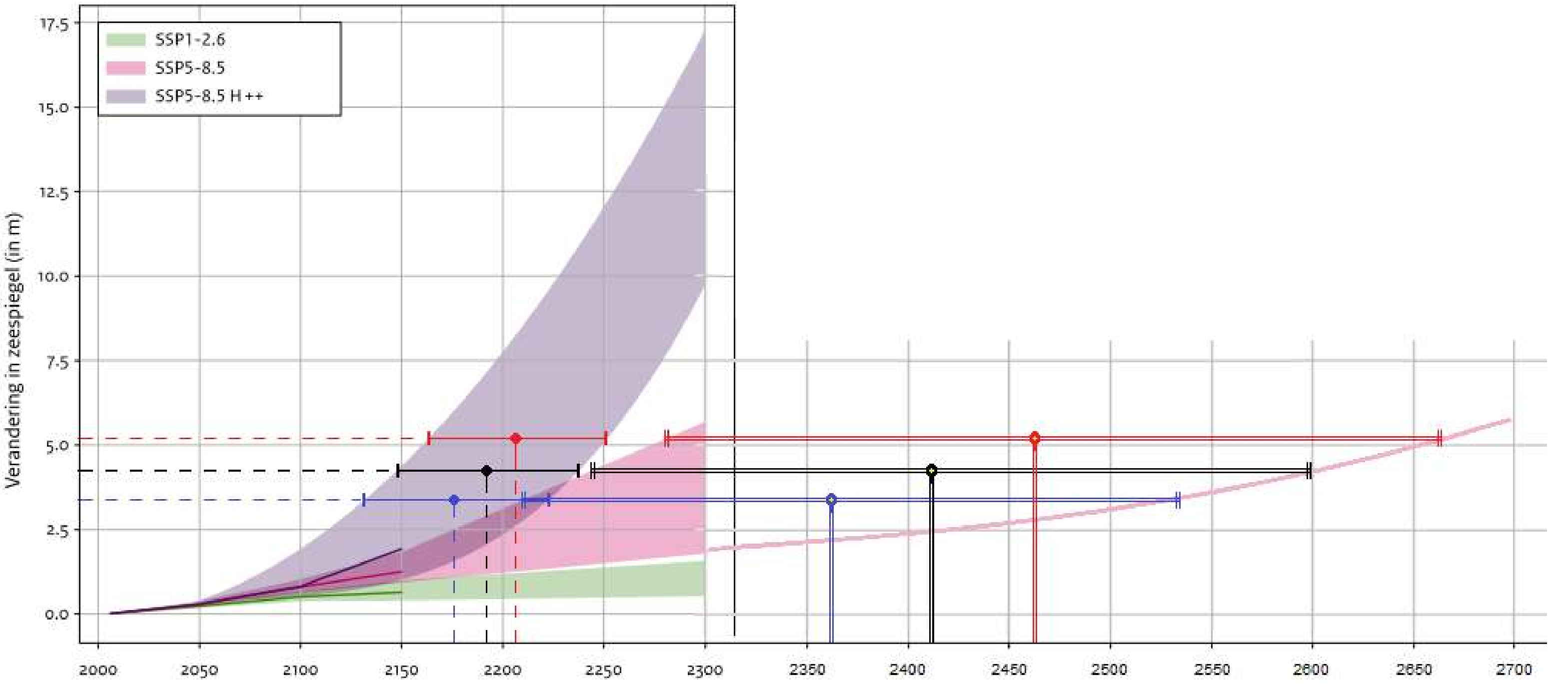



Figure 6.2: Graph of KNMI (2021) with time spans indications of when the estimated GMSLRs for the NEED will occur with scenario SSP5-RCP8.5 and SSP5-RCP8.5 H++.

Table 6.2: Overview of projected time spans when estimated GMSLRs will occur according to scenario SSP5-RCP8.5 and SSP5-RCP8.5 H++ from KNMI (2021).

| | | SSP5-RCP8.5 | SSP5-RCP8.5 H++ |
|---|---|---|---|
| | **GMSLR** | **Time Span** | **Time Span** |
| **NEED (slope 1:4)** | 3.35 m | 2365 [*2210-2535*] | 2175 [*2125-2225*] |
| **NEED (slope 1:5)** | 4.25 m | 2415 [*2245-2600*] | 2195 [*2150-2240*] |
| **NEED (slope 1:6)** | 5.15 m | 2465 [*2280-2660*] | 2210 [*2165-2250*] |

With the GMSLRs and their projected time of occurrence determined, it is of particular interest to assess the required dike raising for each country as a function of GMSLR. The dike raising is dependent on the inundation height found, and this is assessed from the findings of the simulations done with GLOFRIS. These simulations were run up to 2080, which according to the report of IPCC has an estimated (P50) GMSLR of 0.51 metres (Stocker *et al.*, 2013). However, several countries in question require dike raising beyond (twice) the SLR. To illustrate, Figure 6.3 shows the required sea dike raising for Belgium, Denmark, the Netherlands, Poland and the United Kingdom. The aforementioned are the countries which required the highest dike raising. Figure F.1 in Appendix F.1 depicts all countries with regard to their required dike raising.

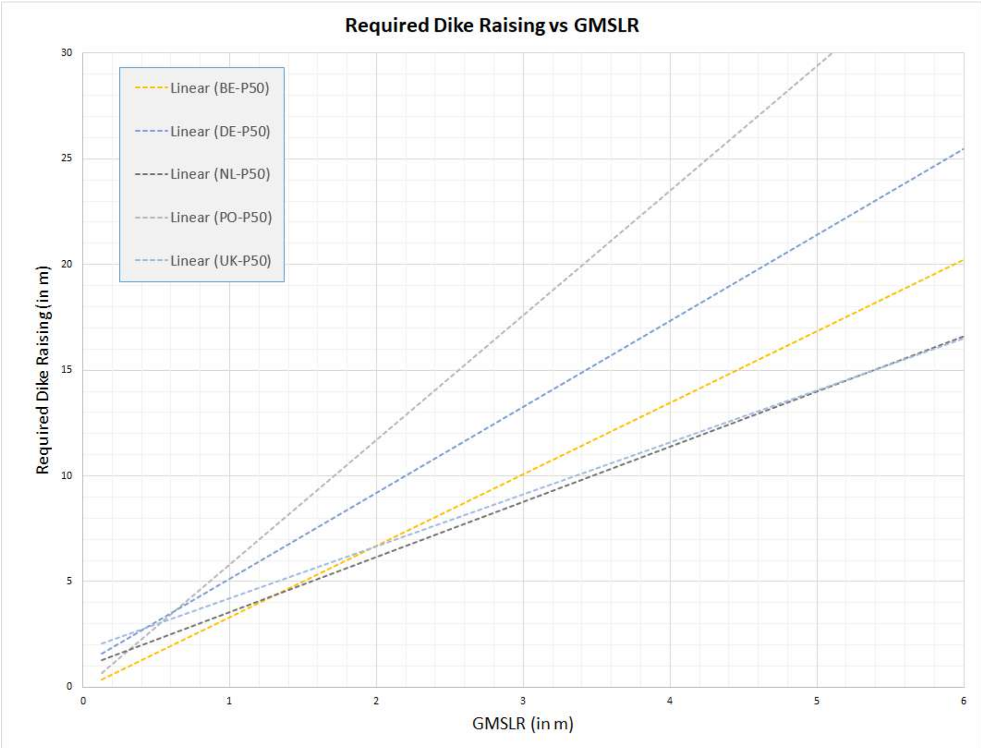



Figure 6.3: Graph of required dike raising (in metres) for BE, DE, NL, PO and UK as a function of GMSLR using the maximum inundation approach for RCP8.5 with RP1000.

As Figure 6.3 shows, Poland requires the highest dike raising per GMSLR, where the dikes need to be raised by roughly 30 metres per 5 metres of GMSLR. This, however, is caused by the rapid increase in maximum inundations for Poland for scenario RCP8.5 with a return period of a 1000 years and by the subsequent linear extrapolation. As can be seen in Table 4.7, the maximum increase in inundation height found in Poland along the coast jumps from roughly 0.20 metres in 2030 to 2.70 metres in 2080. However, this significant jump is not because Poland is not prepared, but simply because they will experience greater inundation heights increases according to the future climate simulation done through GLOFRIS. This substantial increase is not seen in other countries such as the Netherlands or United Kingdom, for example, as these countries already start with an significant large maximum inundation height.

## 6.2. Cost distribution

As the total construction costs of the NEED has been assessed for the GMSLR at which it will become financially favourable over the regional protection costs, the next step is to determine what each country should contribute to the total costs. One could argue that all countries involved should pay an equal sum but, on the other hand, it would not be fair to let countries pay more when less affected. With this reasoning, an equitable distribution should be devised for the construction costs of the NEED for all relevant countries.

Ideally, this cost distribution should also take aspects such as politics into account, but this is beyond the scope of this thesis. However, it is possible to make cost distributions based on four aspects that are scrutinised in this thesis. These are listed below.

- Coastline Reinforcement Length (*C.L.*)
- Inundated Area (*Area*)
- Population Exposed (*POP*)
- Economic Damages (*ECO*)

In order to be able to make an equitable distribution weighted based on these aspects, the total value of each category must be known. In Table 6.3 all values are listed, including each country's share of the total, expressed in percentages. These shares for each aspect will be used in further calculations. Here, it should be noted that these values are derived from the GLOFRIS simulation of 2080 for scenario SSP5 and RCP8.5, which generated the largest values for every aspect.

Table 6.3: Overview of contribution in percentages for the four aspects analysed based on the total value.

| Country | Area | | ECO | | POP | | C.L. | |
|---|---|---|---|---|---|---|---|---|
| | (km$^2$) | (%) | (mil. €) | (%) | (people) | (%) | (km) | (%) |
| Belgium | 466.67 | 3.12 | 85,352 | 8.81 | 520,525 | 5.53 | 57.86 | 0.96 |
| Denmark | 2.55 | 0.02 | 10,484 | 1.08 | 72,125 | 0.77 | 1,066.89 | 17.71 |
| Estonia | 4.48 | 0.03 | 313 | 0.03 | 431 | 0.00 | 29.98 | 0.50 |
| Finland | 89.99 | 0.60 | 1,023 | 0.11 | 12,988 | 0.14 | 334.23 | 5.55 |
| France | 1,427.99 | 9.56 | 39,827 | 4.11 | 706,929 | 7.51 | 510.04 | 8.47 |
| Germany | 3,820.63 | 25.58 | 111,995 | 11.56 | 414,814 | 4.41 | 1,815.18 | 30.13 |
| Latvia | 20.62 | 0.14 | 34 | 0.00 | 589 | 0.01 | 18.72 | 0.31 |
| Lithuania | 40.82 | 0.27 | 119 | 0.01 | 235 | 0.00 | 79.79 | 1.32 |
| Netherlands, the | 5,875.54 | 39.34 | 597,265 | 61.65 | 6,171,640 | 65.60 | 354.56 | 5.89 |
| Norway | 89.84 | 0.60 | 1,626 | 0.17 | 39,655 | 0.42 | 31.51 | 0.52 |
| Poland | 417.54 | 2.80 | 6,354 | 0.66 | 22,941 | 0.24 | 196.29 | 3.26 |
| Russia | 2,058.97 | 13.79 | 3,675 | 0.38 | 4,420 | 0.05 | 210.62 | 3.50 |
| Sweden | 58.38 | 0.39 | 2,733 | 0.28 | 34,935 | 0.37 | 395.46 | 6.56 |
| United Kingdom, the | 559.74 | 3.75 | 107,941 | 11.14 | 1,405,090 | 14.94 | 923.14 | 15.32 |
| **Total** | 14,933.75 | 100.00 | 968,740 | 100.00 | 9,407,317 | 100.00 | 6,024.27 | 100.00 |

With the percentual shares of all countries known for each aspect, the corresponding values can be calculated. In Table 6.4 the median cost values (P50) for each aspect is given for the NEED structures with a slope of 1:6. As expected, the Netherlands has the biggest share and thus generates the largest cost contribution for three out of four aspects. Only when the cost distribution would be weighted based on the coastline reinforcement length would not the Netherlands be the biggest contributor, but rather Germany. Table F.1, Table F.2, Table F.3 and Table F.4 in Section F.2 give all cost distribution values for the three different NEED designs weighted based on the coastal reinforcement length, inundated area, economic damages and population affected, respectively. In a similar fashion, Table F.6, Table F.7 and Table F.8 in Section F.3 show the cost distribution for the NEED structure with a slope of 1:4, 1:5 and 1:6, respectively.

Table 6.4: Medians costs (P50) (in mil. €) for the four weighted aspects of all the countries for the construction of the NEED with slope 1:6.

| Country | Area | ECO | POP | C.L. |
|---|---|---|---|---|
| | (km) | (mil. €) | (people) | (km$^2$) |
| Belgium | 35,781 | 100,882 | 63,355 | 10,997 |
| Denmark | 195 | 12,391 | 8,779 | 202,778 |
| Estonia | 344 | 370 | 52 | 5,698 |
| Finland | 6,900 | 1,209 | 1,581 | 63,525 |
| France | 109,487 | 47,074 | 86,043 | 96,941 |
| Germany | 292,935 | 132,372 | 50,489 | 345,001 |
| Latvia | 1,581 | 40 | 72 | 3,558 |
| Lithuania | 3,130 | 141 | 29 | 15,165 |
| Netherlands, the | 450,489 | 705,936 | 751,174 | 67,389 |
| Norway | 6,888 | 1,922 | 4,827 | 5,989 |
| Poland | 32,014 | 7,510 | 2,792 | 37,308 |
| Russia | 157,865 | 4,343 | 538 | 40,031 |
| Sweden | 4,476 | 3,230 | 4,252 | 75,163 |
| United Kingdom, the | 42,916 | 127,581 | 171,019 | 175,456 |

With the weighted distributions of the NEED costs calculated for all aspects, it should now be possible to determine which of these four distributions are the most and least financially favourable for each country. However, in order to determine if – from the perspective of each country – contributing to the NEED is even favourable at all, it is necessary to determine what the flood protection costs for each country would be. Table 6.5 states these regional protection costs for all countries given a GMSLR of 5.15 metres, as this is when the NEED with a slope of 1:6 becomes financially favourable. Table F.5 in Section F.3 gives the regional protection costs for NEED designs with alternative slopes.

Table 6.5: Regional protection costs (in mil. €) per country projected for GMSLR of 5.15 metres (intersecting point of NEED (slope 1:6)).

| Country | NEED (slope 1:6) Costs P05 | Costs P50 | Costs P95 |
|---|---|---|---|
| Belgium | 11,090 | 11,274 | 12,537 |
| Denmark | 121,215 | 174,141 | 232,258 |
| Estonia | 576 | 984 | 1,376 |
| Finland | 13,939 | 43,841 | 76,531 |
| France | 27,705 | 34,627 | 44,759 |
| Germany | 359,108 | 431,640 | 470,433 |
| Latvia | 352 | 503 | 740 |
| Lithuania | 1,797 | 2,521 | 3,635 |
| Netherlands, the | 112,881 | 120,894 | 125,939 |
| Norway | 2,042 | 3,149 | 4,820 |
| Poland | 13,134 | 21,622 | 22,568 |
| Russia | 89,047 | 142,529 | 228,096 |
| Sweden | 22,490 | 31,947 | 46,571 |
| United Kingdom, the | 41,600 | 140,475 | 163,462 |

Having determined all aspect-weighted costs distributions for the NEED as well as the regional costs, an overview can be made of all these costs. Figure 6.4 depicts each aspect-weighted NEED cost distribution when opting for a 1:6 slope and regional protection costs for all countries. Figure F.2 and Figure F.3 in Section F.4 depict a similar graph for the cost distribution, but for a NEED design with 1:4 and 1:5 slopes, respectively. All graphs show a similar trend since the ratios of all the distributions are derived from the same percentual shares. The only discrepancy between the graphs is the magnitude of the costs.

In Table 6.6, an overview is given of the best and worst aspect-weighted cost distributions for each country. In the last column, a plus sign indicates whether the regional costs of a country are greater than any of the four aspect-weighted cost distributions for the NEED. In other words, this signifies that, for a given country, opting for the NEED would in all cases be financially favourable over regional flood protection, regardless of the way in which the NEED costs were to be distributed. For Finland and Russia, this plus sign is placed in parentheses to point out that, although the estimated costs (diamond symbol in Figure 6.4) of an aspect-weighted NEED cost distribution are greater than the regional costs, the upper bound of the regional costs is greater than the aspect-weighted NEED cost distribution. Meaning that, given the uncertainty of the cost estimate, the NEED may or may not be favourable over the regional flood protection regardless of the way in which the NEED costs were to be distributed.

Table 6.6: Overview of best and worst cost distributions per country, based on Figure 6.4.

| Country | Best | Worst | Regional > NEED |
|---|---|---|---|
| Belgium | C.L. | ECO | |
| Denmark | Area | C.L. | + |
| Estonia | POP | C.L. | |
| Finland | ECO | C.L. | (+) |
| France | ECO | Area | |
| Germany | POP | C.L. | + |
| Latvia | ECO | C.L. | |
| Lithuania | POP | C.L. | |
| Netherlands, the | C.L. | POP | |
| Norway | ECO | Area | |
| Poland | POP | C.L. | |
| Russia | POP | Area | (+) |
| Sweden | ECO | C.L. | + |
| United Kingdom, the | Area | C.L. | |

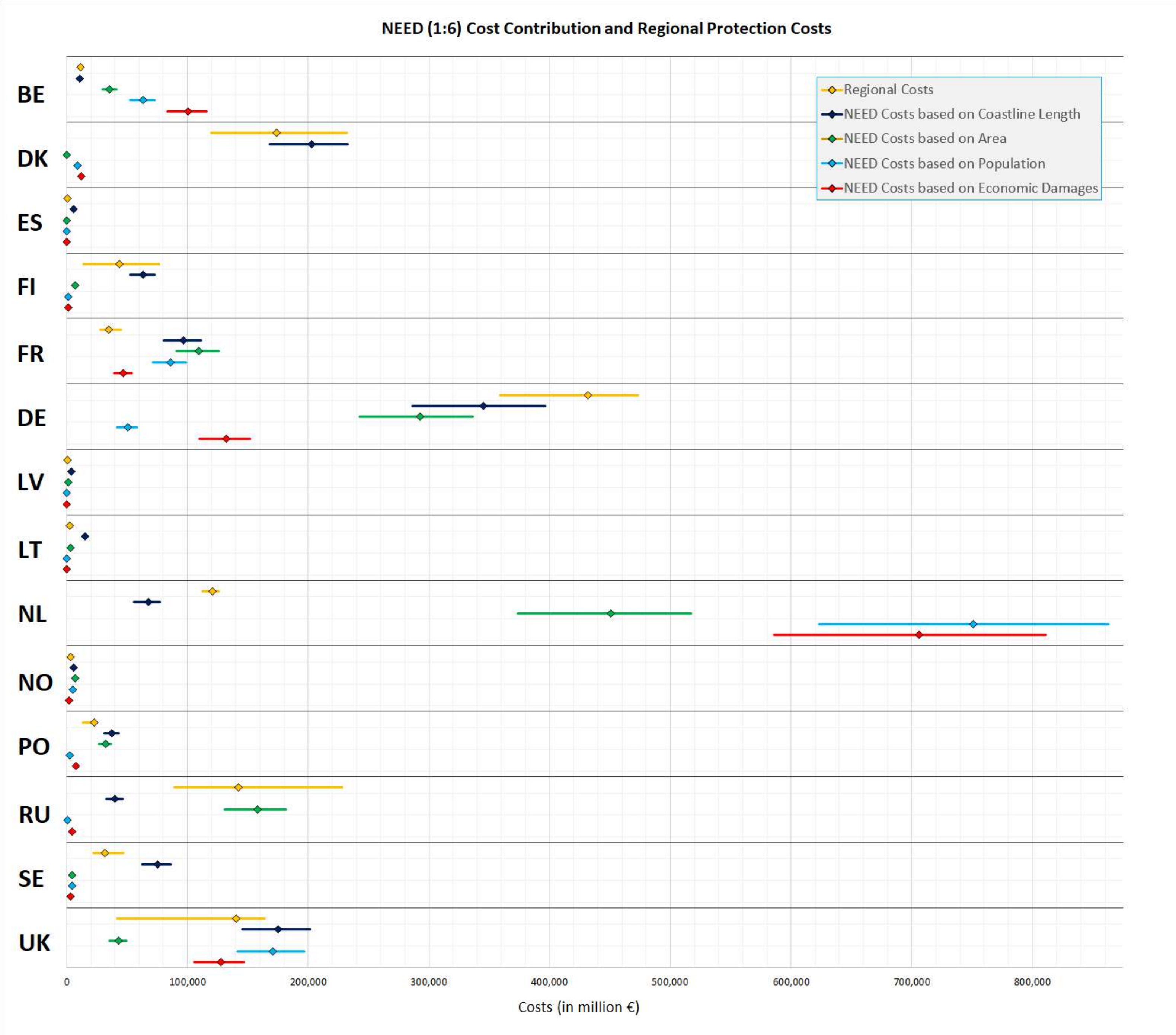



Figure 6.4: Overview of the NEED (1:6) cost contribution ranges per country based on the four distributions and each country's regional costs.

## 6.3. Sensitivity Analysis

For the analysis of both flood protection adaptation strategies, several assumptions were made in the process of obtaining the results. For the NEED flood protection adaptation strategy, in particular, this assessment had to be predominantly based on assumptions. Therefore, reference material on such a gigantic hydraulic structure was lacking.

The assumptions made for the regional flood protection adaptation strategy can be categorised as either pertaining to the reinforcement height or the cost assessment. The most important assumptions made for the regional flood protection adaptation strategy assessment are depicted in Figure 6.5. Here, the '*reinforcement height assessment*' assumed the maximum inundation height along the coast of each country to be the height necessary for its dike raising. The coastal location where reinforcement is required is dependent on this assumption, which in turn influences the length. Also, the model framework that was used to determine the inundation heights did not include the presence of already existing flood protections. To still account for the presence of flood protection, it is assumed that all countries involved did not have any flood problems in 2010. In other words, their flood exposure indicator values (area exposed, people affected and economic damages) were assumed to be zero for the base scenario. For the '*cost assessment*' of the regional flood protection, it is assumed that the entire reinforcement length only consists of sea dike (with the only exception for storm surge barriers) with a fixed price rate for its reinforcement, thus disregarding any cost differences for rural and urban areas.


Figure 6.5: Overview of the most important assumptions made in the assessment of regional flood protection adaptation strategy.

Naturally, changing any of these assumptions will lead to a different price tag for the regional flood protection adaptation strategy estimated in this thesis. In order to scrutinise the uncertainty in the output of the cost calculations, additional sensitivity analyses are performed. These analyses are conducted according to the same categories as those stated in Figure 6.5. For both categories, slight modifications and/or different approaches will be made to assess the uncertainty in the output. The sensitivity analyses are listed and briefly discussed in the following subsections.

### 6.3.1. Average Inundation Height

Instead of assuming the maximum inundation heights for the necessary height for reinforcement, this sensitivity analysis will include the average inundation heights for RCP8.5 with a return period of a 1000 years. In Table 6.7, the average inundation heights obtained using GLOFRIS are stated for the countries for all relevant years. These average heights are the mean inundations found along the coastal protection range of the NEED per country. Compared to the approach of assuming the maximum inundation height, where only a few cells on the GLOFRIS map actually have a value near this maximum, this alternative approach might give a better representation of the inundation. The results for this approach are given in Table 6.7. However, as mentioned in Section 4.4, assuming anything other than the maximum inundation height cannot guarantee complete flood protection for future scenarios.

Table 6.7: Overview of the change in average inundation heights (in m) in the coastal range of the NEED for all countries per year per percentile for RCP8.5 with a return period of a 1000 years.

| Year | Percentile | BE | DK | ES | FI | FR | DE | LV | LT | NL | NO | PO | RU | SE | UK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2030 | 5 | 0.09 | 0.16 | 0.07 | 0.11 | 0.47 | 0.25 | 0.12 | 0.12 | 0.27 | 0.11 | 0.12 | 0.11 | 0.08 | 0.18 |
| | 50 | 0.16 | 0.21 | 0.13 | 0.18 | 0.52 | 0.32 | 0.14 | 0.19 | 0.34 | 0.15 | 0.19 | 0.18 | 0.12 | 0.24 |
| | 95 | 0.25 | 0.29 | 0.23 | 0.28 | 0.57 | 0.40 | 0.25 | 0.30 | 0.42 | 0.22 | 0.30 | 0.29 | 0.17 | 0.32 |
| 2050 | 5 | 0.19 | 0.27 | 0.15 | 0.22 | 0.55 | 0.37 | 0.19 | 0.24 | 0.38 | 0.17 | 0.24 | 0.23 | 0.13 | 0.26 |
| | 50 | 0.30 | 0.36 | 0.24 | 0.31 | 0.63 | 0.46 | 0.30 | 0.35 | 0.48 | 0.26 | 0.35 | 0.33 | 0.21 | 0.37 |
| | 95 | 1.08 | 0.49 | 0.37 | 0.44 | 0.74 | 1.00 | 0.43 | 0.48 | 1.28 | 0.38 | 0.48 | 0.47 | 0.33 | 0.50 |
| 2080 | 5 | 1.12 | 0.47 | 0.31 | 0.36 | 0.71 | 1.00 | 0.38 | 0.43 | 1.46 | 0.29 | 0.43 | 0.42 | 0.22 | 0.40 |
| | 50 | 1.25 | 0.65 | 0.48 | 0.62 | 0.85 | 1.16 | 0.46 | 0.64 | 1.59 | 0.44 | 0.64 | 0.63 | 0.39 | 0.61 |
| | 95 | 1.45 | 0.92 | 0.79 | 0.85 | 1.05 | 1.40 | 0.60 | 0.95 | 1.79 | 0.62 | 0.95 | 0.93 | 0.64 | 0.91 |

In Figure 6.6, the total reinforcement costs when using the average inundation heights from Table 6.7 for all countries are compared with the costs derived using the maximum inundation heights. Through linear regression, trendlines were found for the percentiles, which serve as an upper and lower bound line. By extrapolating these trends, an estimation of the range for the costs associated with a 1-metre GMSLR could be made. The values found for the $5^{th}$, $50^{th}$ and $95^{th}$ are approximately **117**, **150** and **200** billion € with an increase of 115, 150 and 190 billion € per metre, respectively. Figure G.1 and Figure G.2 depict the reinforcement costs per country and can be found in Appendix G.1.

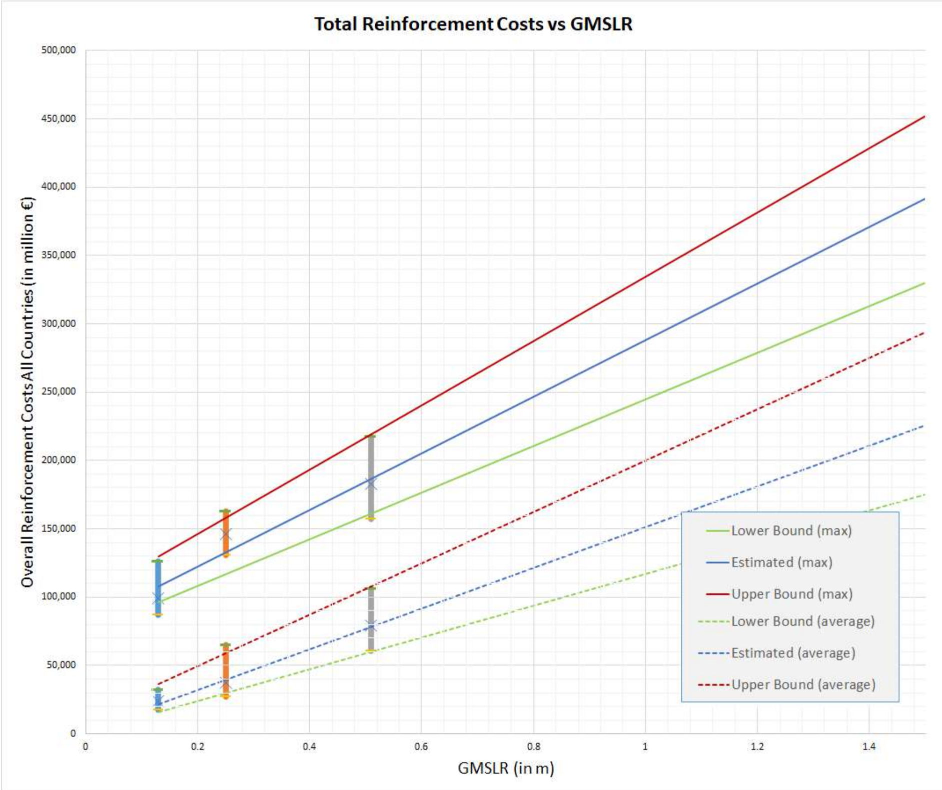



Figure 6.6: Graph illustrating the difference in total reinforcement costs per GMSLR using average inundation height and maximum inundation height.

As anticipated, the total reinforcement costs found are less when using the average inundation height for all countries. With these newly generated regional costs, the GMSLR and the projected costs at which the NEED will become financially favourable is altered. This is illustrated in Figure 6.7 and the GMSLR and costs for the three different NEED designs are listed in Table 6.8. Figure G.3 and Figure G.4 depict the required dike raising per country and can be found in Appendix G.1.

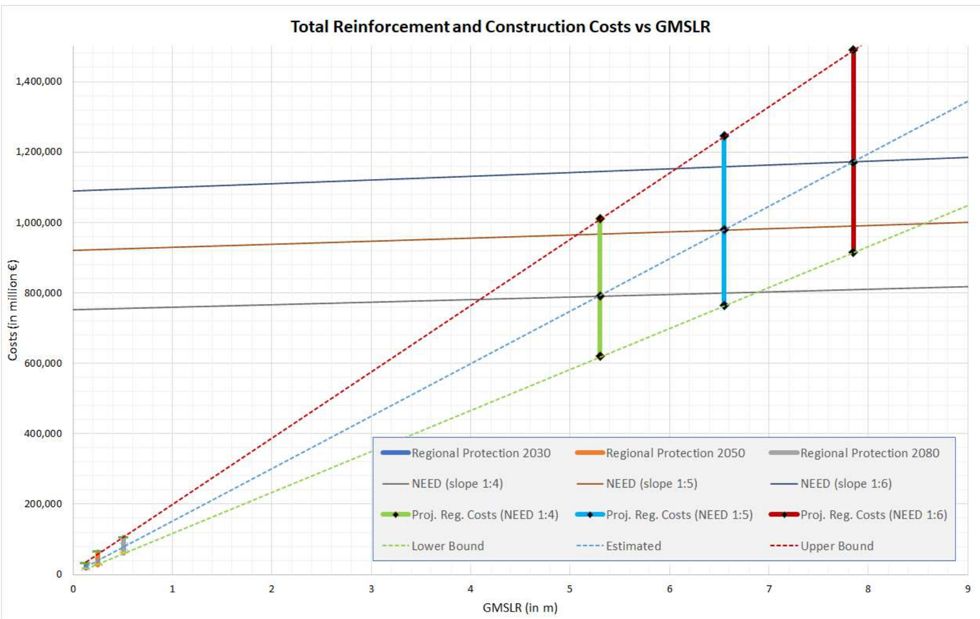



Figure 6.7: Graph depicting the regional reinforcement per GMSLR using the average inundation height and the NEED construction costs.

Table 6.8: Overview of the projected regional costs (in million €) and the intersecting GMSLR (in metres) for the different NEED designs, based on Figure 6.7.

| | GMSLR (metres) | Lower bound (mil. €) | Estimated (mil. €) | Upper bound (mil. €) |
|---|---|---|---|---|
| NEED (slope 1:4) | 5.30 | 620,000 | 790,000 | 1,010,000 |
| NEED (slope 1:5) | 6.55 | 765,000 | 980,000 | 1,245,000 |
| NEED (slope 1:6) | 7.85 | 915,000 | 1,170,000 | 1,490,000 |

Comparing these results with the findings from Section 6.1, it can be concluded that the GMSLR, at which the NEED will become financially favourable, will be greater. This is a logical consequence as the average reinforcement heights, and thus the associated reinforcement costs, are in all cases lower than the maximum heights found per country.

### 6.3.2. Relationship between SLR and dike raising (2x SLR)

An alternative approach could have been to assume twice the GMSLR (2xSLR) as the necessary reinforcement height (Stijnen *et al.*, 2014), as previously mentioned in Section 4.4. In Table 6.9, an overview is given of the necessary reinforcement height when following this assumption.

Table 6.9: Overview of the reinforcement height when assuming it is equal to double GMSLR.

| Year | Percentile | SLR (RCP8.5) | Reinforcement Height |
|---|---|---|---|
| 2030 | 5 | 0.10 | 0.20 |
| | 50 | 0.13 | 0.26 |
| | 95 | 0.17 | 0.34 |
| 2050 | 5 | 0.19 | 0.18 |
| | 50 | 0.25 | 0.50 |
| | 95 | 0.32 | 0.64 |
| 2080 | 5 | 0.37 | 0.72 |
| | 50 | 0.51 | 1.02 |
| | 95 | 0.67 | 1.34 |

In Figure 6.8, the total reinforcement costs when using the values in Table 6.9 for all countries are compared with the costs derived using the maximum inundation heights. Through linear regression, trendlines were found for the percentiles, which serve as an upper and lower bound line. By extrapolating these trends, an estimation of the range for the costs associated with a 1-metre GMSLR could be made. The values found for the $5^{th}$, $50^{th}$ and $95^{th}$ are approximately **122**, **178** and **238** billion € with an increase of 120, 175 and 235 billion € per metre, respectively. Figure G.5 and Figure G.6 depict the reinforcement costs per country and can be found in Appendix G.2.

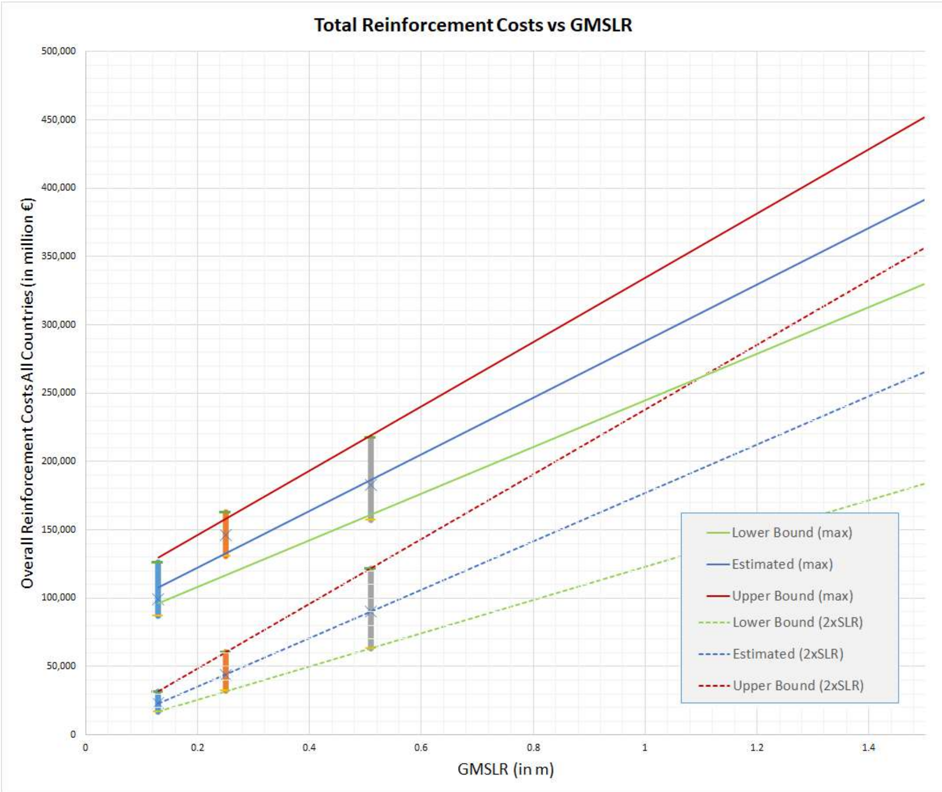



Figure 6.8: Graph illustrating the difference in total reinforcement costs per GMSLR using 2xSLR and maximum inundation height.

With these newly generated regional costs associated with the 2xSLR assumption, the GMSLR and the projected costs at which the NEED will become financially favourable will differ. This is due to the fact that the reinforcement height used which generates the total reinforcement costs clearly differs from the max inundation assessment used in this reports assessment. Figure 6.9 illustrates the GMSLR and costs for the three different NEED designs and the corresponding values are listed in Table 6.10. Figure G.7 in Appendix G.2 depicts the required dike raising per country. However, since the assumption here is to reinforce all sea dikes with twice the SLR per SLR, every country by definition shows the same 1:2 relationship.

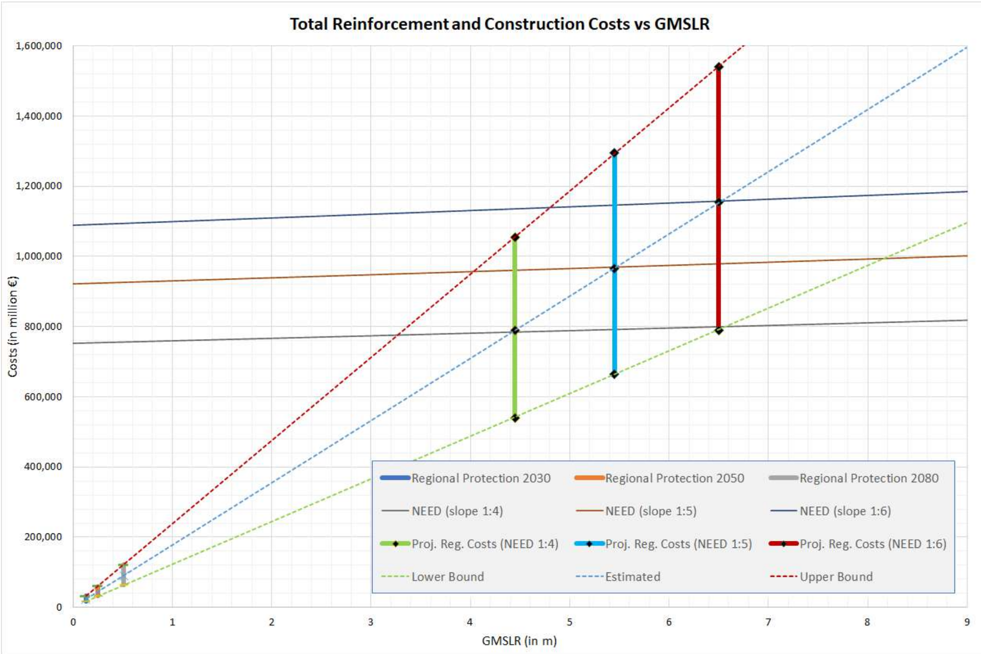



Figure 6.9: Graph depicting the regional reinforcement per GMSLR using 2x SLR and the NEED construction costs.

Table 6.10: Overview of the projected regional costs (in million €) and the intersecting GMSLR (in metres) for the different NEED designs, based on Figure 6.9.

| | GMSLR (metres) | Lower bound (mil. €) | Estimated (mil. €) | Upper bound (mil. €) |
|---|---|---|---|---|
| NEED (slope 1:4) | 4.45 | 540,000 | 790,000 | 1,055,000 |
| NEED (slope 1:5) | 5.45 | 665,000 | 965,000 | 1,295,000 |
| NEED (slope 1:6) | 6.50 | 790,000 | 1,115,000 | 1,540,000 |

Comparing these results with the findings from Section 6.1, it can be concluded that the GMSLR, at which the NEED will become financially favourable, will be greater. In spite of the fact that the cost increase per year for both seems nearly similar, it is caused by the reduction in initial reinforcement height for Belgium, Denmark, Finland, France, Germany, the Netherlands, Poland, Russia and the United Kingdom. Based on the coast lengths alone, it is known that these countries have the greatest contribution to the total regional protection costs. Therefore, a reduction in total initial regional reinforcement costs with the assumption that the cost increase seems nearly similar (as seen in Figure 6.8), leads to a higher GMSLR at which the NEED becomes a more financially attractive option.

### 6.3.3. Reinforcement pricing

In the analysis of the reinforcement, all necessary reinforcements are assumed to regard sea dikes, with the exception of the storm surge barriers. For these dike raising measures, the costs have been generalised to be 13 million euros per kilometre for an increase of 1 metre in crest level. However, as mentioned in Section 4.3, the reinforcement cost rely on the type of area where this reinforcement is needed. A detailed study on this length assessment of the rural and urban coast areas per country will give a more precise regional flood protection cost estimate. Therefore, a sensitivity analysis was conducted to assess whether and to what extent the outcome would differ if this area-dependent cost variability were to be included.

In Figure 6.10, a map of the degree of urbanisation in north Europe is depicted. Based on this map, a rough visual estimation is made to determine the ratio between rural and urban coastal areas. It must be noted that this estimated ratio is based on the total coast length per country within the protection range of the NEED rather than those locations requiring reinforcement, depicted in Figure 4.5. This should have been categorised as either urban or rural, from which a (more accurate) ratio can be derived.

The ratio (expressed in percentages) between urban and rural coastal areas used in further calculation in this sensitivity analysis are listed in Table 6.11 for all countries. These are solely based on the coastlines that fall within the protection range of the NEED. Please note that a 50/50 ratio is assumed for Russia, as for this country no data was available on the degree of urbanisation in Figure 6.10 .

Table 6.11: Overview of the percentages (%) urban and rural coastal regions per country, based on Figure 6.10.

| | BE | DK | ES | FI | FR | DE | LV | LT | NL | NO | PO | RU | SE | UK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Urban** | 90 | 10 | 5 | 15 | 15 | 30 | 20 | 30 | 75 | 35 | 15 | - (50) | 35 | 40 |
| **Rural** | 10 | 90 | 95 | 85 | 85 | 70 | 80 | 70 | 25 | 65 | 85 | - (50) | 65 | 60 |

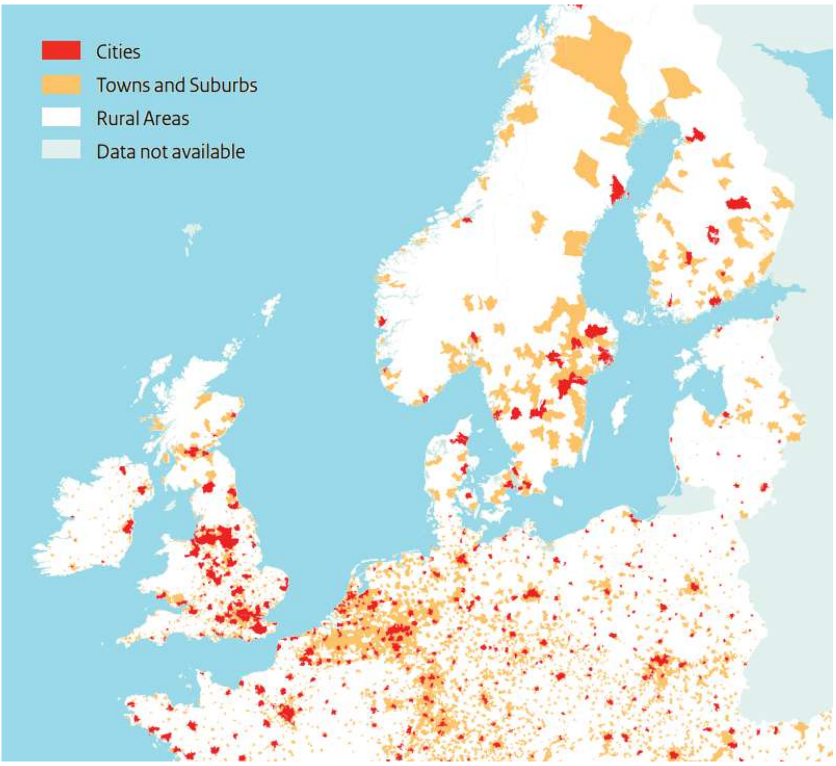



Figure 6.10: Degree of urbanisation based on population grid from 2006 and Local Administrative Units 2011 (Nabielek *et al.*, 2016).

In prior assessment, dike raising along the entire coast length was generalised to have an invariable cost per country. For the Netherlands this was assumed to be 13 million € per kilometre for raising the crest level with 1 metre. This generalisation was based on historic price rates from multiple sources which included both rural and urban prices. From Table 4.2, however, it can be deduced that the costs for raising sea dikes with 1 metre in rural and urban areas in the Netherlands is approximately 10 and 20 million € per kilometre, respectively (Kok *et al.*, 2008). Following the same method for the cost conversion as used in Section 4.3.3, the cost for rural and urban sea dike raising in all countries can be determined. These converted costs are listed in Table 6.12.

Table 6.12: Overview of the costs for rural and urban sea dike reinforcements in € for all countries based on GDP/capita.

| Country | GDP per capita | Rural Costs per km / m | Urban Costs per km / m |
|---|---|---|---|
| Belgium | 50,103 | 8,638,001 | 17,276,003 |
| Denmark | 67,218 | 11,588,711 | 23,177,422 |
| Estonia | 26,525 | 4,573,039 | 9,146,079 |
| Finland | 54,330 | 9,366,757 | 18,733,514 |
| France | 44,995 | 7,757,357 | 15,514,715 |
| Germany | 51,860 | 8,940,917 | 17,881,834 |
| Latvia | 19,831 | 3,418,961 | 6,837,922 |
| Lithuania | 22,532 | 3,836,526 | 7,673,051 |
| Netherlands, the | 58,003 | 10,000,000 | 20,000,000 |
| Norway | 81,995 | 14,136,338 | 28,272,676 |
| Poland | 16,930 | 2,918,815 | 5,837,629 |
| Russia | 11,654 | 2,009,206 | 4,018,413 |
| Sweden | 58,977 | 10,167,922 | 20,335,845 |
| United Kingdom, the | 46,344 | 7,989,932 | 15,979,863 |

With the conversion rate and ratio determined for the rural and urban sea dike reinforcement for all countries, the total (= rural + urban) reinforcement costs per country can subsequently be determine. In Table 6.13, an overview is given of these total reinforcement costs for each country. In Figure 6.11 the total reinforcement costs, summed for all countries, are compared with the costs derived using the maximum inundation heights.. Through linear regression, trendlines were found for the percentiles, which serve as an upper and lower bound line. By extrapolating these trends, an estimation of the range for the costs associated with a 1-metre GMSLR could be made. The values found for the 5$^{th}$, 50$^{th}$ and 95$^{th}$ are approximately **245**, **290** and **330** billion € with an increase of 170, 210 and 235 billion € per metre, respectively. Figure G.8 and Figure G.9 in Appendix G.3 depict the required dike raising per country.

Table 6.13: Overview of total reinforcement costs (urban + rural) per country per year per percentile at the coast in the range of NEED for RCP8.5 with a return period of a 1000 years.

| Year | Percentile | BE | DK | ES | FI | FR | DE | LV | LT | NL | NO | PO | RU | SE | UK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2030 | 05 | 89 | 17,772 | 10 | 1,091 | 10,449 | 23,260 | 9 | 160 | 8,052 | 79 | 78 | 179 | 681 | 21,491 |
| | 50 | 419 | 22,450 | 20 | 1,339 | 10,632 | 24,882 | 15 | 191 | 8,398 | 115 | 128 | 513 | 1,099 | 22,087 |
| | 95 | 503 | 23,873 | 33 | 1,684 | 10,883 | 43,568 | 23 | 232 | 8,874 | 164 | 1,181 | 579 | 1,691 | 22,907 |
| 2050 | 05 | 502 | 23,093 | 21 | 1,456 | 10,792 | 53,604 | 19 | 210 | 8,652 | 137 | 187 | 543 | 1,355 | 22,092 |
| | 50 | 594 | 28,003 | 35 | 1,813 | 11,143 | 55,790 | 26 | 251 | 9,240 | 198 | 1,396 | 609 | 1,943 | 23,093 |
| | 95 | 1,347 | 29,831 | 53 | 2,292 | 11,616 | 58,626 | 37 | 304 | 10,357 | 277 | 1,484 | 694 | 2,672 | 24,436 |
| 2080 | 05 | 1,465 | 28,003 | 45 | 1,960 | 11,514 | 57,655 | 33 | 286 | 13,464 | 235 | 1,454 | 665 | 2,423 | 23,148 |
| | 50 | 1,595 | 29,205 | 78 | 4,093 | 12,152 | 62,004 | 49 | 368 | 14,313 | 355 | 1,780 | 796 | 3,541 | 31,299 |
| | 95 | 1,781 | 37,290 | 113 | 6,497 | 13,065 | 68,445 | 73 | 488 | 15,531 | 530 | 1,982 | 1,153 | 5,199 | 33,837 |

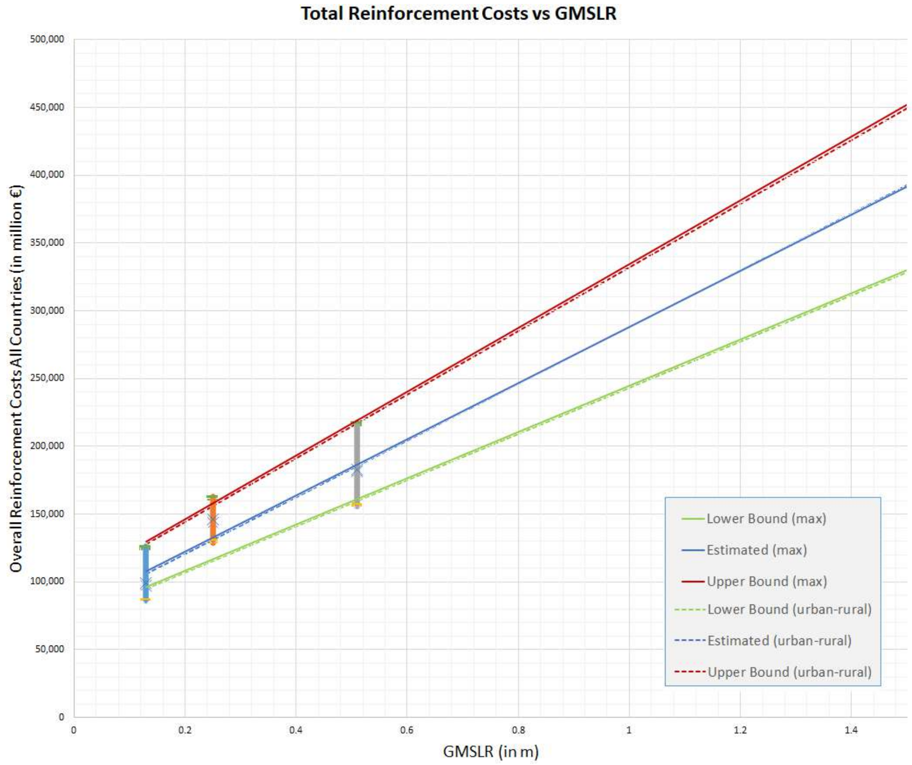



Figure 6.11: Graph illustrating the difference in total reinforcement costs per GMSLR when including and excluding the cost variability in urban and rural areas.

Comparing these newly generated regional costs with the costs for the NEED, the GMSLR and the projected costs at which the NEED will become financially favourable slightly differ. This is illustrated in Figure 6.12 and the GMSLR and costs for the three different NEED designs are listed in Table 6.14. Figure G.10 and Figure G.11 in Appendix G.3 depict the required dike raising per country.

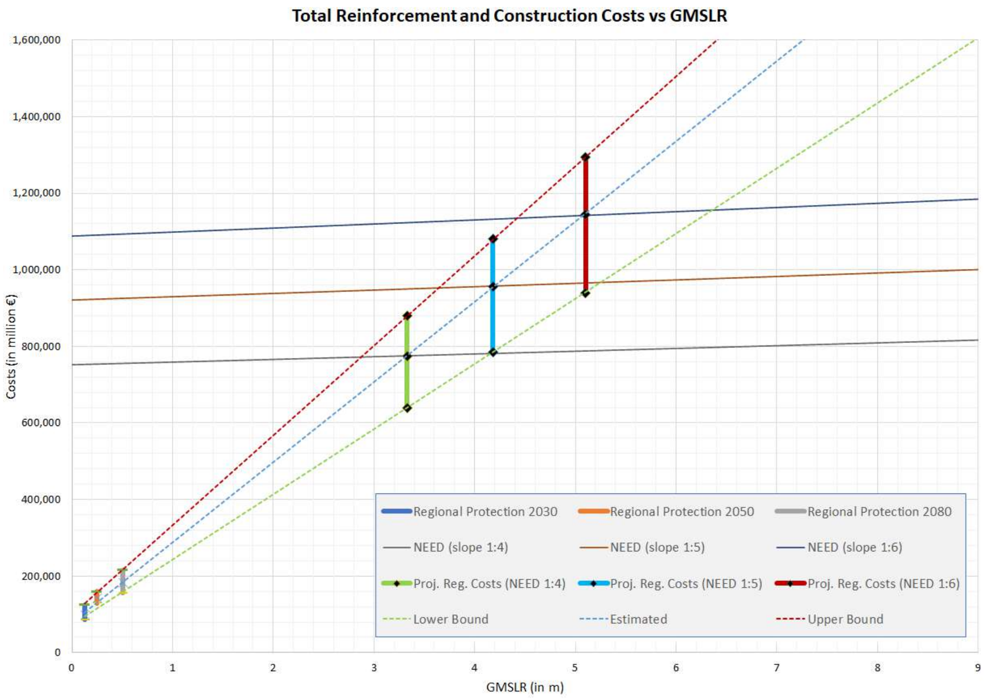



Figure 6.12: Graph depicting the regional reinforcement per GMSLR when implementing the urban-rural distinction and the NEED construction costs.

Table 6.14: Overview of the projected regional costs (in million €) and the intersecting GMSLR (in metres) for the different NEED designs, based on Figure 6.12.

| | GMSLR (metres) | Lower bound (mil. €) | Estimated (mil. €) | Upper bound (mil. €) |
|---|---|---|---|---|
| NEED (slope 1:4) | 3.33 | 640,000 | 770,000 | 880,000 |
| NEED (slope 1:5) | 4.18 | 785,000 | 950,000 | 1,080,000 |
| NEED (slope 1:6) | 5.10 | 940,000 | 1,140,000 | 1,295,000 |

Comparing these results with the findings from Section 6.1, it can be concluded that the GMSLR, at which the NEED will become financially favourable, is surprisingly similar. The corollary being that the total costs generated using the prior assumed price (13 mil. €) per country per kilometre per metre and the total costs generated whilst taking into account the cost variability between rural and urban areas (10 and 20 mil. €), are in the same ballpark.

From these sensitivity analyses, it can be concluded that reinforcement height is the most influential parameter, since changes thereto affect the total costs the most. The average inundation height approach generated the most divergent costs when compared to the assessment used in prior analysis. However, this was to be expected as these heights deviated most from the maximum inundation heights. Following a similar logic, the 2xSLR approach has a lesser influence on the total costs as its height deviated to a lesser extent from the maximum inundation heights. Furthermore, the sensitivity analysis assessing the influence of cost variability between rural and urban areas revealed that this parameter was the least influential. As it turned out, the assumption to generalise the costs for both area types yielded comparable results in this regard. In Figure 6.13, the total reinforcement and construction costs for all the sensitivity analyses are depicted. This allows for a better visual comparison of all analyses relative to one another. In Table 6.15 an overview is given of the intersecting GMSLRs and estimated (regional) costs for all the analyses for the three NEED designs visualised in Figure 6.13.

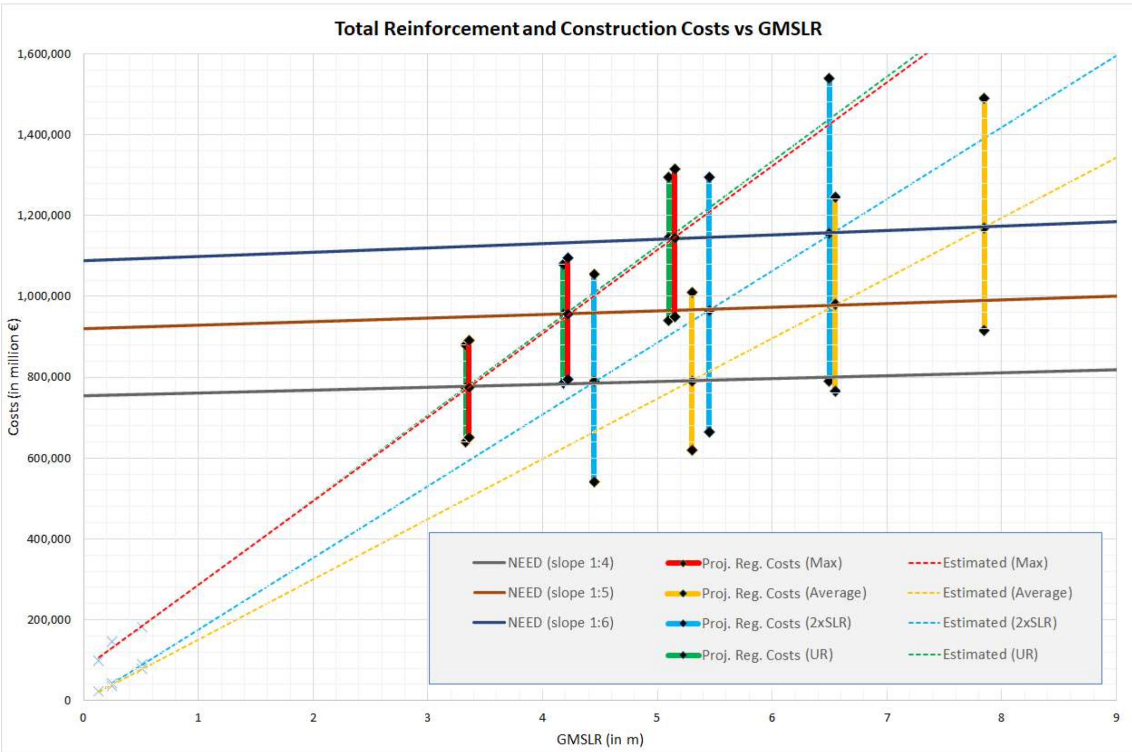



Figure 6.13: Graph depicting all regional reinforcement costs for each method and the NEED construction costs per GMSLR.

Table 6.15: Overview of the intersecting GMSLR (in metres) and the regional costs range (in billion €) for the different NEED designs using the different methods, based on Figure 6.13.

| | Maximum Inun.Height | | Average Inun.Height | | 2x SLR | | Urban Rural distinction | |
|---|---|---|---|---|---|---|---|---|
| | **GMSLR (metres)** | **Cost Range (bil. €)** | **GMSLR (metres)** | **Cost Range (bil. €)** | **GMSLR (metres)** | **Cost Range (bil. €)** | **GMSLR (metres)** | **Cost Range (bil. €)** |
| NEED (slope 1:4) | 3.35 | 775 [*650 - 890*] | 5.30 | 790 [*620-1,010*] | 4.45 | 790 [*540-1,055*] | 3.33 | 770 [*640 - 880*] |
| NEED (slope 1:5) | 4.25 | 955 [*795-1,095*] | 6.55 | 980 [*765-1,245*] | 5.45 | 965 [*665-1,295*] | 4.18 | 950 [*785-1,080*] |
| NEED (slope 1:6) | 5.15 | 1,145 [*950-1,315*] | 7.85 | 1,170 [*915-1,490*] | 6.50 | 1,115 [*790-1,540*] | 5.10 | 1,140 [*940-1,295*] |

Returning to the required dike raising (visualised in Figure 6.3), it was seen that Poland for instance needs a fairly large raising in order to withstand future GMSLRs and, as briefly explained in Section 6.1, the extrapolated required dike raising is greatly dependent on the future climate simulation and the assumed reinforcement height. After having performed sensitivity analyses that assumed different reinforcement approaches, its effect can clearly be seen on the required dike raising. Figure 6.14 depicts the required dike raisings as a function of GMSLR for Poland for all reinforcement height approaches considered in this report. From this it can be concluded that, especially for Poland, the approach using maximum inundation height as the required dike reinforcement height after linear extrapolation generates extreme values that lead to values that are arguable too excessive.

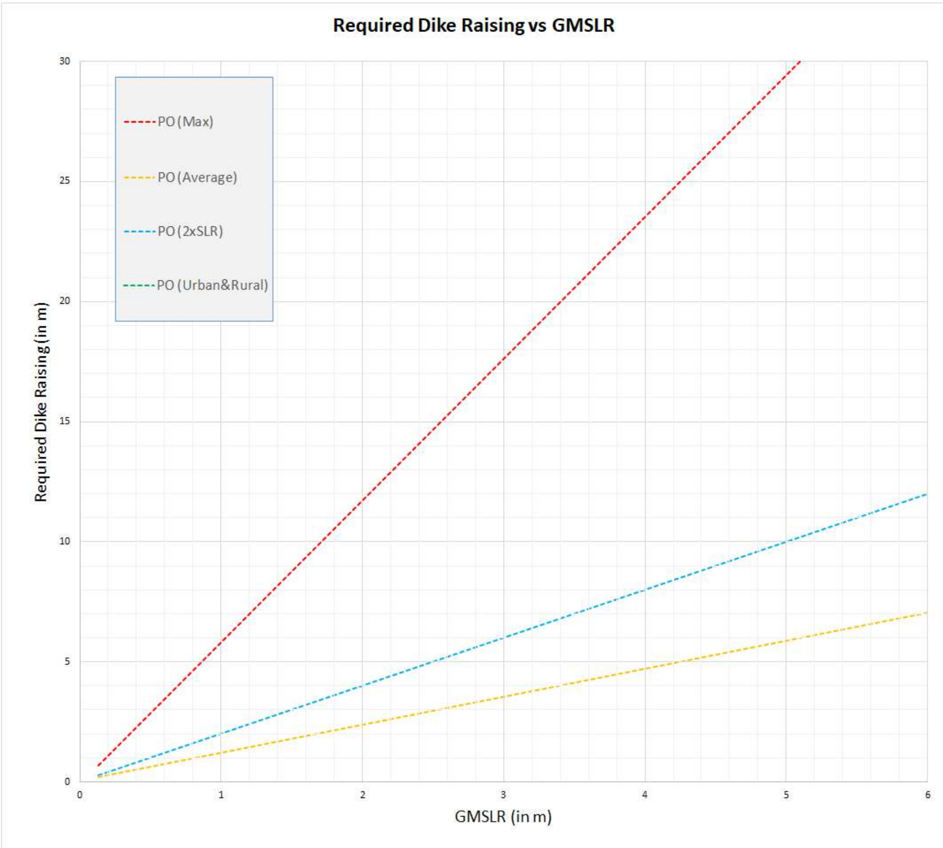



Figure 6.14: Graph depicting the dike raising of Poland as a function of GMSLR when looking at the different sensitivity analyses.

# 7

# Conclusion, Discussion and Recommendations

*The objective of this thesis is to investigate the financial benefit of the NEED when compared with raising coastal defences around the North Sea. Section 7.1 answers the research questions and will conclude the findings of this research. Section 7.2 provides a discussion on the findings, assumptions and limitations of this research. Lastly, Section 7.3 discusses and offers recommendations for future research.*


## 7.1. Conclusion

In conclusion, this study researched the applicability and economical benefit of the Northern European Enclosed Dam (NEED), which is designed to reduce the risk of flooding caused by SLR for the countries in question, when compared to raising coastal defences around the North Sea on a country-by-country basis. The most important conclusions of this report are briefly summarised in bullet points below.

- The installation of the NEED will potentially prevent approximately:
  **15,000 km$^2$** of inundated land
  **9.5 million people** of being affected by inundation (scenario; SSP5-RCP8.5)
  **1 trillion €** in economic damages caused by flooding (scenario; SSP5-RCP8.5)

- According to the GLOFRIS-generated inundation maps, roughly **6,000 km** of coast length will require dike raising by 2080 if the NEED would not be constructed. The total associated regional reinforcement costs to guarantee a flood protection exceedance probability of 1 in 1000 years in future climate scenario RCP8.5 for all countries in question will range between **245 and 335 billion € for an 1-metre GMSLR**, with an additional **170 and 235 billion € per metre GMSLR increase**.

- Constructing the NEED (earth-fill dam design with a 1:6 slope) will roughly cost **1.1 trillion €** with an additional **11 billion € per metre GMSLR increase**.

- Constructing the NEED **will be a more favourable adaptation strategy** in terms of cost than raising coastal defences on a country-by-country basis around the North Sea after a **GMSLR of 5.15 metres**. This GMSLR is expected to occur for the SSP5-RCP8.5 scenario **between the year 2280 and 2660** when intuitively extrapolating the latest KNMI projections.

- The GMSLR and the associated construction costs are strongly dependent on the adopted slope in the earth-fill dam design of the NEED, because the **costs for the core-material of the dam is the key-driver of the total costs**. Opting for a design with 1:4 or 1:5 will reduce the NEED costs with roughly 17% and 34%, respectively, and make this adaptation strategy favourable sooner compared to the country-by-country coastal defence reinforcements.

This research was sectionalised and five sub-questions were formulated to answer the main question accordingly. Below, a more elaborate conclusion is given derived from answering all sub-questions and ultimately the main research question.

1. *What are the **exposed (flood-prone) areas** around the North Sea?*
The area around the North Sea exposed to future flooding was determined through the inundation maps retrieved from the GLOFRIS model framework. These GLOFRIS inundation maps did not include the current flood protection for the countries. However, to still be able to show the flood-prone areas for the fourteen countries taking into consideration the already existing flood protections, the base inundation map (year 2010) is subtracted from the future inundation map. The base inundation map for each country is modelled using the country's flood protection level based on the FLOPROS database, expressed in return period years. The future inundation maps used in the final assessment are generated with a 1000-year return period (RP) for scenario RCP8.5 in 2080, which is the most extreme scenario GLOFRIS can simulate. The total inundated area for these fourteen countries is estimated to be approximately **15,000 km$^2$**. The Netherlands, as its name alludes to, mostly lies below sea level and thus is the country with the largest flood-prone area, accounting for roughly a third of the total inundated area. In reality, the Netherlands will most likely be protected against GMSLR in 2080 as its flood protection level is extremely high compared to other countries. However, it should be noted that the maximum input for a country flood protection level that could be used in GLOFRIS is a 1000-year RP.

2. *What is the **size of the population** and **economic damages** in these exposed areas?*
The population affected and the economic damage caused by flooding was estimated using the GLOFRIS model framework. To this end, it was necessary to further specify the scenario through selection of certain elements. Subsequently, the results for all relevant Shared Socioeconomic Pathways (SSP) scenarios were generated. These revealed that SSP5 and SSP3 resulted in the greatest and lowest value increase, respectively, for both the size of population exposed as the economic damages for both scenario RCP4.5 and RCP8.5. Again, to still somewhat include the current flood protection of the countries, the same reduction approach is used as explained above, only now expressed in the country-based flood exposure indicator values people exposed and economic damages instead of in inundation maps. In the most extreme scenario (i.e. SSP5-RCP8.5 with a 1000-year RP), an additional **9.5 million people** would be exposed in 2080 on top of the 4.5 million already exposed in 2010, and the extra generated damages would be in the vicinity of **1 trillion €** in addition to the already present 110 billion € from 2010. In a more conservative scenario (i.e. SSP3-RCP4.5 with a 1000-year RP), however, an increase of **1.5 million people** affected in 2080, and the increase in damages would only be approximately **210 billion €**. The Netherlands unsurprisingly, as it is the lowest lying country, is most severely impacted as it accounted for approximately 60% of both total population exposed and total economic damages in all scenarios.

3. *What is the **length of coastal defences around the North Sea** that would need to be reinforced to combat SLR and at which **costs**?*
The total length of the coastal defences around the North Sea that requires reinforcement is determined based on the inundation maps. Here, only coastal regions that fall within the protection range of the NEED are analysed, as this will give a fair, one-to-one comparison for both adaptation strategies. The coastal reinforcement length was assessed for all countries individually and amounted to a total of roughly **6,000 km**. The findings show that Germany will require the greatest reinforcement (in terms of length) with roughly a third of the total reinforcement needed located along the German coast. Percentually, however, Belgium is subject to the greatest reinforcement, as nearly its entire coastline is in need of reinforcement. Again, it should be noted that excluded flood protections and limited return period input in the GLOFRIS simulation may cause the findings to deviate from reality.

   In order to subsequently determine the costs associated with the country-by-country coast defences, the expenses are separately analysed for two cost elements: sea dikes and storm surge barriers. For both elements it was necessary to first determine the pricing of reinforcement as well as the reinforcement height. The pricing is determined through cross-referencing the Dutch price rates from various scientific papers and converting these to costs in other countries by accounting for the GDP per capita.

Firstly, the pricing of reinforcement was determined. The costs for the reinforcement of sea dikes is dependent on the area, as there is a price difference for urban and rural regions. However, in this research the entire reinforcement coast length is generalised to have the same price rate per country per 1-metre increase in crest level. For the Netherlands, this is 13 million € per kilometre. The storm surge barrier reinforcement price rate for raising the crest level with one metre is estimated to be 1000 million € per kilometre.

Secondly, the reinforcement height was determined. To this end, the assumption is made that this height is equal to the maximum inundation height found per country for the entire country's necessary reinforcement length. This assumption will inevitably lead to an overestimation of the reinforcement height. However, with this assumption it can be guaranteed that no future flooding problems will occur as all countries are protected against the highest future inundation modulated.

With the reinforcement pricing, length and height assessed, the costs for all countries can be determined. Storm surge barrier reinforcement costs are added to the sea dike reinforcement costs for the countries that have these barriers in the protection range of the NEED. Through linear extrapolation it is estimated that the total cost associated with a 1-metre GMSLR lies around **245 to 335 billion €**, with an increase in cost between 170 and 235 billion € per metre GMSLR. However, the costs are highly dependent on the assumed relationship between SLR and required dike raising. These costs are obtained through the conservative approach of using maximum inundation heights as the necessary reinforcement.

4. *What are the **costs estimates** of the NEED as a function of SLR?*
In this research, the NEED structure is designed to have an earth-fill dam with a slope of 1:6. Here, it is opted for this structure design because this allows for a fair comparison with the earth-fill dam estimates from Groeskamp. The costs for the NEED are contingent on five crucial elements: core material (sand), revetment, geotextile, pumps and sluices. All elements are priced and quantified according to the dimensions of the NEED design, which are in turn dependent on the bathymetry.

The total costs for the NEED is estimated to be slightly less than **1.1 trillion €**, with an increase of approximately **11 billion € per metre GMSLR**. The main driver of the NEED design costs is the core material, which accounts for roughly 95% of the total costs.

The total NEED costs estimated by Groeskamp initially range between 250 and 550 billion €. However, when using the same methods but applying the finding of this thesis, the costs of the NEED range roughly between 0.4 and 1.5 trillion €. Although this range is enormous, the estimate made in this report does fall within this range. The main reason for the misalignment between the estimates made by Groeskamp and Kjellsson (2020) and the estimates from this thesis boils down to the discrepancy in volume. Groeskamp and Kjellsson (2020) opted for a NEED design with sloping sides with a 1:2 ratio, whereas this thesis assumed a ratio of 1:6. The latter results in a greater dam volume and therefore higher costs.

The majority of the total NEED costs consists of the costs for the core material. By modifying its design, and more specifically its slope, to be able to reduce the volume of sand needed, and thus its costs, this would greatly benefit the total NEED costs. The disparity in costs comparing the three different NEED slope angles significantly reduces the total construction costs. For a NEED structure design with a slope of 1:4 and 1:5, the estimated intersection of the two adaptation strategies are at 3.25 and 4.25 metres GMSLR, respectively. The corresponding estimated costs are 775 and 955 billion €. When comparing the 1:4 and 1:5 slope NEED designs to 1:6, it can be concluded that by opting for slightly steeper slope designs, the total NEED costs is reduced by roughly 17% and 34%, respectively.

5. *How do the coastal reinforcement costs **compare** to the costs of the NEED and **at which SLR** would the NEED become favourable over raising coastal defences?*
This research has found that the regional flood protection strategy (*Adaptation Strategy 1*) has lower initial costs compared to the NEED flood protection strategy (*Adaptation Strategy 2*). However, the additional costs per GMSLR for Adaptation Strategy 1 are greater than for Adaptation Strategy 2. Therefore, Strategy 1 will, in the long run, become more costly than Adaptation Strategy 2 assuming that the GMSLR will continue to increase over time.

The costs of the two flood protection adaptation strategies are extrapolated as a function of GMSLR, to be able to find the GMSLR at which the trends intersect. For a NEED structure design with a slope of 1:6, it is estimated that both adaptation strategies intersect at approximately **5.15 metres** GMSLR and has an estimated cost of roughly **1.15 trillion €** (range between 0.95 and 1.3 trillion €). This however can be seen as the upper bound, due to the assumptions made through out this research and the assumption that future construction will more likely be cheaper. Through multiple sensitivity analyses that scrutinised e.g. the effect of different reinforcement heights on the NEED's total costs and GMSLR found at the intersection still using the 1:6 slope design, the adaptation strategies intersection range between 5.10 up to 7.85 metres and the estimated costs range between 1.12 to 1.17 trillion €. This answers the main research question of this thesis:

***At which SLR does the NEED become a more financially favourable strategy than raising coastal defences on a country-by-country basis in the countries around the North Sea?***

With the latest KNMI projection, it would be possible to indicate the projected time span within which this GMSLR of 5.15 metres would become reality for scenario SSP5-RCP8.5. Yet, since this intersection falls outside the visualised range, no concrete estimate can be given. Although, when intuitively extrapolating the trend, this GMSLR can be expected roughly between 2280 and 2660. If the unstable ice-sheet processes in the Antarctic were to be included in the scenario (as in SSP5-RCP8.5 H++), a GMSLR of 5.15 metres would be projected to already become reality between 2165 and 2250.

## 7.2. Discussion

Several assumptions were made in this analysis and certain restrictions presented themselves along the way, which cause this research to have some limitations. In the same order of the report, all parts are briefly discussed, together with their limitations and assumptions.

- **Model Framework GLOFRIS**
  The GLOFRIS model framework generated the inundation maps and flood exposure indicator values caused in future scenarios. However, a limiting factor in the GLOFRIS simulation is that the vulnerability of the population was assessed as a binary condition. In other words, if a cell has an inundation height greater than zero, the population within that cell was considered 100 percent vulnerable, while in reality this does not have to be the case. Considering that a cell size in this model roughly equals 1 by 1 kilometres, the population in densely populated areas are now simply stacked according to the cell size, not taking into account the spread and location within that cell. For this assessment, where locations along the coast are of interest and inundation is expected solely as a result of SLR, the spread of people within a single cell could be important.

  Besides the vulnerability of the model in terms of the population, GLOFRIS generates the flood exposure indicator values based on its inundation maps. Yet, this model did not include the presence of existing flood protection. To still somewhat account for these protection, this thesis report assumed that there is no coastal flooding problem in the year 2010 in all the countries in question. By doing so, it created a baseline, from which there onward, future increase in inundation height can be assessed. However, chances are that certain countries already had to deal with flooding problems by 2010. Also, countries that have great existing coastal flood protections like the Netherlands might for example already be protected for future flooding until 2050 or even longer. Therefore, the results do not fully align with reality due to the fact that a country flood protection level in GLOFRIS could only be set to a maximum of a 1000-year RP. Moreover, this assessment assumed a fixed return period for the baseline based on the flood protection level of each country, but this will most likely differ from the return period of the future protection.

  Staying on the topic of existing flood protection, the country implementations of existing flood protections was based on the FLOPROS database (Scussolini *et al.*, 2016). Despite it being an extensive database of protection standards for riverine and coastal areas, the amount of sources for coastal protection standards still remains limited. Hence, assumptions had to be made for certain countries in order to conduct this research.

In the assessment of the flood exposure indicator values, the country-based values are retrieved for further analysis. However, some countries will not entirely be protected by the NEED. The corollary being that the values retrieved concerning these countries do not have the correct magnitude of the flood exposure indicator value that will actually be avoided by constructing the NEED.

- **Regional Protection Adaptation Strategy**
For the regional flood protection adaptation strategies it was assumed that all required reinforcements consisted of either sea dikes or storm surge barriers. Not differentiating other types of defences, such as dunes and sea walls, simplified further calculations and gave an simpler overview. For the assessment of the regional reinforcement costs the lengths, pricing and heights for all countries are needed, as well as the differentiation of other types of flood defences and their costs.

The reinforcement length assessment for both elements had to be done manually in QGIS. For this determination it was checked manually along the coasts of the countries whether inundation was present within the protection range of the NEED. This process would have been difficult to computerise as it may call for more profound analysis on each cell location independently. Therefore, chances are that manual errors have occurred in the process that may have influenced the results.

The sea dike reinforcement is assumed to have a generalised pricing of 13 million € per kilometre for an increase of 1 metre in crest level. Yet, in reality the price differs depending on the location of reinforcement. Naturally, raising sea dikes with 1 metre in rural areas is less costly compared to in urban areas, thus for a complete analysis both urban and rural reinforcement coast lengths and costs have to be determined. In the sensitivity analysis in Section 6.3.3, this has been explored with regard to the total costs based on a crude interpretation of Figure 6.10. Surprisingly, the total costs with the implementation of separating urban and rural reinforcement and the assumed generalised pricing for reinforcement appear to be virtually the same. Which implies that the generalisation of 13 million € carried out in combination with the ratio urban to rural reinforcement lengths and costs, was accurate.

In this thesis, the assessment of the reinforcement height was based on the maximum inundation height findings at the coast per country obtained from the GLOFRIS maps. This height is then applied to the entire reinforcement length, ensuring that countries will be protected against future flooding scenarios. In the determination of the maximum inundation height along the coast per country, it is should be noted that the number of cells in the range of this height is very limited. In other words, the maximum inundation height is (by definition) an outlier, which does not accurately represent the bulk of the data. Therefore, this particular approach results in an overestimation of cost. In the sensitivity analysis in Section 6.3.1 and Section 6.3.2, two alternative reinforcement heights have been considered for analysing its effect on the total costs. One being the average inundation height and the other being two times the GMSLR. As to be expected, the total costs are significantly reduced when considering a reinforcement heights that is lower than the maximum inundation heights used prior. However, when opting for one of the alternative reinforcement heights over the maximum inundation height, it should be noted that the estimated total costs will likely be an underestimation and, therefore, full protection against future flooding scenarios cannot be guaranteed.

Although an underestimation for these alternative approaches was expected, after extrapolation it appears to generate reasonable results when looking at their required dike raising for higher GMSLR values, as is depicted in in Figure 6.14 for Poland. This would arguably make these approaches a better estimate than the maximum heights approach. It can be concluded that the consideration of the height outliers for all countries in the costs assessment will drastically increase. Possibly enough to even consider potentially neglecting the coastal locations that require higher dike raisings at these limited locations to save on costs. However, this requires a more detailed study on these exact locations in all the relevant countries.

With regard to the dike reinforcement, it should be noted that this thesis has only analysed the effects on the reinforcement heights. As can be seen from Figure 4.2, an increase in crest height is paired with a significant increase in dike width. However, in this research it is assumed that all countries have enough space available in the coastal areas to cope with the increase in dike width when raising the sea dikes, while this does not necessarily have to be the case. When dike widening must additionally be accounted for, it will undoubtedly have an big impact on the reinforcement costs of the dikes and will lead to local and political resistance to conserve cultural heritage or private land, for example.

Another important consequence that the assumptions have on the assessment are the effects of the reinforcement coast length for the regarding countries. Table 4.1 states the reinforcement coast lengths for the year 2080 when considering scenario RCP8.5. In the regional cost assessment this length has been assumed to be fixed due to the lack of inundation maps in GLOFRIS that extend beyond 2080. The subsequent linearly extrapolated GMSLR are in reality paired with greater reinforceable lengths. In Figure 4.4, the length assessment of the Netherlands did not include the length of the dunes, as these appear to withstand the projected GMSLR up to 2080. However, analysing more extreme scenarios or looking further in the future where greater GMSLRs are projected, these dunes will probably need reinforcement as well. This will be the case for all the countries around Europe. This will influence the outcome of the comparison graph (Figure 6.1), as the trends that are assumed to be linear will likely be exponential instead. Thus resulting in a shift towards a lower bound for when the regional reinforcement costs equal the costs for the NEED.

- **NEED Protection Adaptation Strategy**
  For the NEED flood protection adaptation strategy, several assumptions are made. This is necessary since a project of this magnitude has never been executed before and therefore there are no references it can be compared to. Regarding the NEED's design, it is chosen for an earth-fill dam as this allows for a one-to-one comparison with the estimates retrieved from Groeskamp. Although other design options such as a caisson dam could be more practical or cheaper.

  In this thesis, the NEED's earth-fill dam design is assumed to consist solely of the following five cost-generating elements; core material (sand), revetment, geotextile, pumps and sluices. Naturally, more elements and actions are involved in constructing an enclosure dam. However, it is opted for a simplified design, which is illustrated in Figure 5.3. As can be seen from the figure, extra width on top of the structure is considered for a possible highway design. The construction costs of the highway itself are not taken into account in the total costs of the NEED, as the highway does not have a flood protecting purpose and will thus unnecessarily inflate the total costs, therefore hindering a fair cost comparison between the NEED and regional flood protection.

  For the NEED design it has been concluded that the key driver of the total costs is the core material (sand), as the volume of this massive structure is enormous. For context, roughly 150 billion tons is needed for the entire enclosure dam which equals three years' worth of global sand use (Peduzzi, 2014). In this report, it has been assumed that this amount is readily available for the construction. However, in practice this great volume of sand will obviously be rather challenging to come by.

  Comparing the findings of the NEED costs with the estimates retrieved from Groeskamp and Kjellsson (2020) – after conversion to the dimensions used in this thesis – it can be concluded that the findings do fall in the same cost estimate range, though this range is fairly large. In Figure 7.1, the difference in total reinforcement costs between the NEED design used by Groeskamp and the design used in this report is visualised. If Groeskamp's design were to be adopted instead, the NEED would already be financially favourable over the regional flood protection at a GMSLR of 1.65 metres, which is associated with a cost range between 355 and 490 billion €. This GMSLR is, according the latest projections of KNMI, expected to occur within the time spans of 2090-2175 and 2140-2275 for scenarios SSP5-RCP8.5 and SSP-RCP8.5 H++, respectively. This modification in design would have drastically changed the outcome of this report. Although the design proposed by Groeskamp would be more cost effective, it omits critical aspects related to the reduction to wave loading, which are included in the design proposed in this thesis.

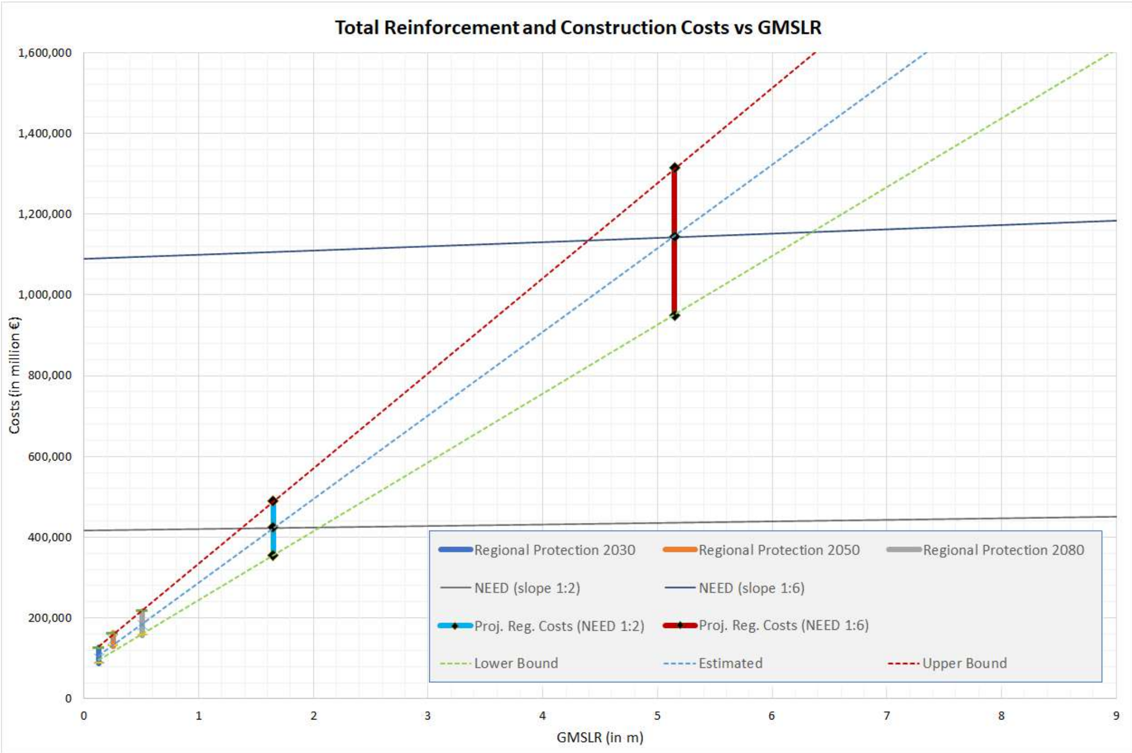



Figure 7.1: Graph depicting the regional reinforcement and the NEED construction costs for NEED 1:2 and 1:6 slope designs.

- **Comparison Adaptation Strategies**
  For the comparison of the two flood protection adaptation strategies, visualised in Figure 6.1, the costs found for the regional flood protection is extrapolated linearly. However, this linear trend does not have to be the case in reality. This assumption does simplify the calculation and made such an comparison possible for costs associated with higher GMSLRs.

  In Figure 6.1 the three estimated GMSLRs, affiliated with the different NEED designs, and their corresponding costs at which the regional flood protection costs will surpass the costs for the NEED, are depicted. According to the latest KNMI projections depicted in Figure 6.2, these GMSLRs are projected to occur in 2175, 2190 and 2210, respectively, for scenario RCP8.5 with SSP5 (SSP5-RCP8.5 H++) where the unstable ice-sheet processes in Antarctica are included. For the SSP5-RCP8.5 scenario, the trajectories are intuitively extrapolated to extend beyond 2300. As such, it was found that the GMSLRs are projected to occur in 2365, 2415 and 2465, respectively. Since there is no scientific basis for the extrapolation of the trajectory, it should be borne in mind that the estimates found for this scenario are by no means conclusive.

  The five countries that require the greatest dike raising in relation to the GMSLR are depicted in Figure 6.3. Surprisingly, as mentioned in Section 6.1, Poland needs the greatest dike raising per GMSLR as it has the most rapid increase in maximum inundation height found along the coast in GLOFRIS. In Figure 6.14, where the required dike raisings for Poland are depicted for all approaches done in the sensitivity analyses, it once again highlights the significant impact the chosen maximum inundation height assumption has on the outcome of the assessment.

  This report analysed the effects of GMSLR in an extreme climate scenario to protect the countries from flooding. However, flood hazard does not solely come from the sea but can also arise from rivers. In July 2021, parts of the Netherlands, Belgium and Germany were affected by extreme river water levels due to large amounts of precipitation, making it the second most expensive natural disaster of the year with total damages of roughly 38 billion € (NOS, 2021). The construction of the NEED, which creates an enclosed basin of the North Sea, will unfortunately not ameliorate this phenomenon. Even with the inclusion of the necessary pumps in the NEED design in this research, climate change keeps throwing extreme surprises our way with more extreme weather events making it difficult to predict the number of pumps needed. However, in making a full assessment on the effects of the NEED, this should be taken into account.

One of the most important challenges will be finding the perfect balance in an adaptation strategy that includes having regional reinforcement in short term and the NEED flood protection in the long term. Forecasting that the entire construction of the NEED could potentially take 50+ years, the countries must seek a short-term solution to combat the rising sea levels in the meantime.

Lastly, it must be realized that even after combining the perfect NEED design with a flawless balance for regional dike raisings which concludes that its construction will indeed be the best action to combat future SLR, it is still possible that due to other factors such as political or environmental reasons countries do not endorse its construction. Which is fine, as long as the danger of SLR is acknowledged and it is known that one way or another some form of strategy must be conducted as ignoring this future problem will come back to haunt us later.

## 7.3. Recommendations

The results retrieved from this analysis give an insight into when the NEED flood protection adaptation strategy will become a better alternative to regional flood protection reinforcement. Several points of attention within this research are already pointed out in Section 7.2. Additionally, to further build on the research, the following aspects can be explored:

**Improvements of the model**

- Solely analysing the coastal regions instead of the entire countries in question in the GLOFRIS model framework. In doing so a more accurate estimate can be made of the flood exposure indicator values that will be prevented by the construction of the NEED.
- A valuable addition to the model would be to refine the determination of the reinforcement height and length. In this report a fixed reinforcement height is applied over the entire reinforcement length, as depicted in Figure 7.2b. However, this will be an overestimation of the height on large stretches of the coastline. Instead, if the exact reinforcement height needed for each section of the coastline, as illustrated in 7.2c, were to be determined, this would lead to a more accurate estimation of the regional costs necessary. As an aid for the spatial interpretation of Figures 7.2b and 7.2c, Figure 7.2a depicts the coastal front view in the three-dimensional domain, with the map of the Netherlands for reference.

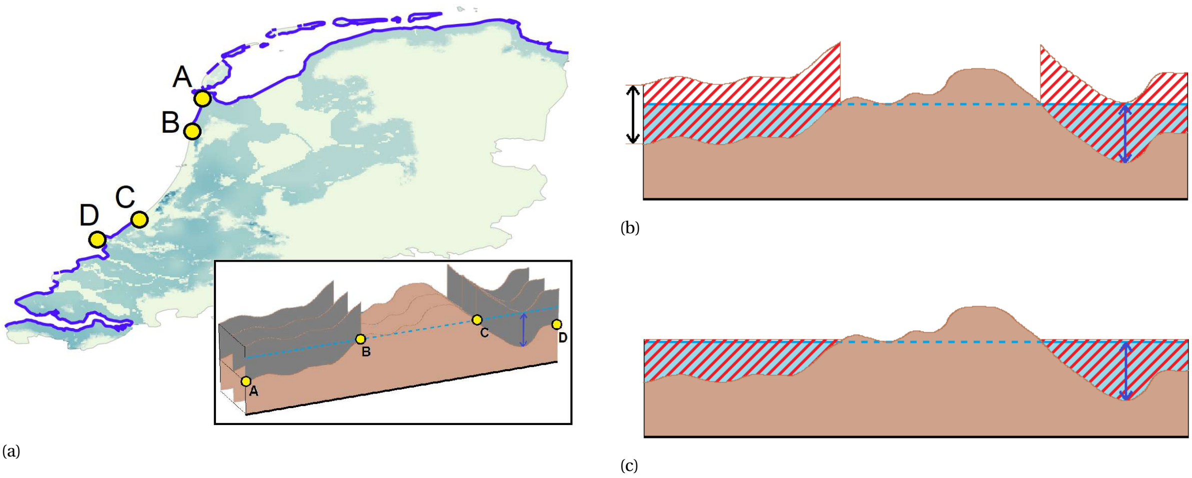



Figure 7.2: Longitudinal coastal front views illustrating the different reinforcement methods:
(a) Map of the Netherlands with indications of the four points (A to D) with an 3D figure of the coastal front view, (b) the reinforcement methods used in this report and (c) the recommended reinforcement method for future research. In (b) and (c) the horizontal blue line indicates the future sea level, the blue arrow the maximum inundation depth, the black arrow indicates the reinforcement height which is equal to the maximum inundation depth (blue arrow) and the red hatched area indicates the difference in modulated dike reinforcement methods.

- A more detailed study on the ratio between rural and urban coastal areas with regards to the sea dike reinforcement. In the sensitivity analysis, a rough estimation was made for the ratio between rural and urban coastal lengths. Implementing this to future research will give an more accurate estimate of the regional flood protection costs.
- In the analysis regarding the sea dike reinforcement, this study solely scrutinised the effect of increasing the crest height to withstand the future water level and assumed that the countries have enough room available for dike widening. However, this may not be the case. Therefore subsequent research into this availability along the entire coastline would be an valuable addition.

**Improvements of the NEED (design)**

- Create a more detailed design of the earth-fill NEED structure. Including all required elements and materials will provide a better estimation of the total costs of the NEED. Futhermore, an analysis on the subsoil of the sea floor is needed to guarantee safe and smooth installation of the NEED.
- Analyse other potential NEED design options and research the possible construction methods. This analysis will be useful for a comparison of all possible structure options, of which the cheapest and most durable can subsequently be selected for construction.
- Investigate all possible failure possibilities of the NEED structure and determine what the potential impact would be in case of such failures. Naturally, protection measures should be in place to limit the damage in these circumstances.
- Create one cost distribution for all countries in question including multiple factors using Multi-Criteria Analysis (MCA). The addition of such a distribution is highly desirable, as that could potentially convince countries to either participate in or refrain from the project. In other words, a broader cost benefit analysis of the NEED versus the regional protection adaptation strategy.
- Finally, as a follow-up study, it would be interesting to conduct a detailed study into the 'adaptive pathways' when opting for the NEED. Here, it is assumed that the decision has been made to commit to the NEED adaptation strategy. However, while the NEED is under construction, the regional flood protections still require maintenance and minor reinforcements to combat the unabated GMSLR. Such an 'adaptive pathway' would be of great importance to still guarantee safety during the installation of the NEED.

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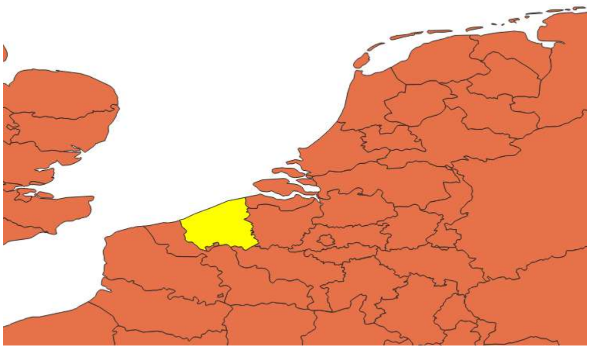
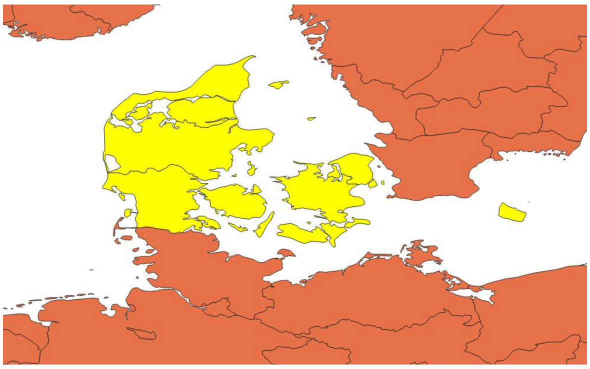
# A

# APPENDIX A

## A.1. FLOPROS HIGHLIGHTED COASTAL STATES PER COUNTIES

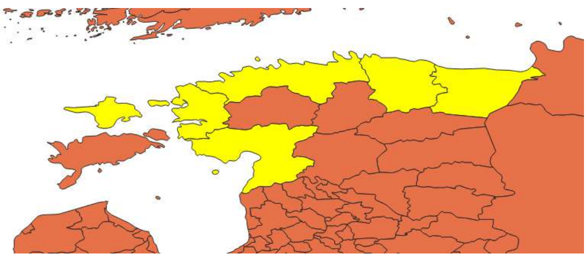


(a) Belgium

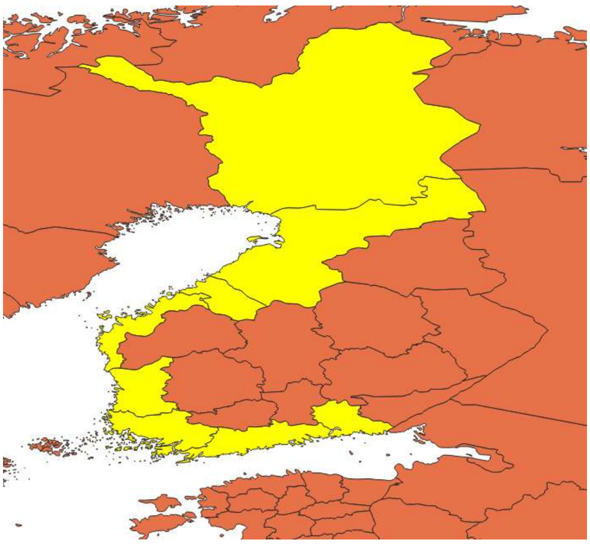


(b) Denmark

Figure A.1: Coastal highlighted states for Belgium and Denmark from FLOPROS database.

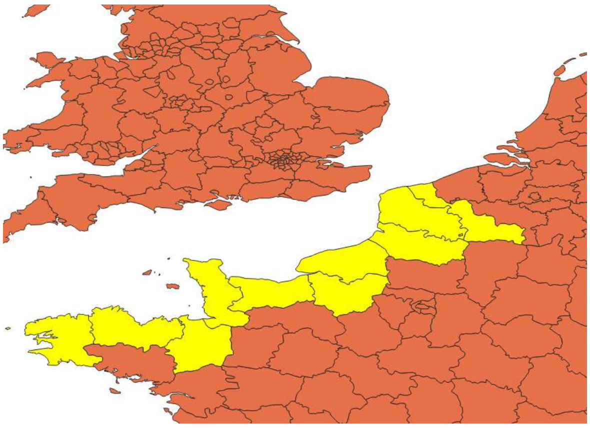


(a) Estonia

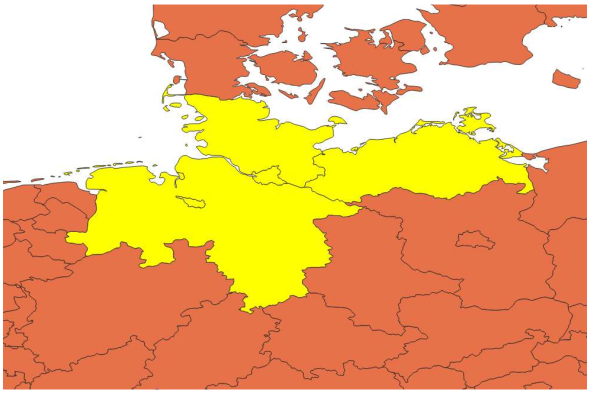


(b) Finland

Figure A.2: Coastal highlighted states for Estonia and Finland from FLOPROS database.

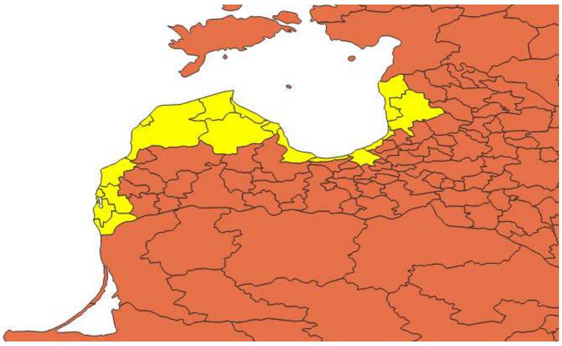


(a) France

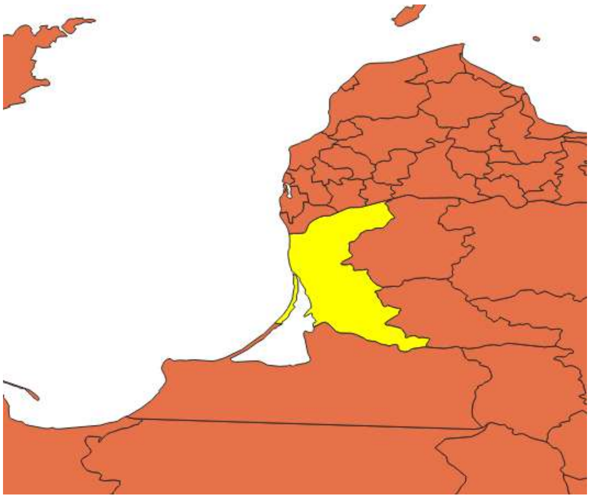


(b) Germany

Figure A.3: Coastal highlighted states for France and Germany from FLOPROS database.

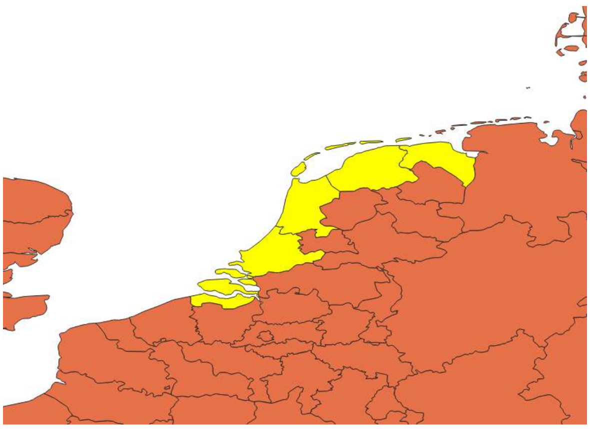


(a) Latvia

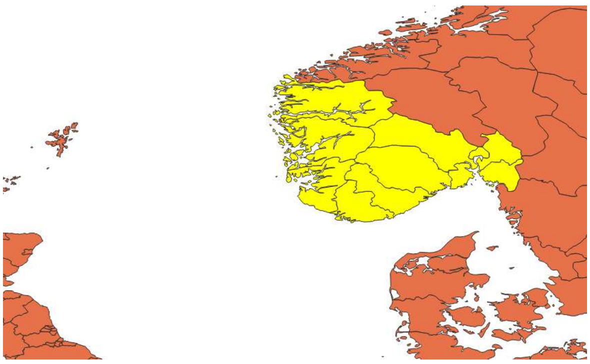


(b) Lithuania

Figure A.4: Coastal highlighted states for Latvia and Lithuania from FLOPROS database.

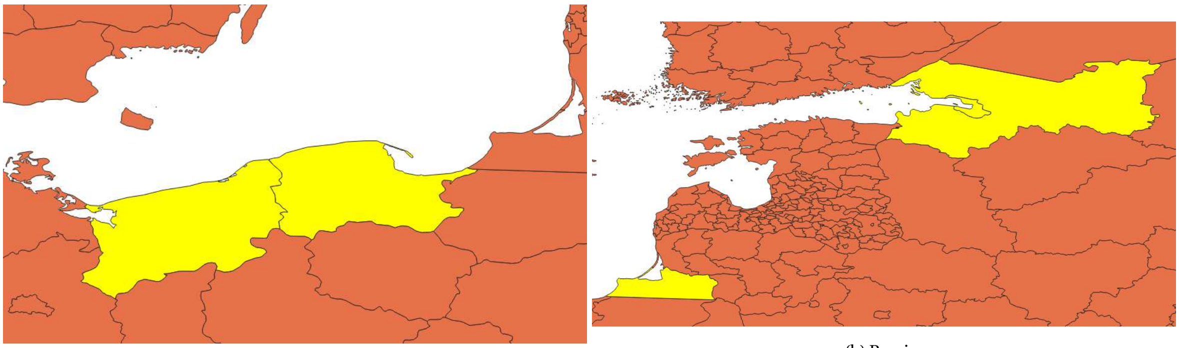


(a) The Netherlands



(b) Norway

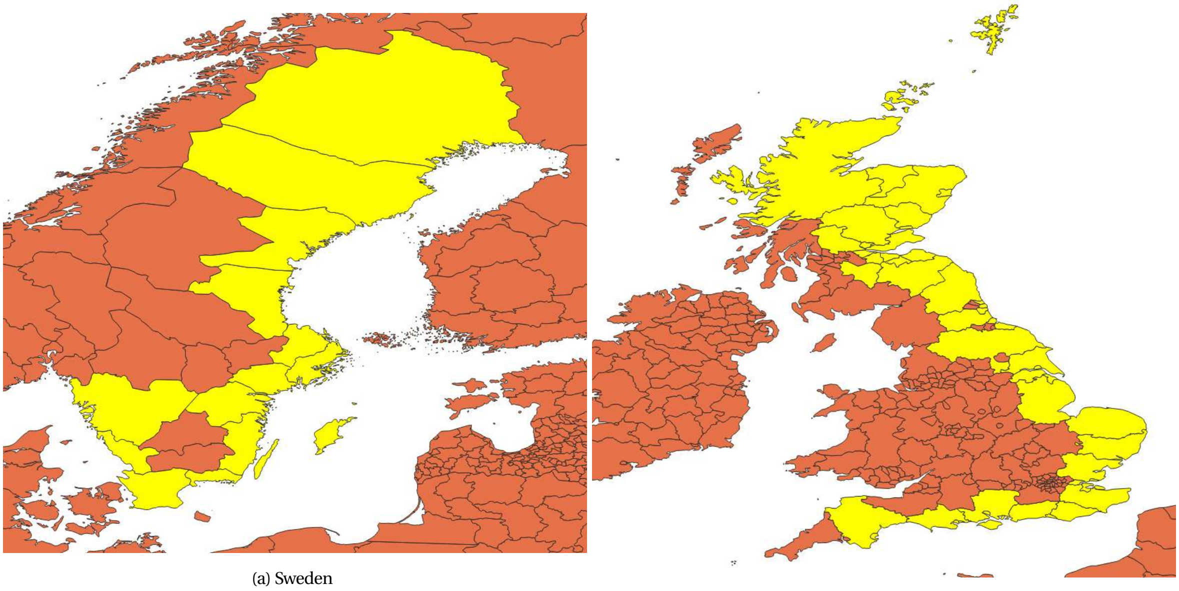
Figure A.5: Coastal highlighted states for the Netherlands and Norway from FLOPROS database.



(a) Poland

(b) Russia

Figure A.6: Coastal highlighted states for Poland and Russia from FLOPROS database.



(a) Sweden

(b) United Kingdom

Figure A.7: Coastal highlighted states for Sweden and United Kingdom from FLOPROS database.

## A.2. FLOPROS Overview Flood Protection Standards Coastal States

Table A.1: Overview 1 of flood protections for all coastal states according to FLOPROS (Scussolini *et al.*, 2016).

| Country | Country Code | State | DL_Min_Co | DL_Max_Co | PL_Min_Co | PL_Max_Co |
|---|---|---|---|---|---|---|
| Belgium | BE | West Flanders | 1000 | 1000 | 1000 | 1000 |
| Denmark | DK | Midtjylland | 0 | 0 | 50 | 1000 |
| | | Syddanmark | 0 | 0 | 50 | 1000 |
| | | Nordjylland | 0 | 0 | 50 | 1000 |
| | | Hovedstaden | 0 | 0 | 50 | 1000 |
| | | Sjaælland | 0 | 0 | 50 | 1000 |
| Estonia | ES | Harju | 0 | 0 | 0 | 0 |
| | | Ida-Viru | 0 | 0 | 0 | 0 |
| | | Lääne-Viru | 0 | 0 | 0 | 0 |
| | | Hiiu | 0 | 0 | 0 | 0 |
| | | Lääne | 0 | 0 | 0 | 0 |
| | | Pärnu | 0 | 0 | 0 | 0 |
| Finland | FI | Lapland | 0 | 0 | 100 | 100 |
| | | Northern Ostrobothnia | 0 | 0 | 100 | 100 |
| | | Central Ostrobothnia | 0 | 0 | 100 | 100 |
| | | Ostrobothnia | 0 | 0 | 100 | 100 |
| | | Kymenlaakso | 0 | 0 | 100 | 100 |
| | | Finland Proper | 0 | 0 | 100 | 100 |
| | | Satakunta | 0 | 0 | 100 | 100 |
| | | Uusimaa | 0 | 0 | 100 | 100 |
| France | FR | Calvados | 0 | 0 | 0 | 0 |
| | | Côtes-d'Armor | 0 | 0 | 0 | 0 |
| | | Eure | 0 | 0 | 0 | 0 |
| | | Finistère | 0 | 0 | 0 | 0 |
| | | Ille-et-Vilaine | 0 | 0 | 0 | 0 |
| | | Manche | 0 | 0 | 0 | 0 |
| | | Nord | 0 | 0 | 0 | 0 |
| | | Pas-de-Calais | 0 | 0 | 0 | 0 |
| | | Seine-Maritime | 0 | 0 | 0 | 0 |
| | | Somme | 0 | 0 | 0 | 0 |
| Germany | DE | Bremen | 0 | 0 | 100 | 100 |
| | | Niedersachsen | 0 | 0 | 100 | 100 |
| | | Hamburg | 0 | 0 | 100 | 100 |
| | | Schleswig-Holstein | 100 | 100 | 100 | 100 |
| | | Mecklenburg-Vorpommern | 0 | 0 | 100 | 100 |
| Latvia | LV | Limbai | 0 | 0 | 0 | 0 |
| | | Talsi | 0 | 0 | 0 | 0 |
| | | Riga | 0 | 0 | 0 | 0 |
| | | Liepaja | 0 | 0 | 0 | 0 |
| | | Ventspils | 0 | 0 | 0 | 0 |
| | | Grobinas | 0 | 0 | 0 | 0 |
| | | Nicas | 0 | 0 | 0 | 0 |
| | | Rucavas | 0 | 0 | 0 | 0 |
| | | Pavilostas | 0 | 0 | 0 | 0 |
| | | Dundagas | 0 | 0 | 0 | 0 |
| | | Rojas | 0 | 0 | 0 | 0 |
| | | Mersraga | 0 | 0 | 0 | 0 |
| | | Carnikavas | 0 | 0 | 0 | 0 |
| | | Engures | 0 | 0 | 0 | 0 |
| | | Jurmala | 0 | 0 | 0 | 0 |
| | | Salacgrivas | 0 | 0 | 0 | 0 |
| | | Saulkrastu | 0 | 0 | 0 | 0 |
| | | Ventspils | 0 | 0 | 0 | 0 |
| Lithuania | LT | Klaipedos | 0 | 0 | 0 | 0 |

Table A.2: Overview 2 of flood protections for all coastal states according to FLOPROS (Scussolini *et al.*, 2016).

| Country | Country Code | State | DL_Min_Co | DL_Max_Co | PL_Min_Co | PL_Max_Co |
|---|---|---|---|---|---|---|
| Netherlands | NL | Zuid-Holland | 10000 | 10000 | 300 | 1000 |
| | | Noord-Holland | 10000 | 10000 | 300 | 1000 |
| | | Friesland | 4000 | 4000 | 300 | 1000 |
| | | Groningen | 4000 | 4000 | 300 | 1000 |
| | | Zeeland | 4000 | 4000 | 300 | 1000 |
| Norway | NO | Aust-Agder | 0 | 0 | 0 | 0 |
| | | Hordaland | 0 | 0 | 0 | 0 |
| | | Rogaland | 0 | 0 | 0 | 0 |
| | | Sogn og Fjordane | 0 | 0 | 0 | 0 |
| | | Vest-Agder | 0 | 0 | 0 | 0 |
| | | Akershus | 0 | 0 | 0 | 0 |
| | | Buskerud | 0 | 0 | 0 | 0 |
| | | Oslo | 0 | 0 | 0 | 0 |
| | | Telemark | 0 | 0 | 0 | 0 |
| | | Vestfold | 0 | 0 | 0 | 0 |
| | | Østfold | 0 | 0 | 0 | 0 |
| Poland | PO | Pomeranian | 0 | 0 | 100 | 200 |
| | | West Pomeranian | 0 | 0 | 100 | 200 |
| Russia | RU | Kaliningrad | 0 | 0 | 0 | 0 |
| | | Leningrad | 0 | 0 | 0 | 0 |
| | | City of St. Petersburg | 1000 | 10000 | 0 | 0 |
| Sweden | SE | Gävleborg | 0 | 0 | 0 | 0 |
| | | Kalmar | 0 | 0 | 0 | 0 |
| | | Östergötland | 0 | 0 | 0 | 0 |
| | | Södermanland | 0 | 0 | 0 | 0 |
| | | Halland | 0 | 0 | 0 | 0 |
| | | Norrbotten | 0 | 0 | 0 | 0 |
| | | Västernorrland | 0 | 0 | 0 | 0 |
| | | Västerbotten | 0 | 0 | 0 | 0 |
| | | Gotland | 0 | 0 | 0 | 0 |
| | | Stockholm | 0 | 0 | 0 | 0 |
| | | Uppsala | 0 | 0 | 0 | 0 |
| | | Blekinge | 0 | 0 | 0 | 0 |
| | | Västra Götaland | 0 | 0 | 0 | 0 |
| | | Skåne | 0 | 0 | 0 | 0 |
| United Kingdom | UK (EN) | Durham | 0 | 0 | 100 | 200 |
| | | Hartlepool | 0 | 0 | 100 | 200 |
| | | Redcar and Cleveland | 0 | 0 | 100 | 200 |
| | | Northumberland | 0 | 0 | 100 | 200 |
| | | Hampshire | 0 | 0 | 100 | 200 |
| | | Southampton | 0 | 0 | 100 | 200 |
| | | Bournemouth | 0 | 0 | 100 | 200 |
| | | Dorset | 0 | 0 | 100 | 200 |
| | | Poole | 0 | 0 | 100 | 200 |
| | | Kingston upon Hull | 0 | 0 | 100 | 200 |
| | | North East Lincolnshire | 0 | 0 | 100 | 200 |
| | | North Lincolnshire | 0 | 0 | 100 | 200 |
| | | Lincolnshire | 0 | 0 | 100 | 200 |
| | | East Riding of Yorkshire | 0 | 0 | 100 | 200 |
| | | North Yorkshire | 0 | 0 | 100 | 200 |
| | | Essex | 0 | 0 | 100 | 200 |
| | | Suffolk | 0 | 0 | 100 | 200 |
| | | Norfolk | 0 | 0 | 100 | 200 |
| | | Brighton and Hove | 0 | 0 | 100 | 200 |
| | | Thurrock | 0 | 0 | 100 | 200 |
| | | East Sussex | 0 | 0 | 100 | 200 |
| | | Medway | 0 | 0 | 100 | 200 |
| | | Southend-on-Sea | 0 | 0 | 100 | 200 |
| | | Orkney | 0 | 0 | 100 | 200 |

Table A.3: Overview 3 of flood protections for all coastal states according to FLOPROS (Scussolini *et al.*, 2016).

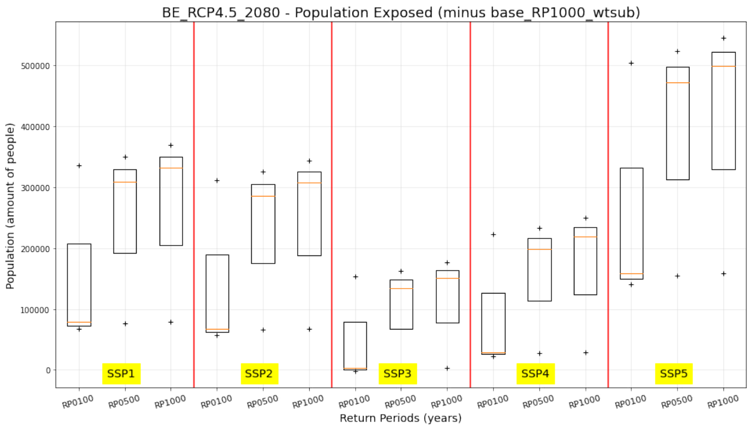
| Country | Country Code | State | DL_Min_Co | DL_Max_Co | PL_Min_Co | PL_Max_Co |
|---|---|---|---|---|---|---|
| United Kingdom | UK (EN) | Highland | 0 | 0 | 100 | 200 |
| | | Shetland Islands | 0 | 0 | 100 | 200 |
| | | West Sussex | 0 | 0 | 100 | 200 |
| | | Isle of Wight | 0 | 0 | 100 | 200 |
| | | Portsmouth | 0 | 0 | 100 | 200 |
| | | Kent | 0 | 0 | 100 | 200 |
| | | North Tyneside | 0 | 0 | 100 | 200 |
| | | South Tyneside | 0 | 0 | 100 | 200 |
| | | Sunderland | 0 | 0 | 100 | 200 |
| | UK (SC) | Aberdeen | 0 | 0 | 100 | 200 |
| | | Aberdeenshire | 0 | 0 | 100 | 200 |
| | | Moray | 0 | 0 | 100 | 200 |
| | | Falkirk | 0 | 0 | 100 | 200 |
| | | Stirling | 0 | 0 | 100 | 200 |
| | | Clackmannanshire | 0 | 0 | 100 | 200 |
| | | Perthshire and Kinross | 0 | 0 | 100 | 200 |
| | | Angus | 0 | 0 | 100 | 200 |
| | | Dundee | 0 | 0 | 100 | 200 |
| | | Fife | 0 | 0 | 100 | 200 |
| | | East Lothian | 0 | 0 | 100 | 200 |
| | | Edinburgh | 0 | 0 | 100 | 200 |
| | | Midlothian | 0 | 0 | 100 | 200 |
| | | West Lothian | 0 | 0 | 100 | 200 |
| | | Scottish Borders | 0 | 0 | 100 | 200 |

# B

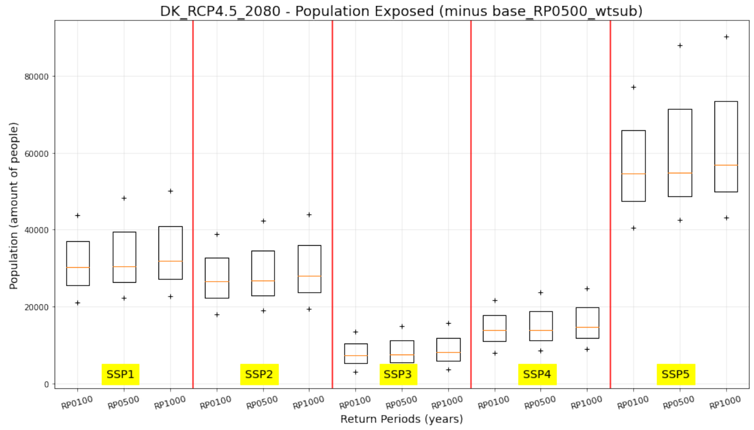
# Appendix B

## B.1. GLOFRIS Simulation Results

### B.1.1. Boxplots - Population (POP) Exposed - RCP4.5 | 2080

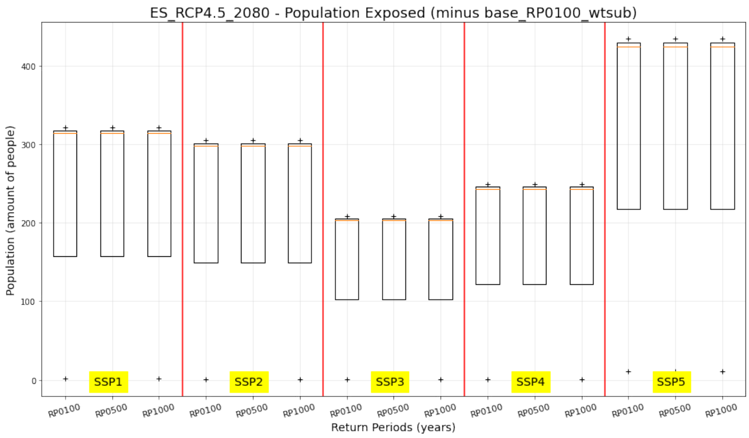



(a) Belgium

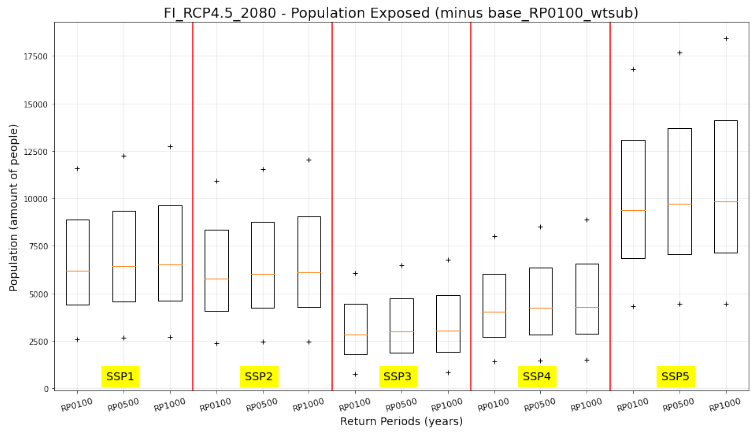



(b) Denmark

Figure B.1: POP Boxplot of all SSP for Belgium (a) and Denmark (b), scenario RCP4.5 - 2080.

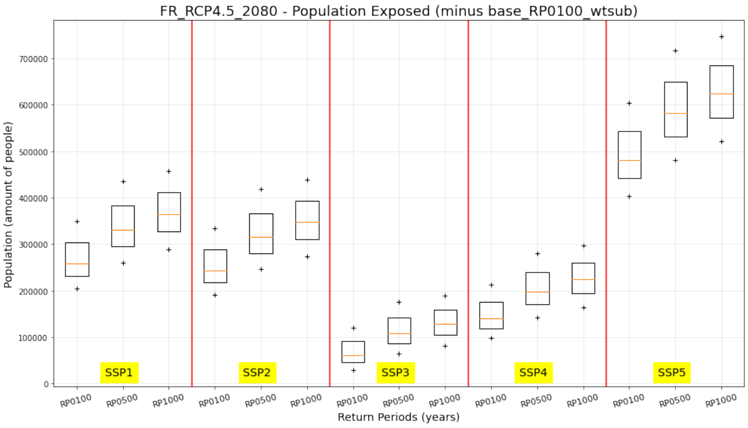



(a) Estonia

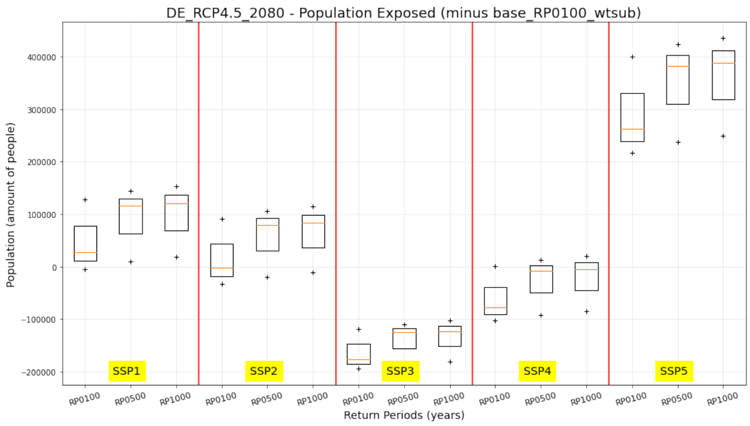



(b) Finland

Figure B.2: POP Boxplot of all SSP for Estonia (a) and Finland (b), scenario RCP4.5 - 2080.

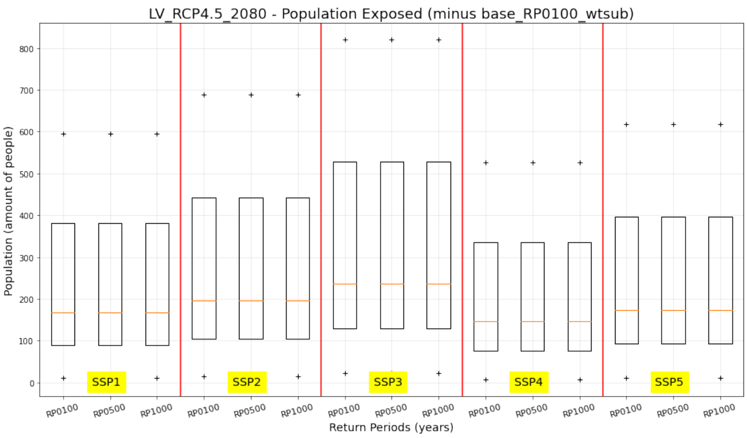



(a) France

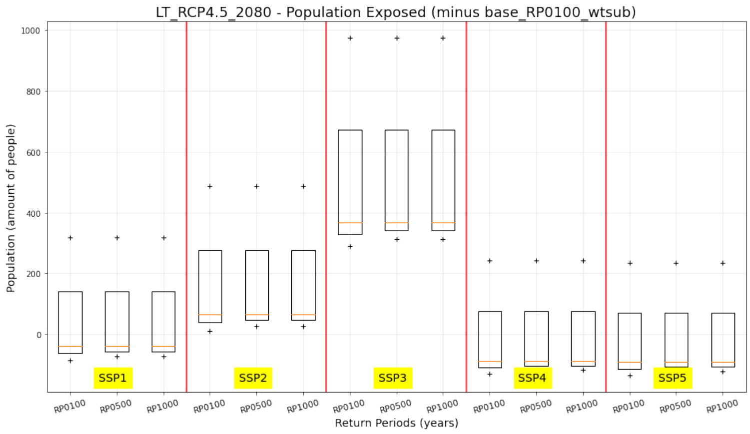



(b) Germany

Figure B.3: POP Boxplot of all SSP for France (a) and Germany (b), scenario RCP4.5 - 2080.

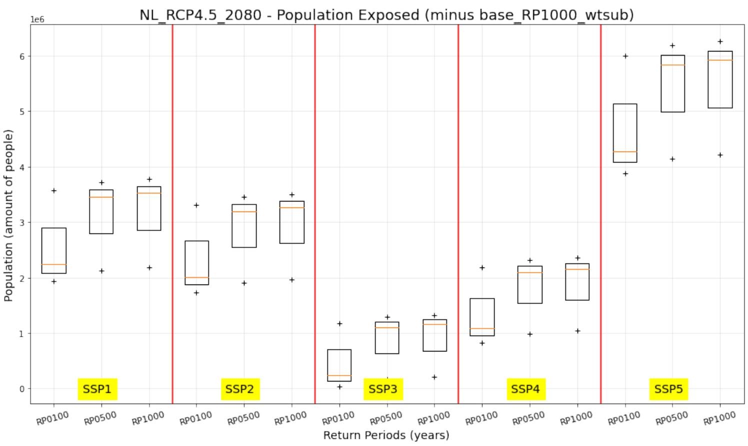



(a) Latvia

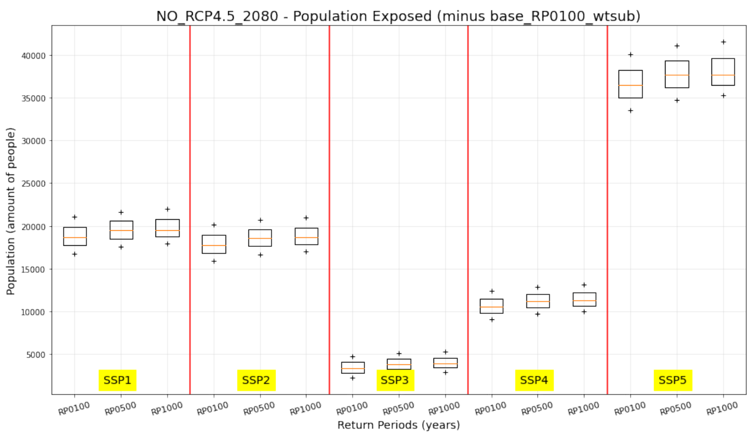



(b) Lithuania

Figure B.4: POP Boxplot of all SSP for Latvia (a) and Lithuania (b), scenario RCP4.5 - 2080.

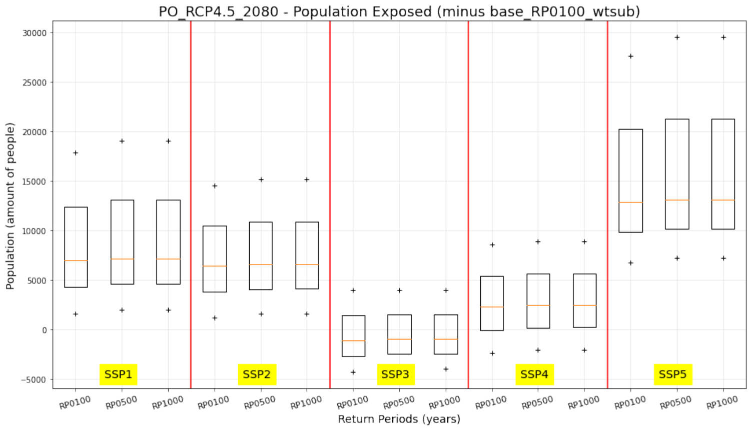



(a) the Netherlands

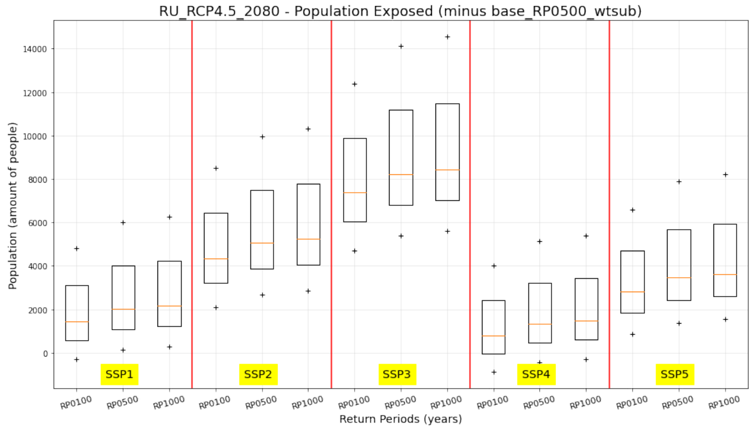



(b) Norway

Figure B.5: POP Boxplot of all SSP for the Netherlands (a) and Norway (b), scenario RCP4.5 - 2080.

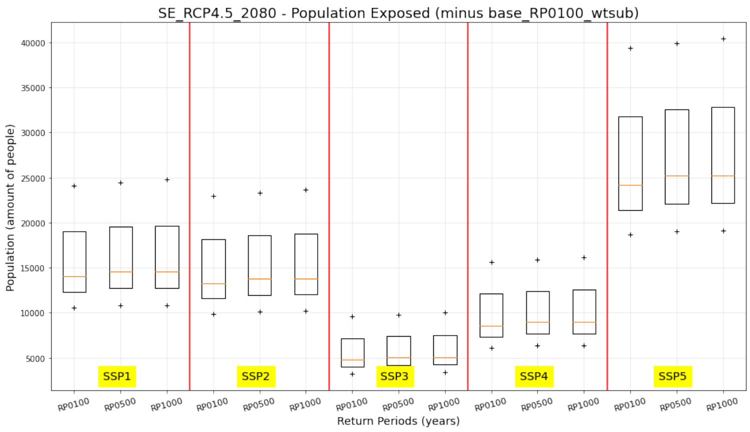



(a) Poland

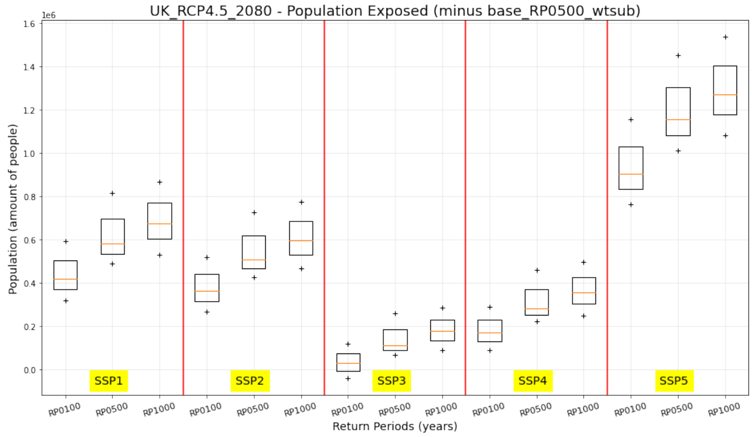



(b) Russia

Figure B.6: POP Boxplot of all SSP for Poland (a) and Russia (b), scenario RCP4.5 - 2080.



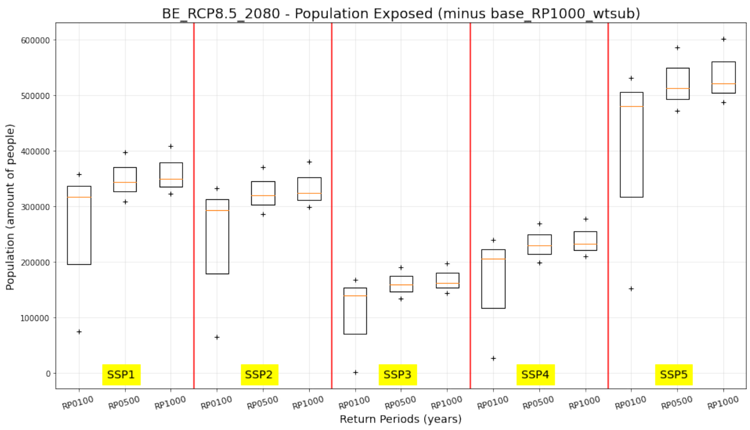

(a) Sweden



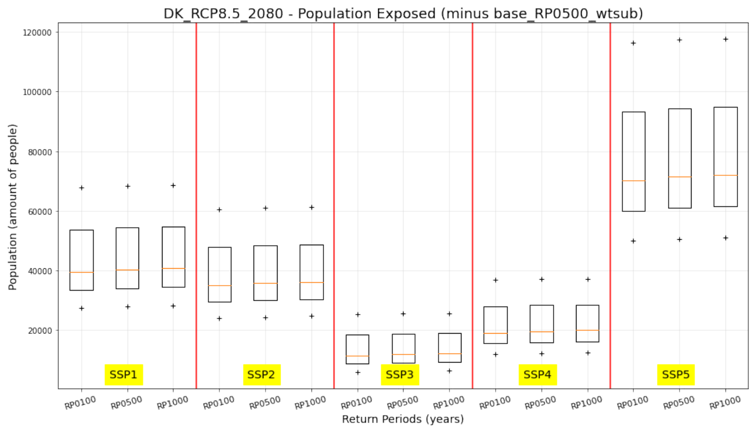

(b) the United Kingdom

Figure B.7: POP Boxplot of all SSP for Sweden (a) and the United Kingdom (b), scenario RCP4.5 - 2080.

### B.1.2. Boxplots - Population (POP) Exposed - RCP8.5 | 2080

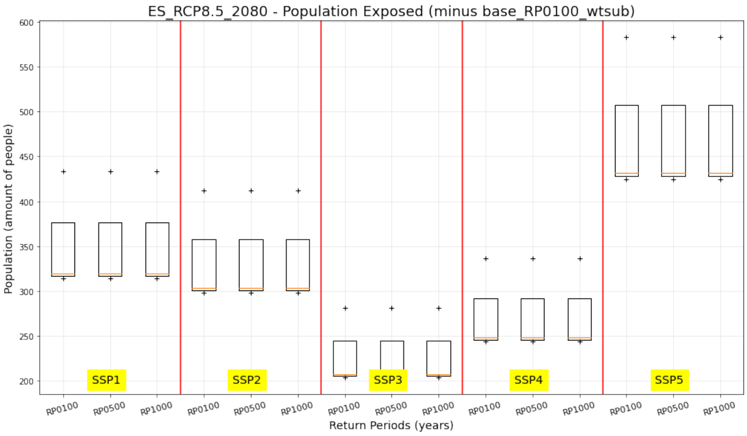



(a) Belgium

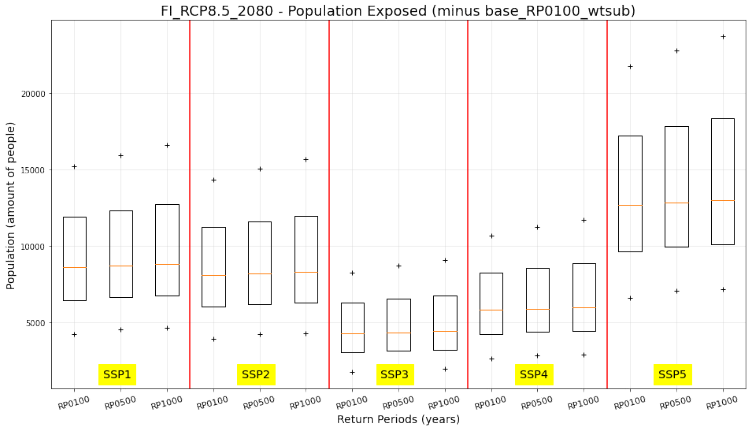



(b) Denmark

Figure B.8: POP Boxplot of all SSP for Belgium (a) and Denmark (b), scenario RCP8.5 - 2080.

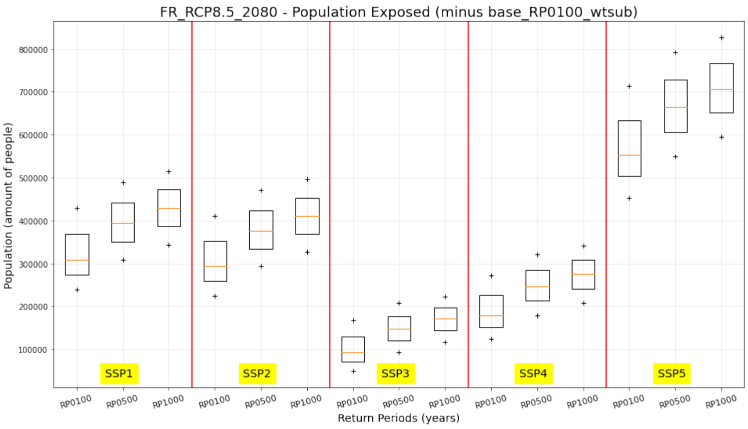



(a) Estonia

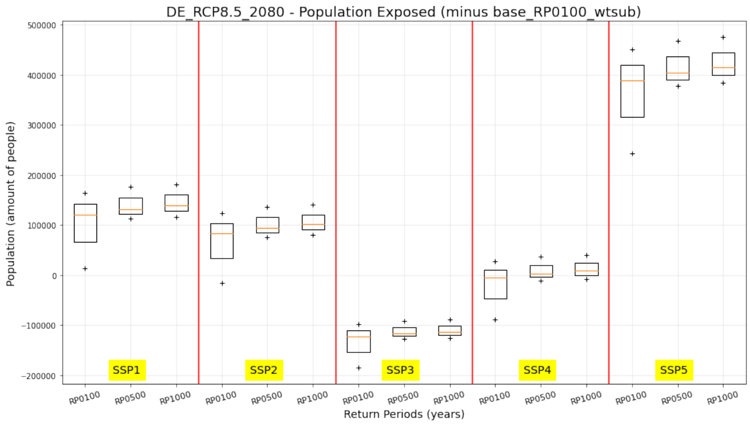



(b) Finland

Figure B.9: POP Boxplot of all SSP for Estonia (a) and Finland (b), scenario RCP8.5 - 2080.

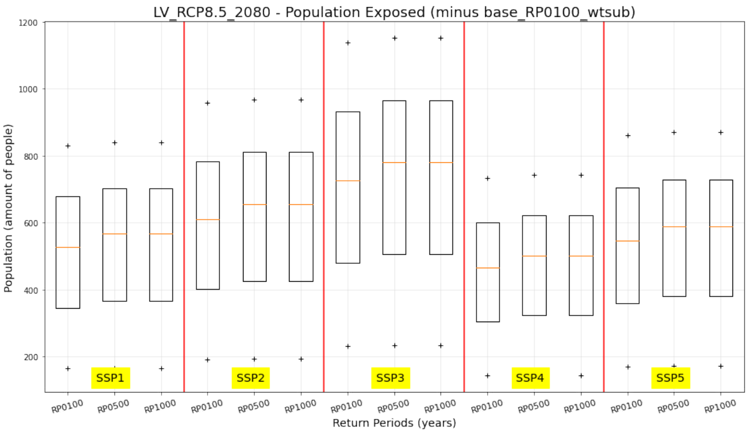



(a) France

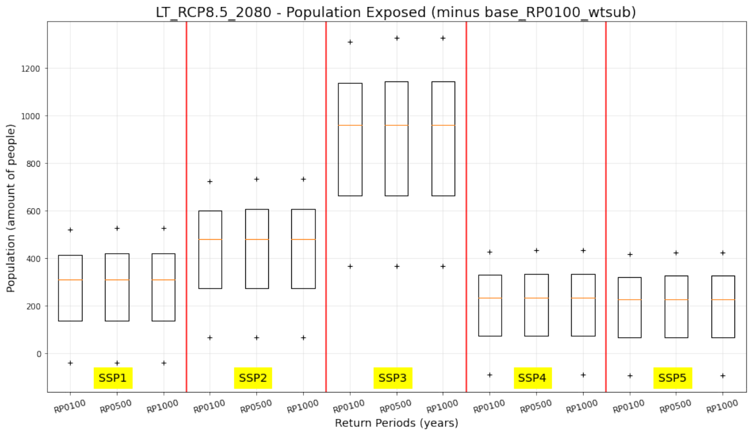



(b) Germany

Figure B.10: POP Boxplot of all SSP for France (a) and Germany (b), scenario RCP8.5 - 2080.

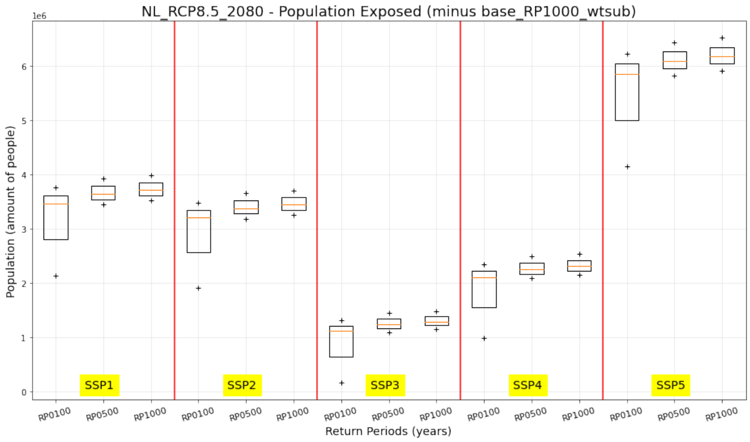



(a) Latvia

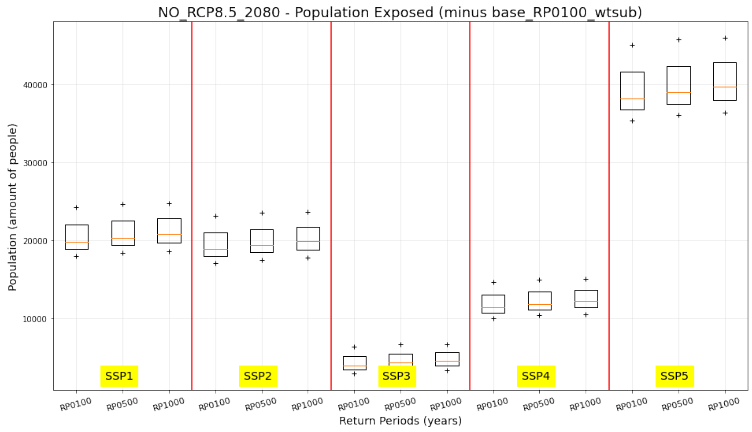



(b) Lithuania

Figure B.11: POP Boxplot of all SSP for Latvia (a) and Lithuania (b), scenario RCP8.5 - 2080.

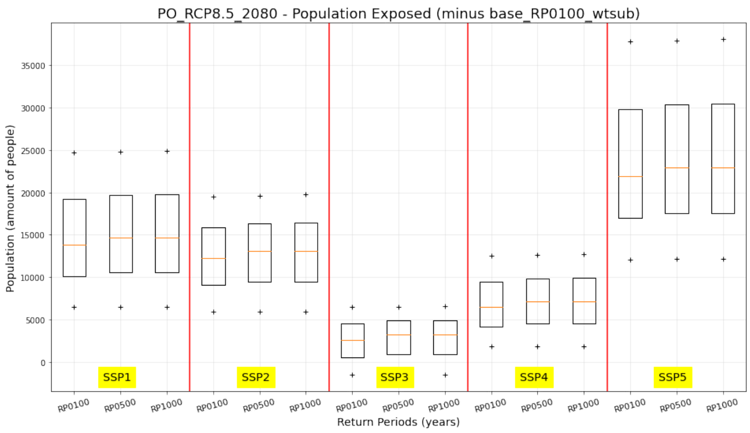



(a) the Netherlands

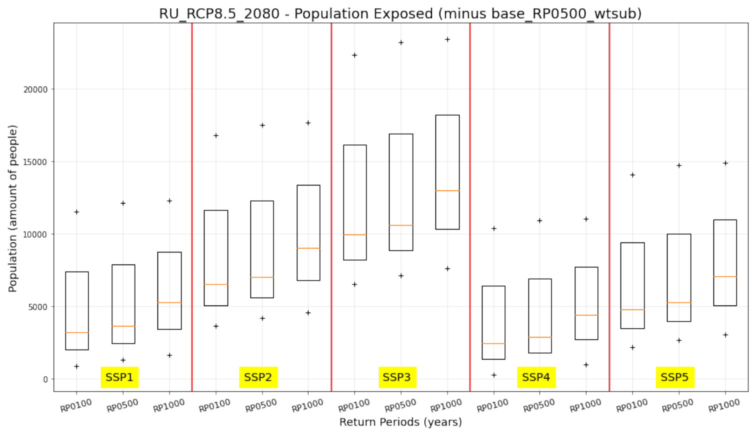



(b) Norway

Figure B.12: POP Boxplot of all SSP for the Netherlands (a) and Norway (b), scenario RCP8.5 - 2080.

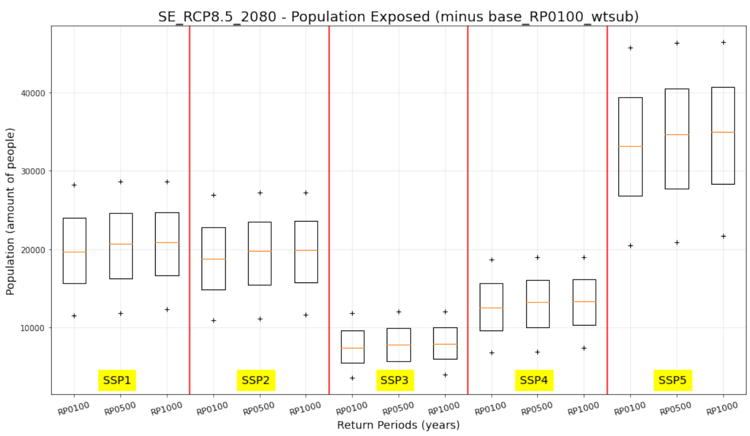



(a) Poland

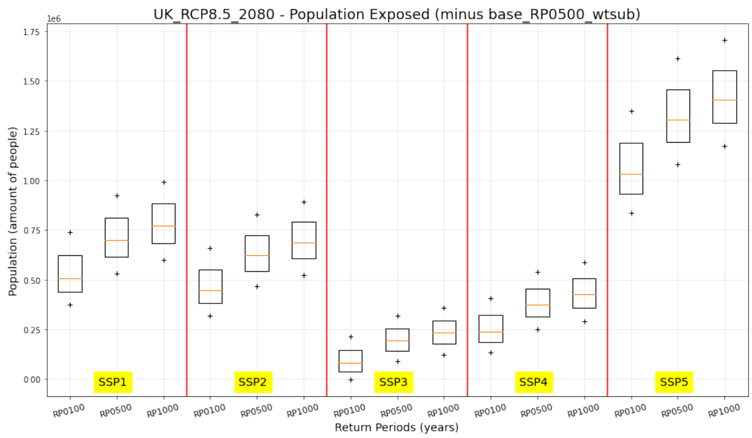



(b) Russia

Figure B.13: POP Boxplot of all SSP for Poland (a) and Russia (b), scenario RCP8.5 - 2080.



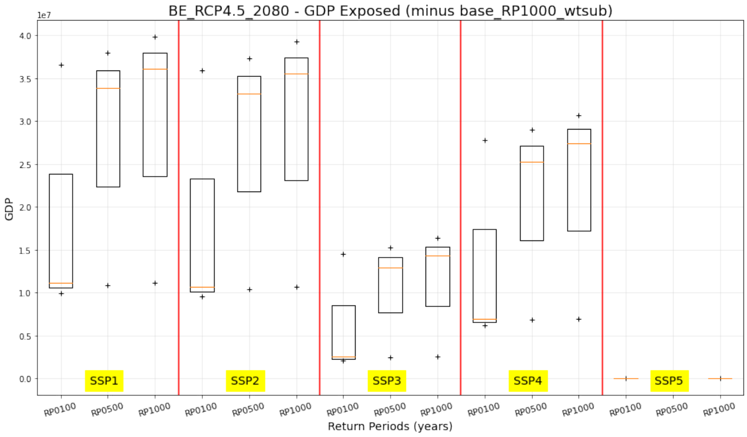

(a) Sweden



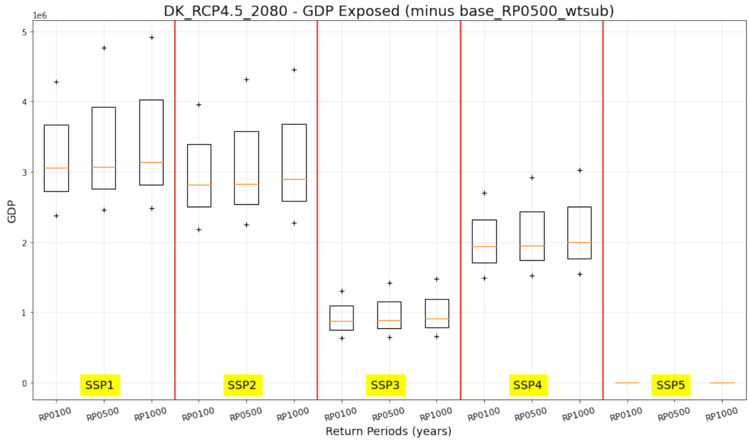

(b) the United Kingdom

Figure B.14: POP Boxplot of all SSP for Sweden (a) and the United Kingdom (b), scenario RCP8.5 - 2080.

### B.1.3. Boxplots - Gross Domestic Product (GDP) Exposed - RCP4.5 | 2080

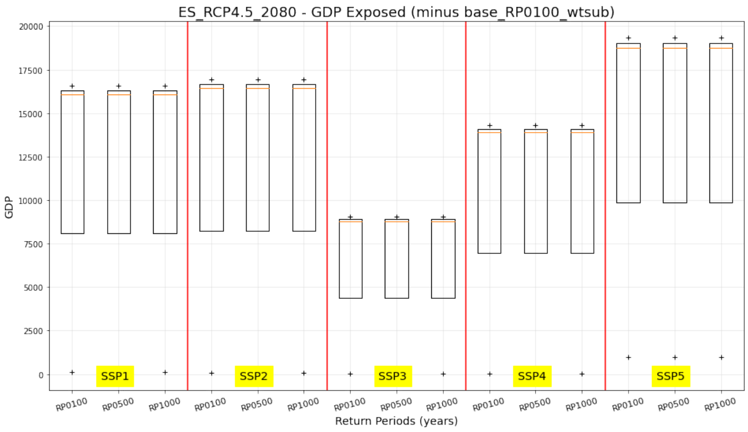



(a) Belgium

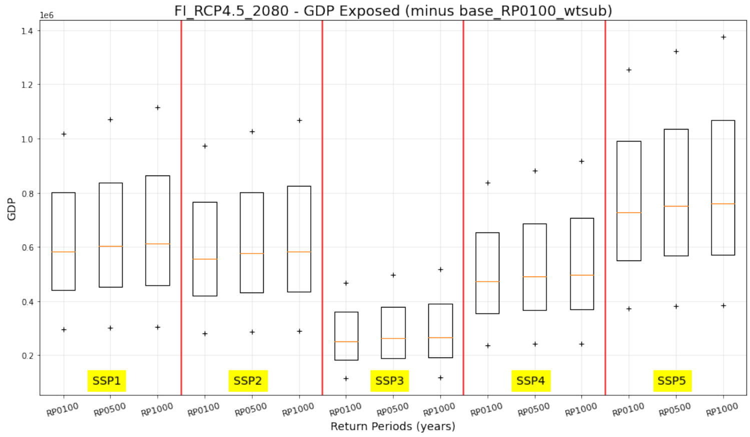



(b) Denmark

Figure B.15: GDP Boxplot of all SSP for Belgium (a) and Denmark (b), scenario RCP4.5 - 2080.

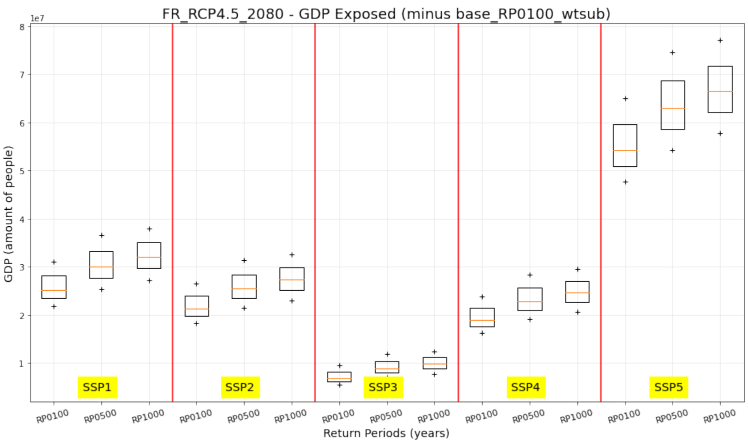



(a) Estonia

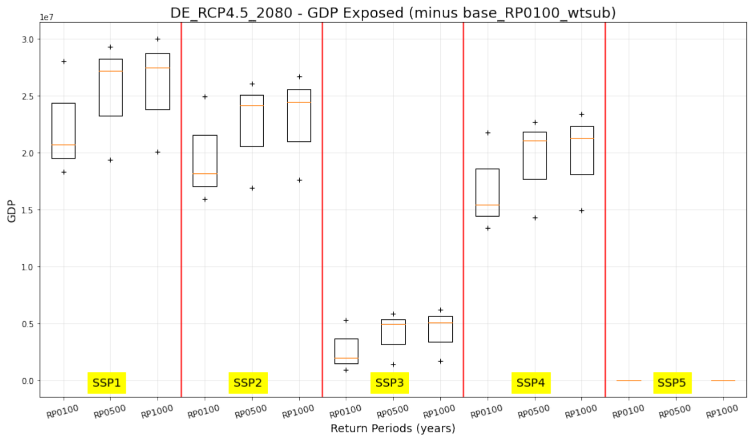



(b) Finland

Figure B.16: GDP Boxplot of all SSP for Estonia (a) and Finland (b), scenario RCP4.5 - 2080.

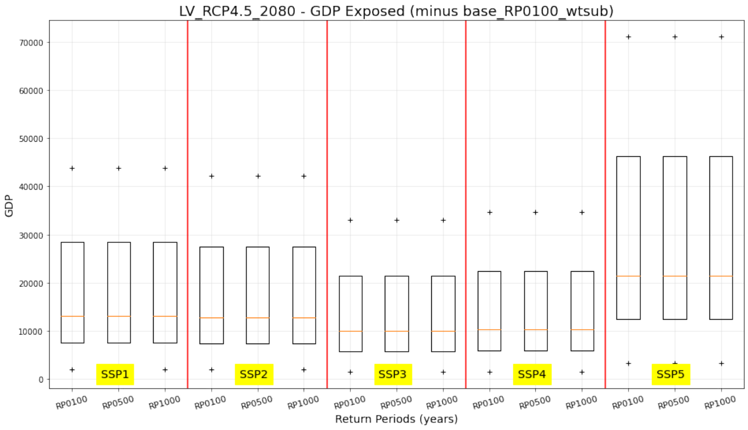



(a) France

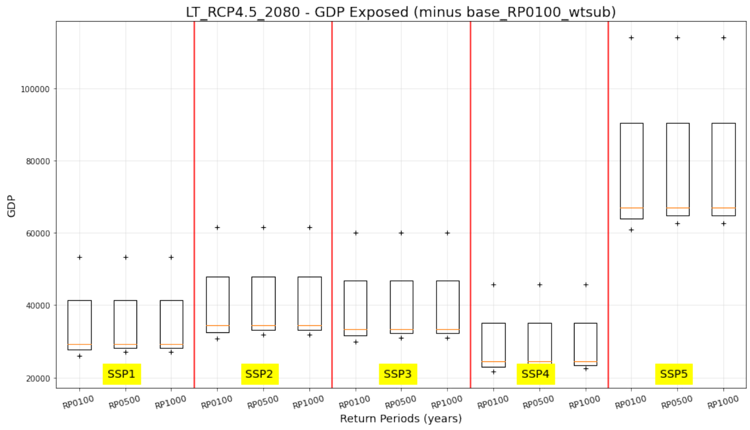



(b) Germany

Figure B.17: GDP Boxplot of all SSP for France (a) and Germany (b), scenario RCP4.5 - 2080.

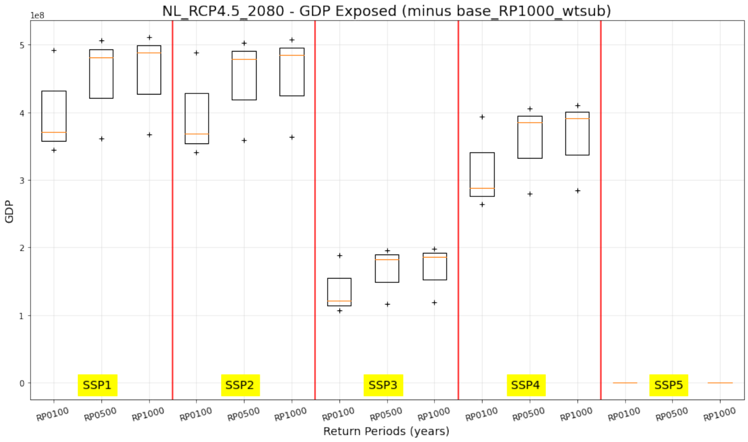



(a) Latvia

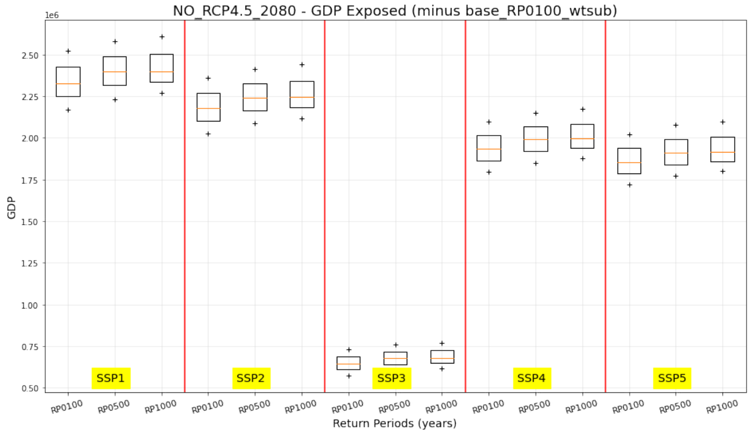



(b) Lithuania

Figure B.18: GDP Boxplot of all SSP for Latvia (a) and Lithuania (b), scenario RCP4.5 - 2080.

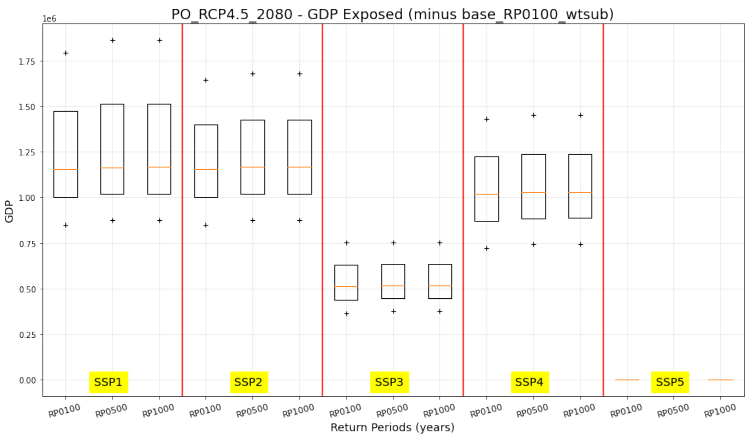



(a) the Netherlands

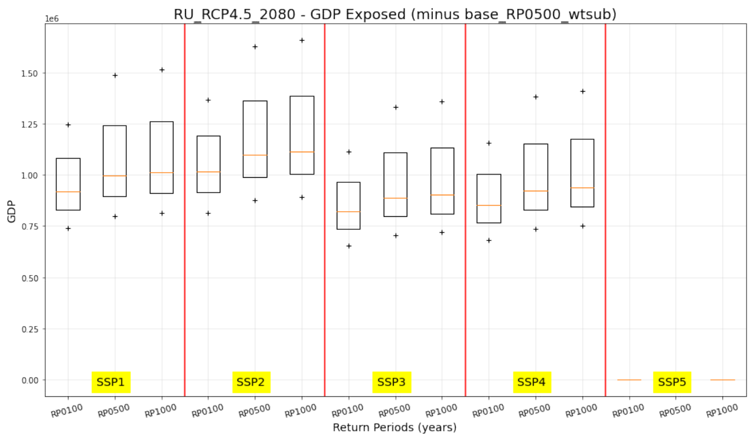



(b) Norway

Figure B.19: GDP Boxplot of all SSP for the Netherlands (a) and Norway (b), scenario RCP4.5 - 2080.

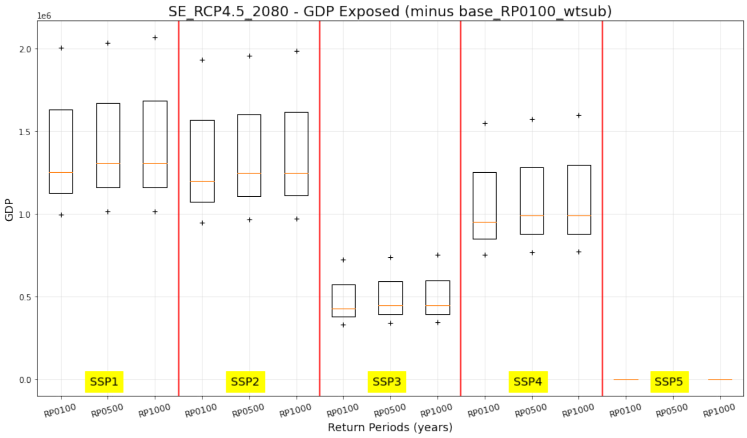



(a) Poland

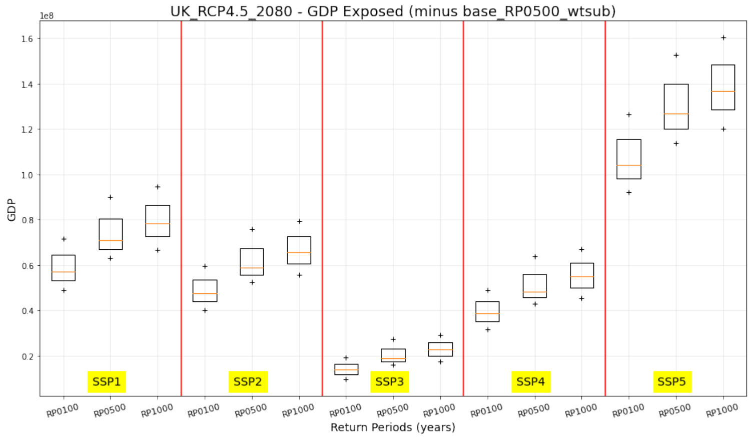



(b) Russia

Figure B.20: GDP Boxplot of all SSP for Poland (a) and Russia (b), scenario RCP4.5 - 2080.



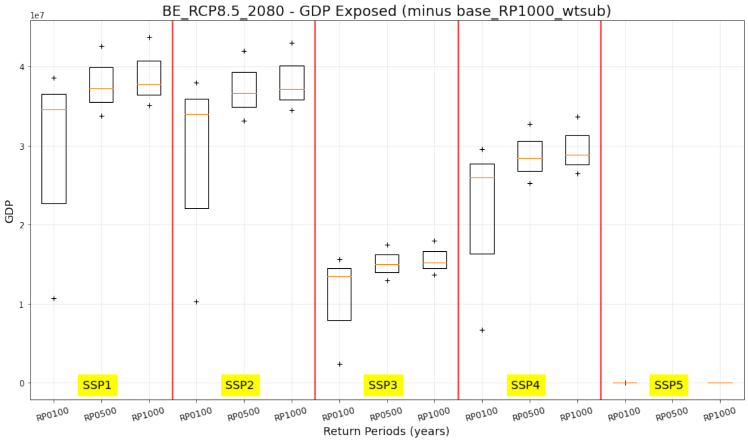

(a) Sweden



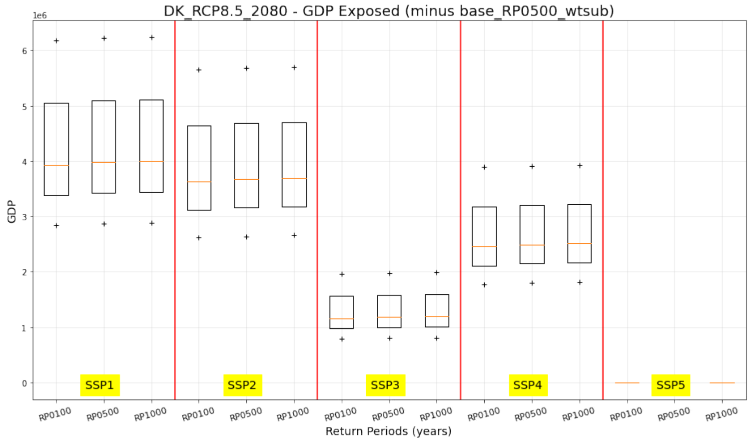

(b) the United Kingdom

Figure B.21: GDP Boxplot of all SSP for Sweden (a) and the United Kingdom (b), scenario RCP4.5 - 2080.

### B.1.4. Boxplots - Gross Domestic Product (GDP) Exposed - RCP8.5 | 2080

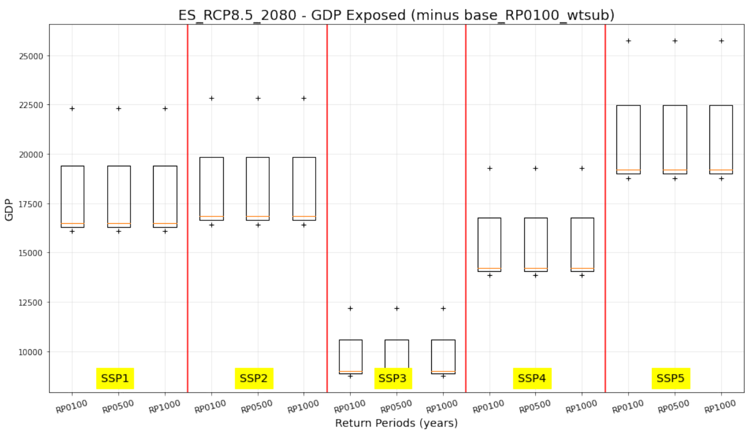



(a) Belgium

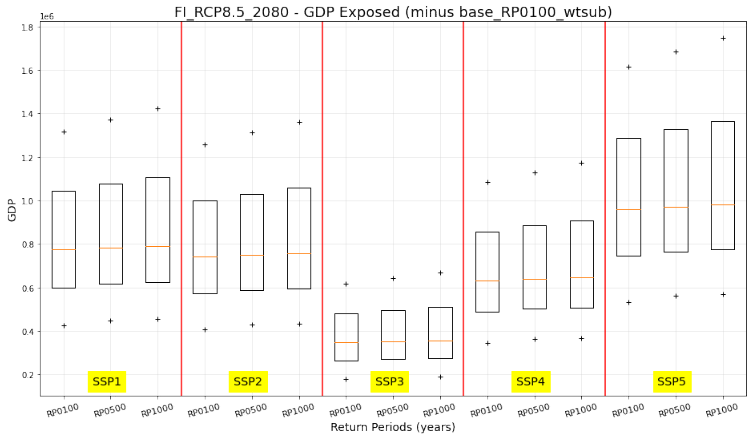



(b) Denmark

Figure B.22: GDP Boxplot of all SSP for Belgium (a) and Denmark (b), scenario RCP8.5 - 2080.

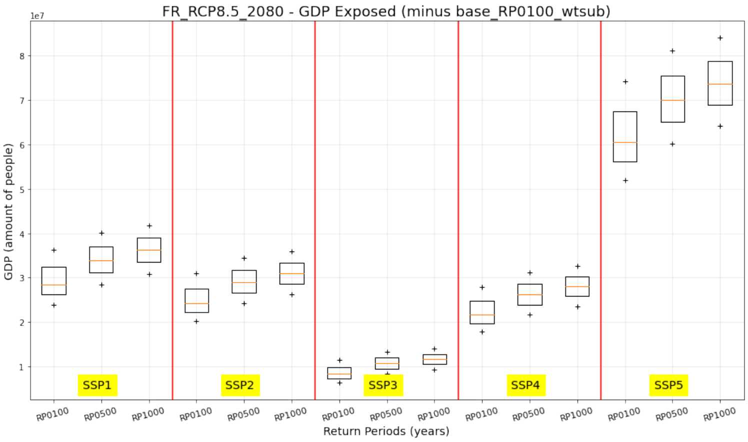



(a) Estonia

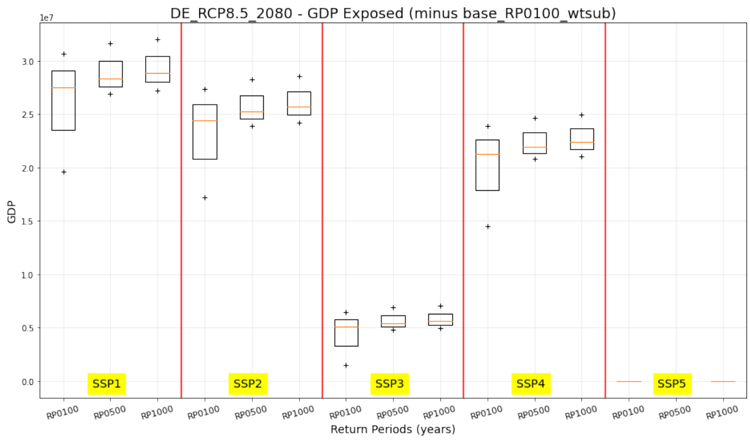



(b) France

Figure B.23: GDP Boxplot of all SSP for Estonia (a) and France (b), scenario RCP8.5 - 2080.

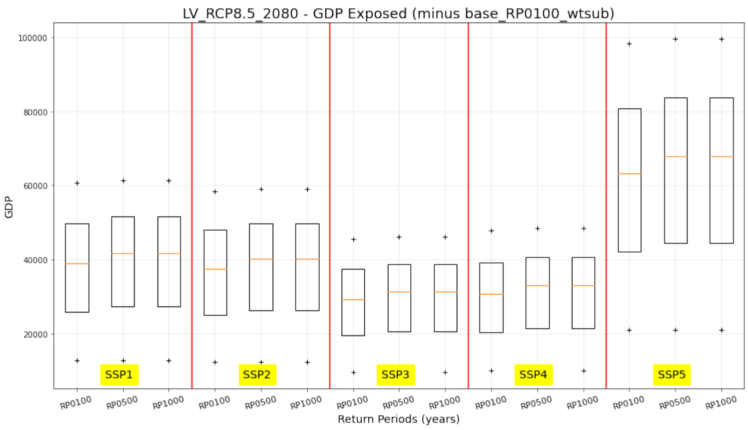



(a) France

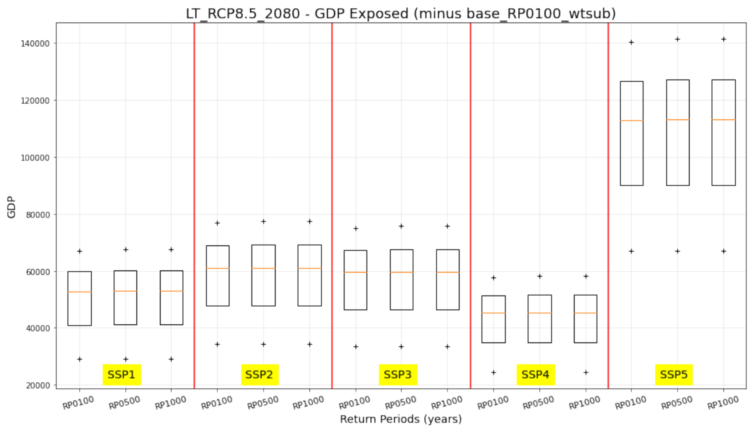



(b) Germany

Figure B.24: GDP Boxplot of all SSP for France (a) and Germany (b), scenario RCP8.5 - 2080.

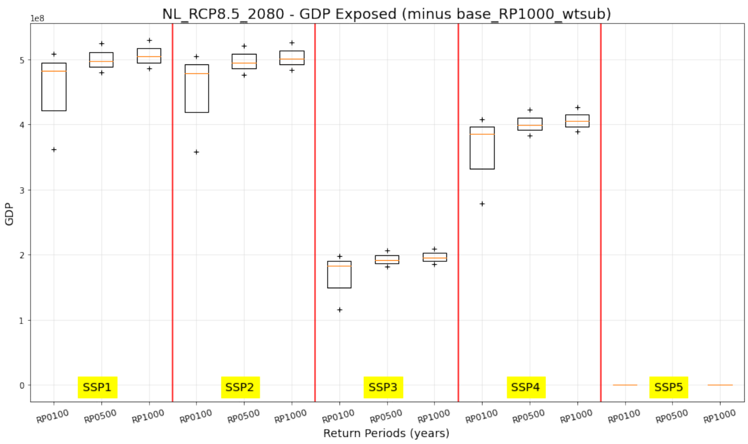



(a) Latvia

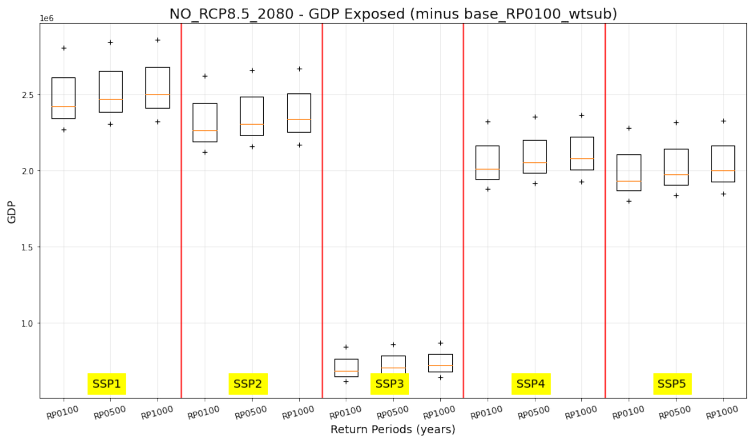



(b) Lithuania

Figure B.25: GDP Boxplot of all SSP for Latvia (a) and Lithuania (b), scenario RCP8.5 - 2080.

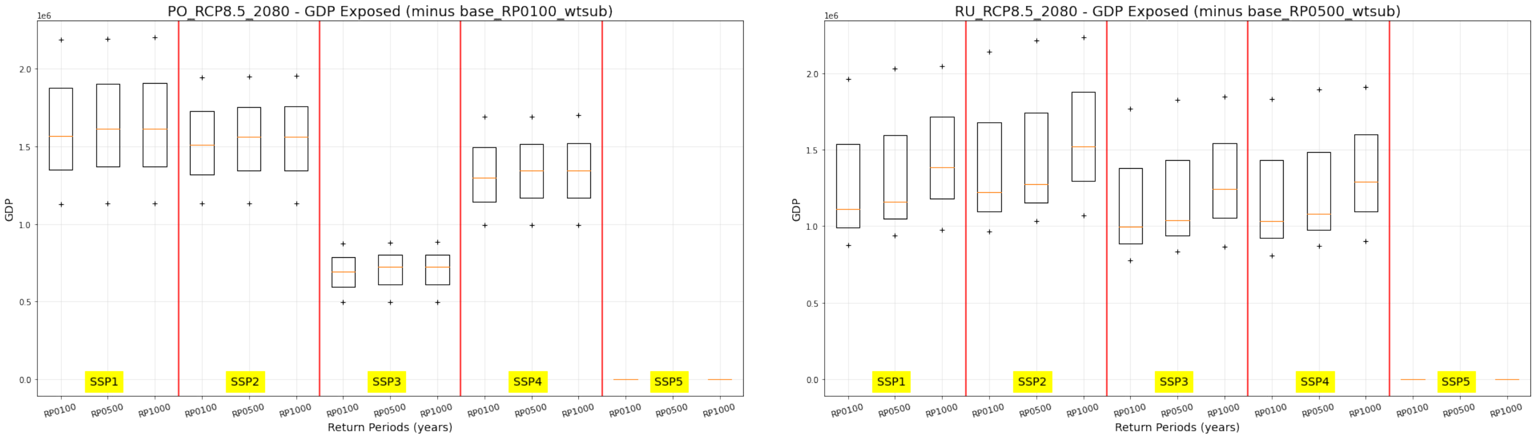



(a) the Netherlands




(b) Norway

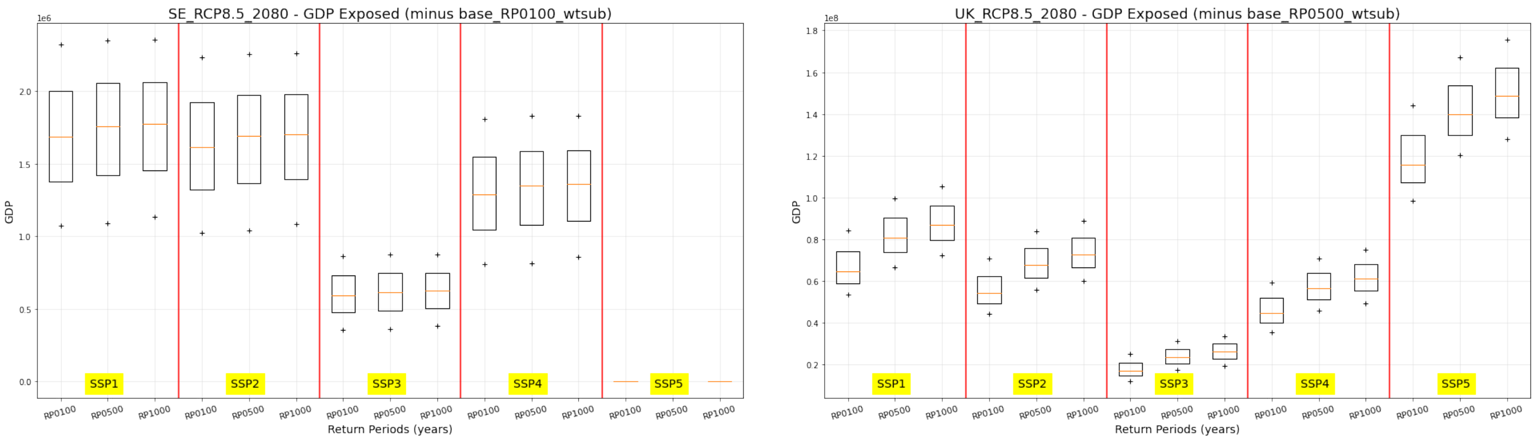
Figure B.26: GDP Boxplot of all SSP for the Netherlands (a) and Norway (b), scenario RCP8.5 - 2080.




(a) Poland

(b) Russia

Figure B.27: GDP Boxplot of all SSP for Poland (a) and Russia (b), scenario RCP8.5 - 2080.

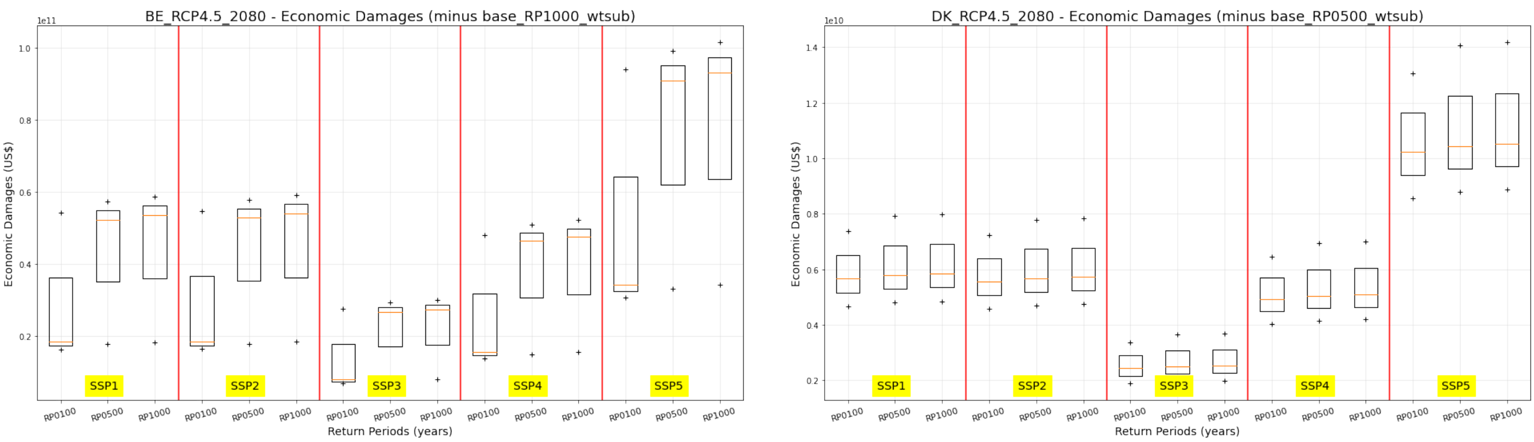



(a) Sweden

(b) the United Kingdom

Figure B.28: GDP Boxplot of all SSP for Sweden (a) and the United Kingdom (b), scenario RCP8.5 - 2080.

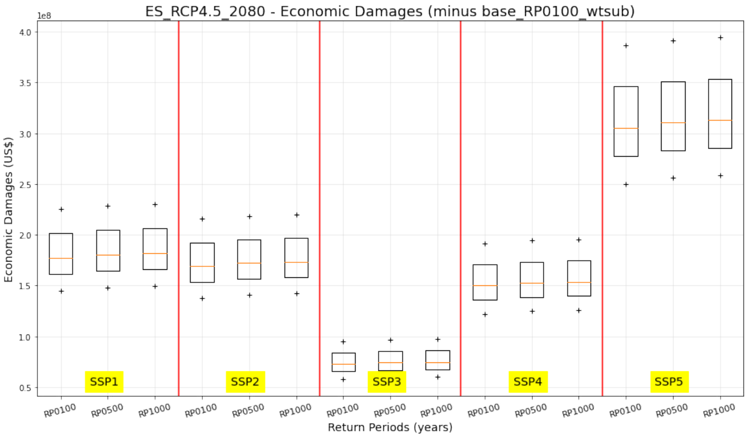
### B.1.5. Boxplots - Economic Damages (ECO) - RCP4.5 | 2080



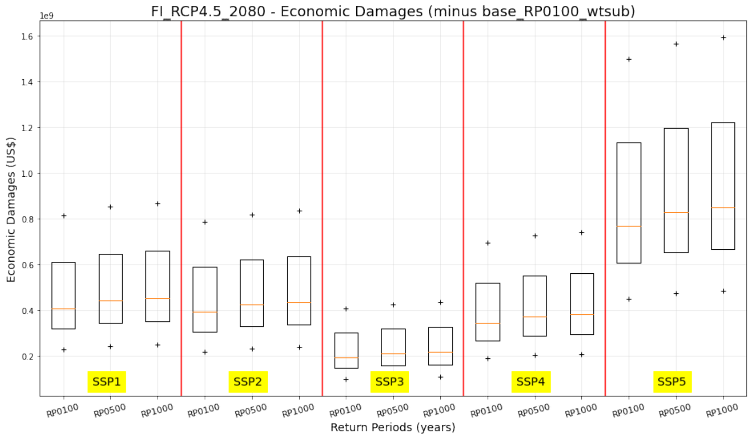

(a) Belgium

(b) Denmark

Figure B.29: ECO Boxplot of all SSP for Belgium (a) and Denmark (b), scenario RCP4.5 - 2080.

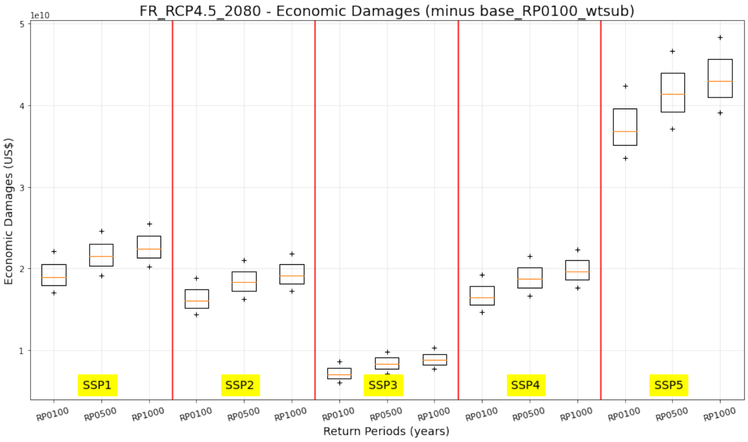



(a) Estonia

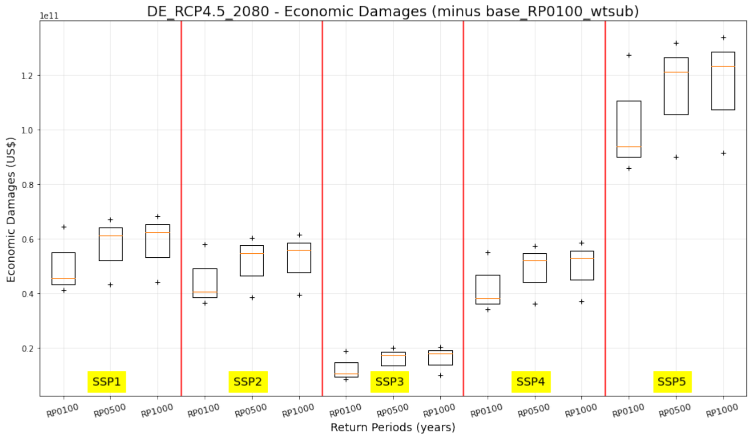



(b) Finland

Figure B.30: ECO Boxplot of all SSP for Estonia (a) and Finland (b), scenario RCP4.5 - 2080.

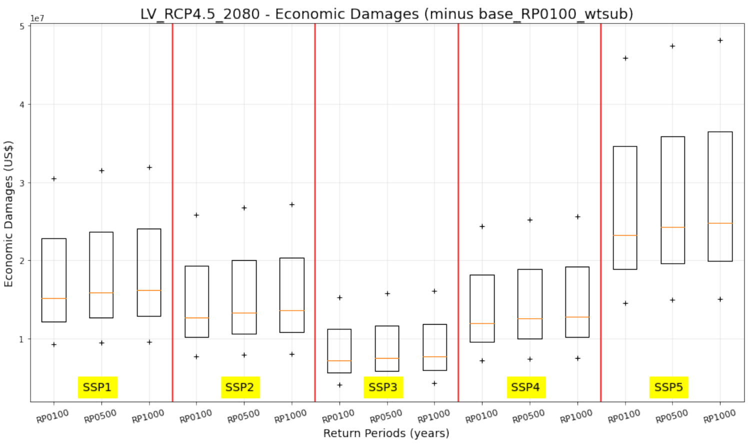



(a) France

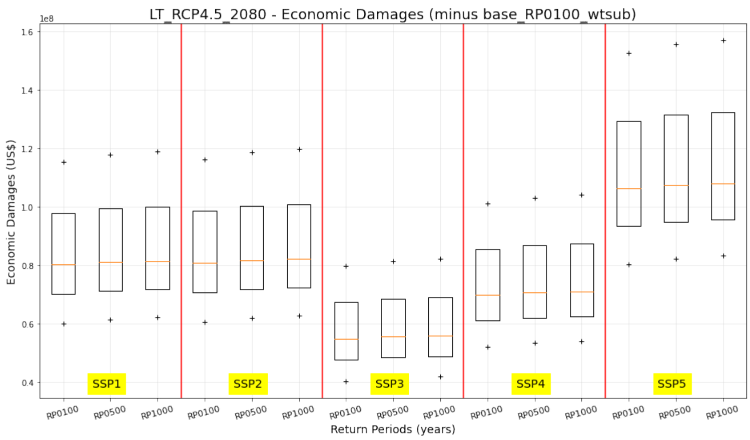



(b) Germany

Figure B.31: ECO Boxplot of all SSP for France (a) and Germany (b), scenario RCP4.5 - 2080.

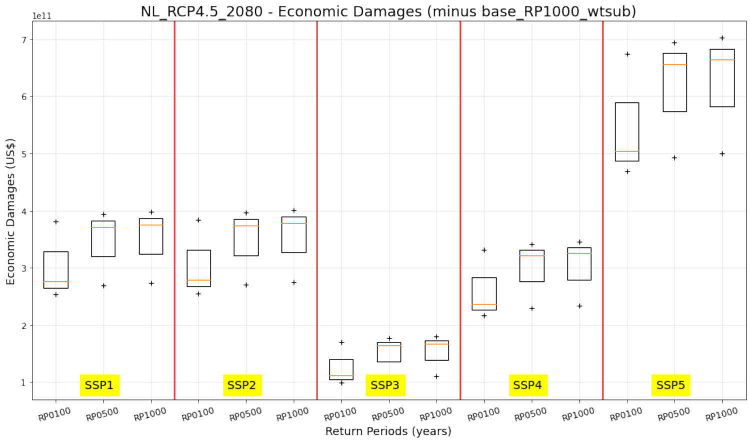



(a) Latvia

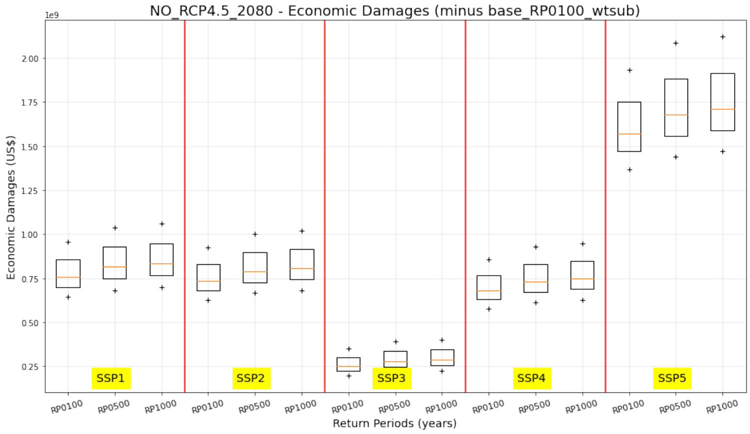



(b) Lithuania

Figure B.32: ECO Boxplot of all SSP for Latvia (a) and Lithuania (b), scenario RCP4.5 - 2080.

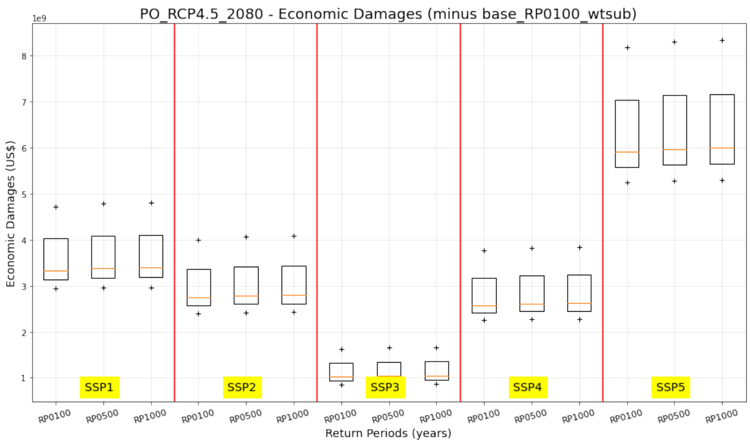



(a) the Netherlands

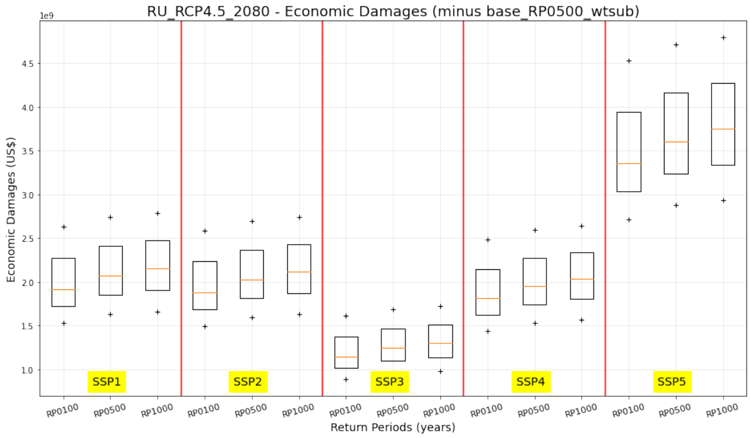



(b) Norway

Figure B.33: ECO Boxplot of all SSP for the Netherlands (a) and Norway (b), scenario RCP4.5 - 2080.

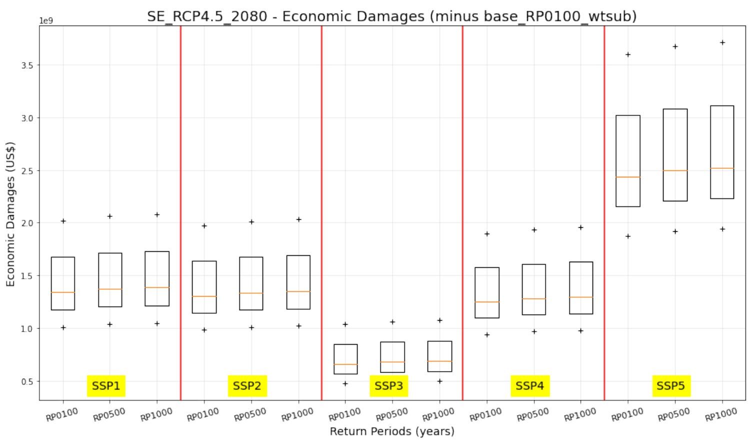



(a) Poland

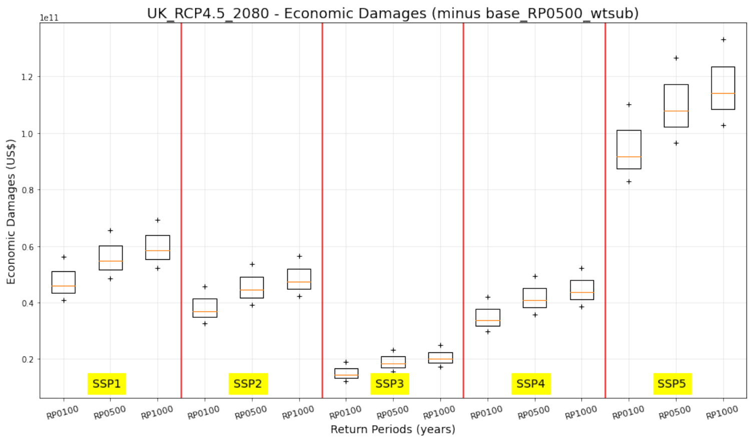



(b) Russia

Figure B.34: ECO Boxplot of all SSP for Poland (a) and Russia (b), scenario RCP4.5 - 2080.



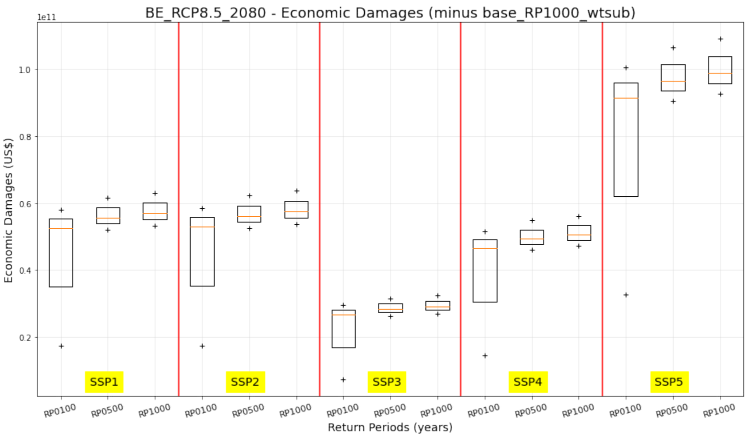

(a) Sweden



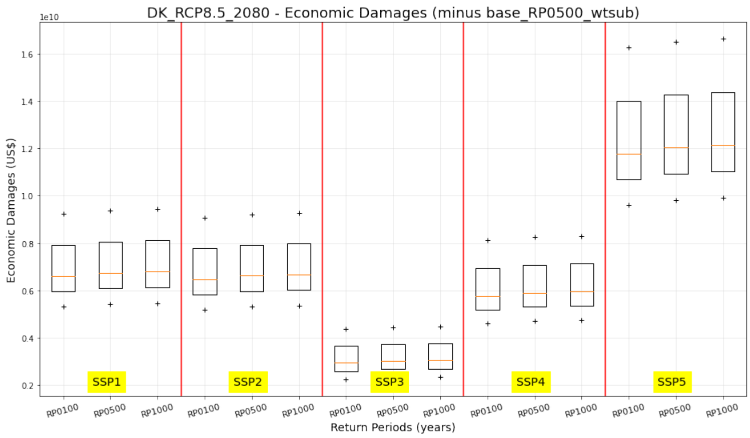

(b) the United Kingdom

Figure B.35: ECO Boxplot of all SSP for Sweden (a) and the United Kingdom (b), scenario RCP4.5 - 2080.

### B.1.6. Boxplots - Economic Damages (ECO) - RCP8.5 | 2080

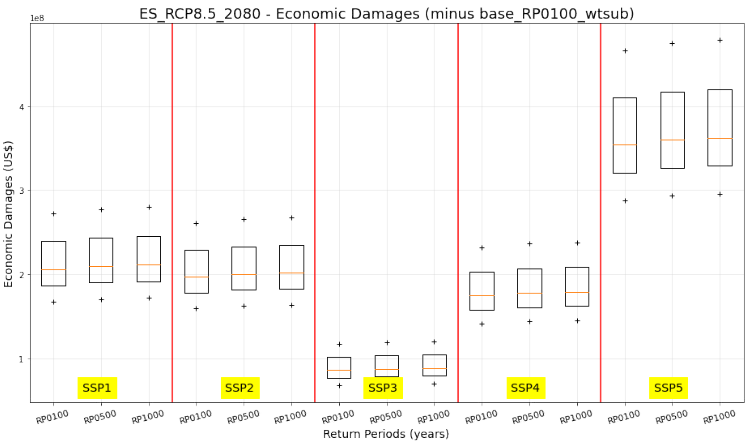



(a) Belgium

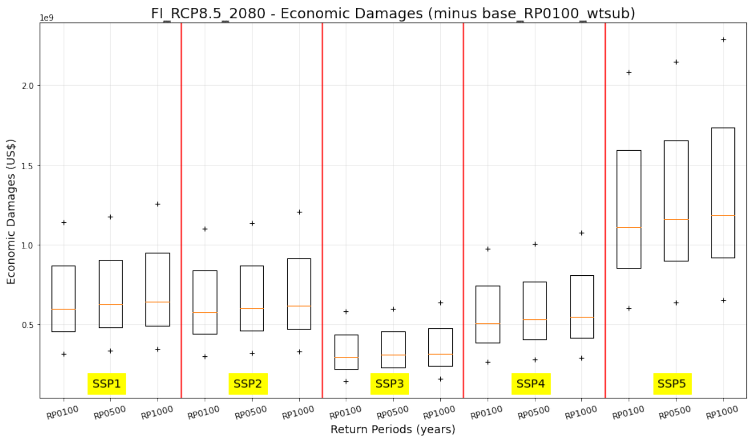



(b) Denmark

Figure B.36: ECO Boxplot of all SSP for Belgium (a) and Denmark (b), scenario RCP8.5 - 2080.

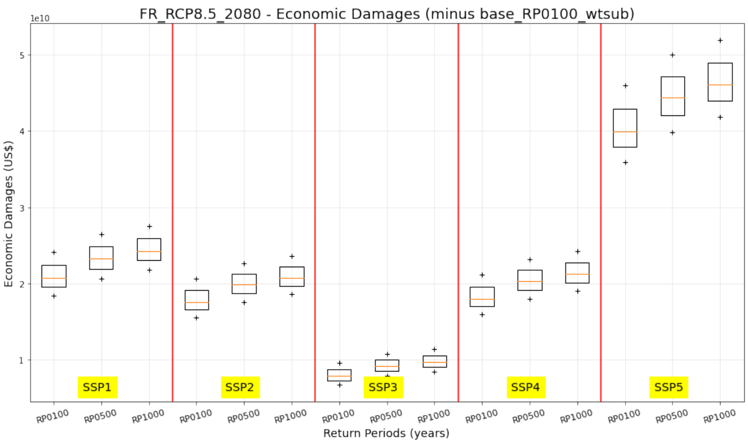



(a) Estonia

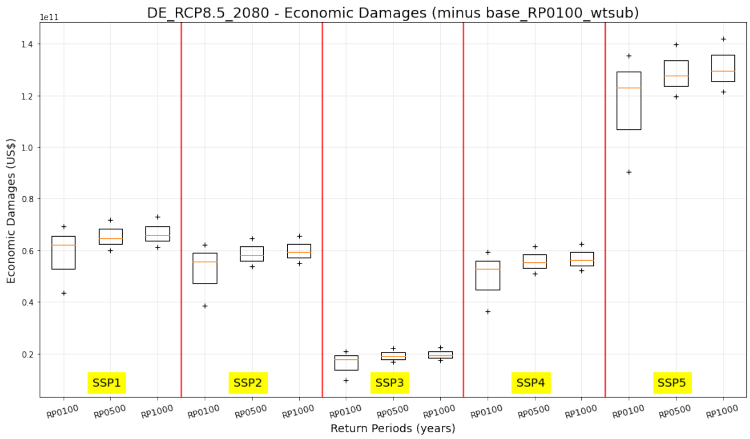



(b) Finland

Figure B.37: ECO Boxplot of all SSP for Estonia (a) and Finland (b), scenario RCP8.5 - 2080.

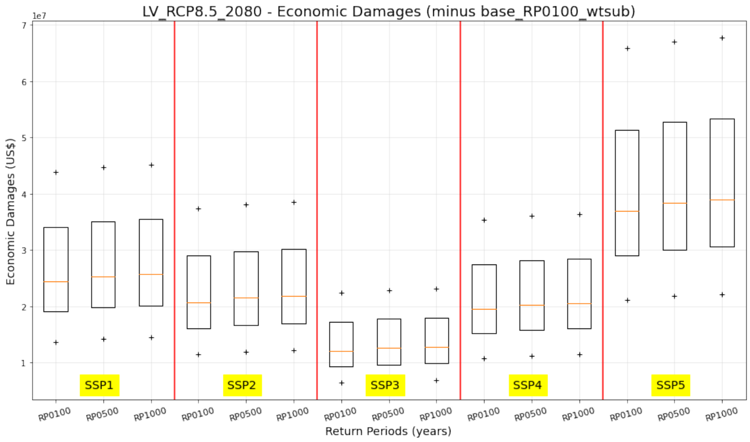



(a) France

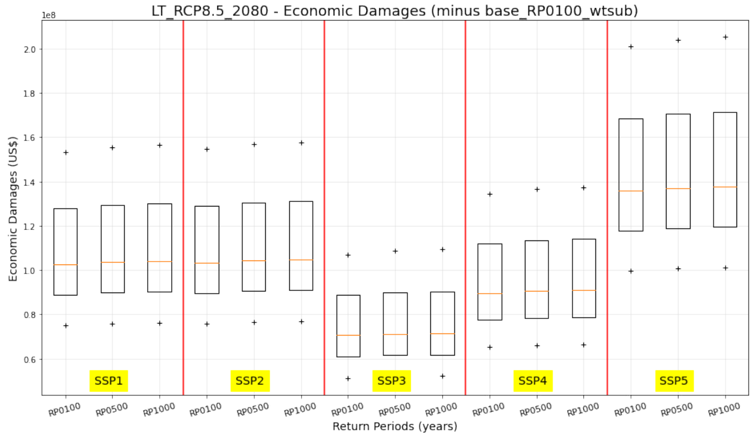



(b) Germany

Figure B.38: ECO Boxplot of all SSP for France (a) and Germany (b), scenario RCP8.5 - 2080.

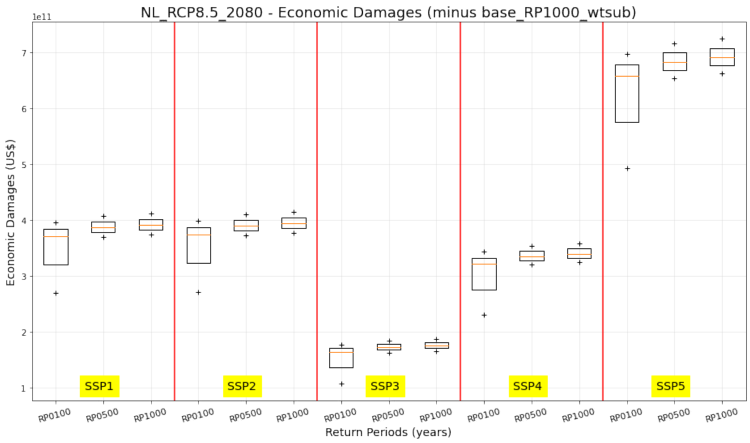



(a) Latvia

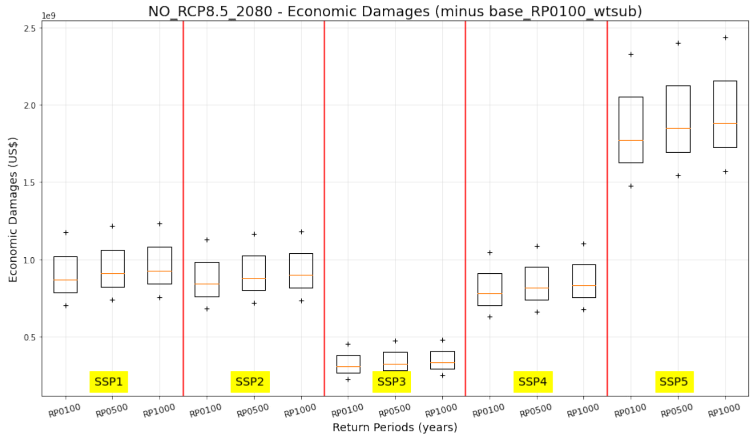



(b) Lithuania

Figure B.39: ECO Boxplot of all SSP for Latvia (a) and Lithuania (b), scenario RCP8.5 - 2080.

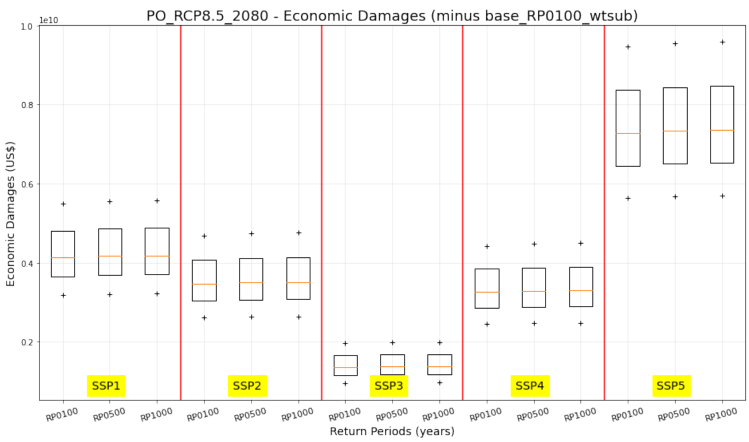



(a) the Netherlands

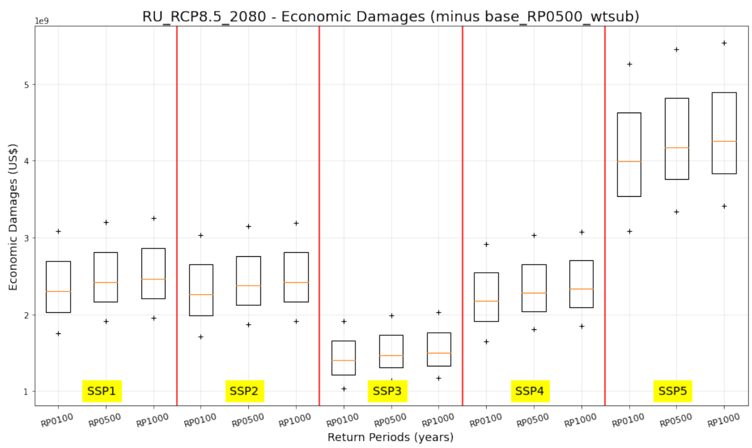



(b) Norway

Figure B.40: ECO Boxplot of all SSP for the Netherlands (a) and Norway (b), scenario RCP8.5 - 2080.

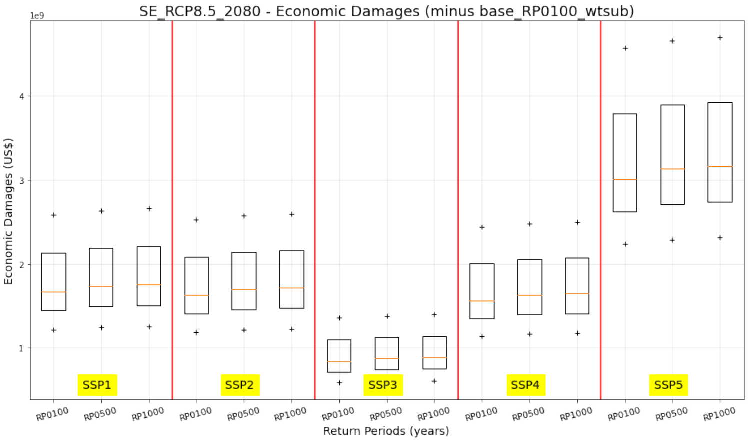



(a) Poland

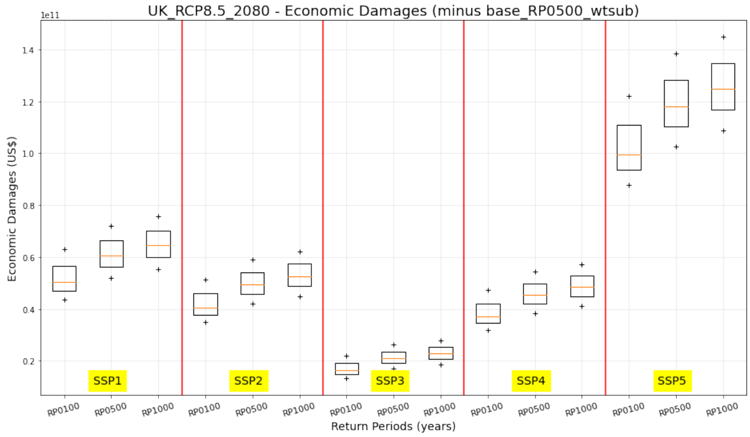



(b) Russia

Figure B.41: ECO Boxplot of all SSP for Poland (a) and Russia (b), scenario RCP8.5 - 2080.




(a) Sweden




(b) the United Kingdom

Figure B.42: ECO Boxplot of all SSP for Sweden (a) and the United Kingdom (b), scenario RCP8.5 - 2080.

## B.2. Shared Socioeconomic Pathways (SSP) Overview

Table B.1: Overview of narratives for all Shared Socioeconomic Pathways (Riahi *et al.*, 2017).

| SSP # | Narrative description |
|---|---|
| SSP1 | **Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)**<br>The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity. |
| SSP2 | **Middle of the Road (Medium challenges to mitigation and adaptation)**<br>The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain. |
| SSP3 | **Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)**<br>A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions. |
| SSP4 | **Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)**<br>Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas. |
| SSP5 | **Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)**<br>This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary. |

## B.3. GLOFRIS Overview Simulation Scenarios

Table B.2: Overview of all possible combinations for each indicator.

| RCP | SSP | Year | Subsidence | Number of Return Period | Number of Percentile | Number of Output Result |
|---|---|---|---|---|---|---|
| - | - | 2010 (base) | N | 3 (*100, 500, 1000*) | - | 3 |
| - | - | 2010 (base) | Y | 3 | - | 3 |
| RCP4.5 | SSP1 | 2030 | Y | 3 | 3 (*5$^{th}$, 50$^{th}$, 95$^{th}$*) | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| | SSP2 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| | SSP3 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| | SSP4 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| | SSP5 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| RCP8.5 | SSP1 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| | SSP2 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| | SSP3 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| | SSP4 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| | SSP5 | 2030 | Y | 3 | 3 | 9 |
| | | 2050 | Y | 3 | 3 | 9 |
| | | 2080 | Y | 3 | 3 | 9 |
| **Total number of output results per country for 1 indicator** | | | | | | 276 |
| **Total number of output results for all 14 country for 1 indicator** | | | | | | 3864 |
| **Total number of output results for all 14 country for all 3 indicator** | | | | | | 11592 |

# C

# Appendix C

## C.1. Population - Base Values

Table C.1: Overview of the base values for indicator Population for all countries.

| Country | FP Standard RP | Base Value |
|---|---|---|
| Belgium | 1000 | 56,719 |
| Denmark | 500 | 16,039 |
| Estonia | 100 | 0 |
| Finland | 100 | 1,934 |
| France | 100 | 222,530 |
| Germany | 100 | 422,385 |
| Latvia | 100 | 20 |
| Lithuania | 100 | 634 |
| the Netherlands | 1000 | 3,294,912 |
| Norway | 100 | 18,107 |
| Poland | 100 | 18,041 |
| Russia | 500 | 10,790 |
| Sweden | 100 | 4,073 |
| the United Kingdom | 500 | 428,090 |

## C.2. Population - RCP4.5

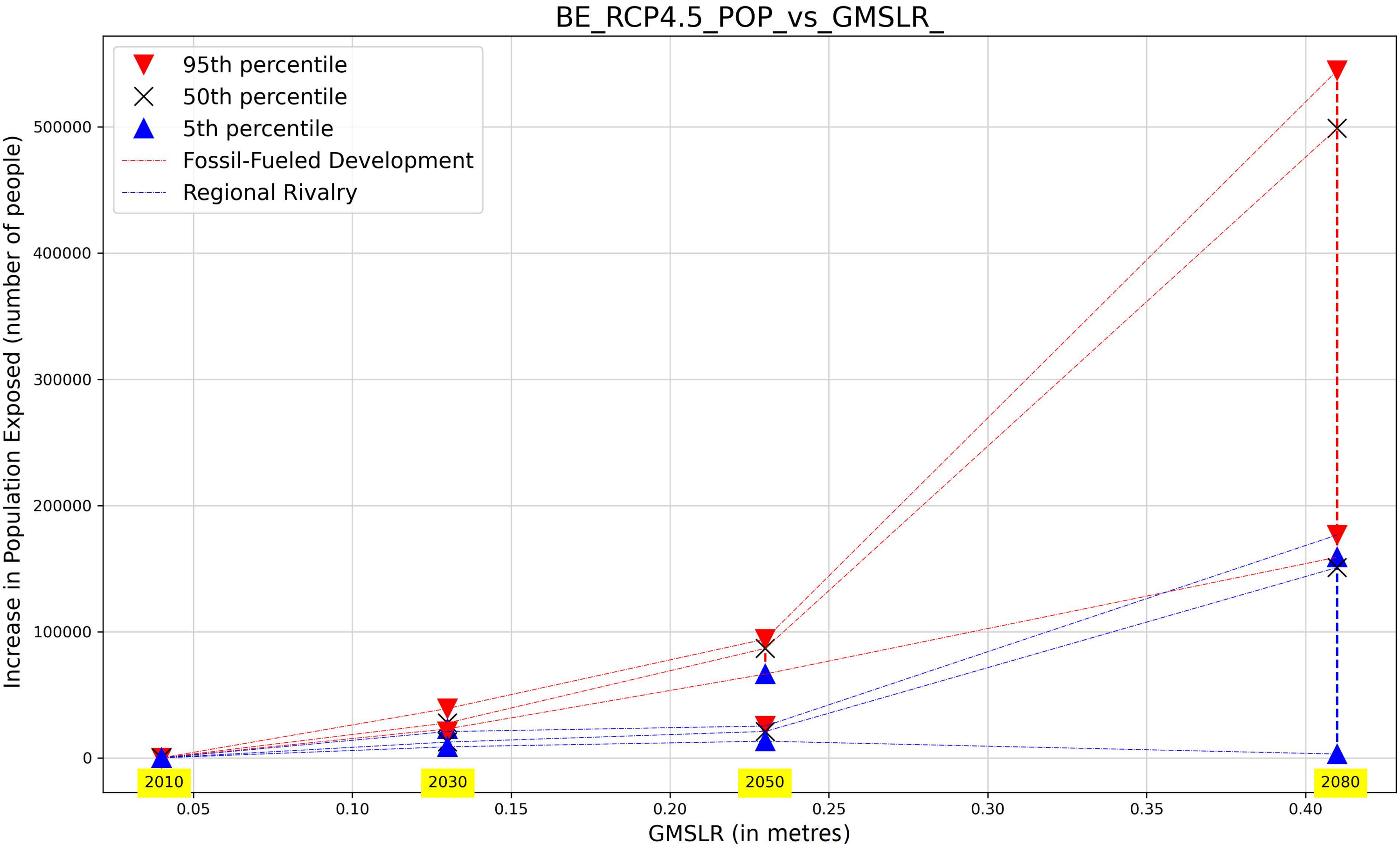



Figure C.1: Graph of BE_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.2: Overview of BE_POP_RCP4.5_vs_GMSLR values.

| Belgium - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 8,760 | 12,514 | 20,849 | 22,970 | 27,674 | 39,125 |
| **2050** | 13,195 | 20,958 | 25,213 | 66,448 | 86,765 | 94,151 |
| **2080** | 3,032 | 150,927 | 176,717 | 159,056 | 498,970 | 544,888 |

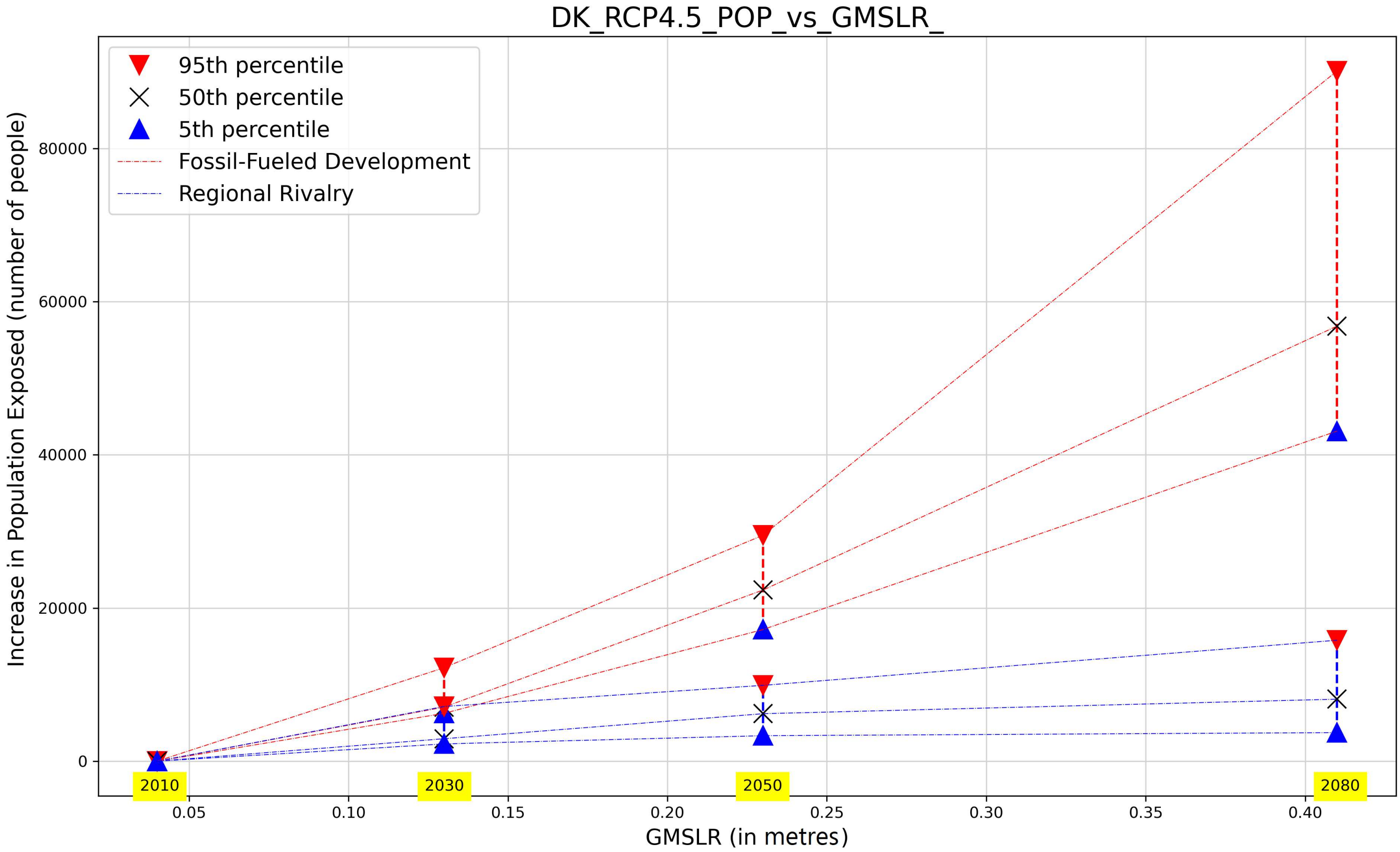



Figure C.2: Graph of DK_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.3: Overview of DK_POP_RCP4.5_vs_GMSLR values.

| **Denmark - Population (number of people) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 2,254 | 2,931 | 7,142 | 6,246 | 7,062 | 12,208 |
| **2050** | 3,325 | 6,198 | 9,890 | 17,189 | 22,348 | 29,497 |
| **2080** | 3,731 | 8,096 | 15,791 | 43,101 | 56,810 | 90,126 |

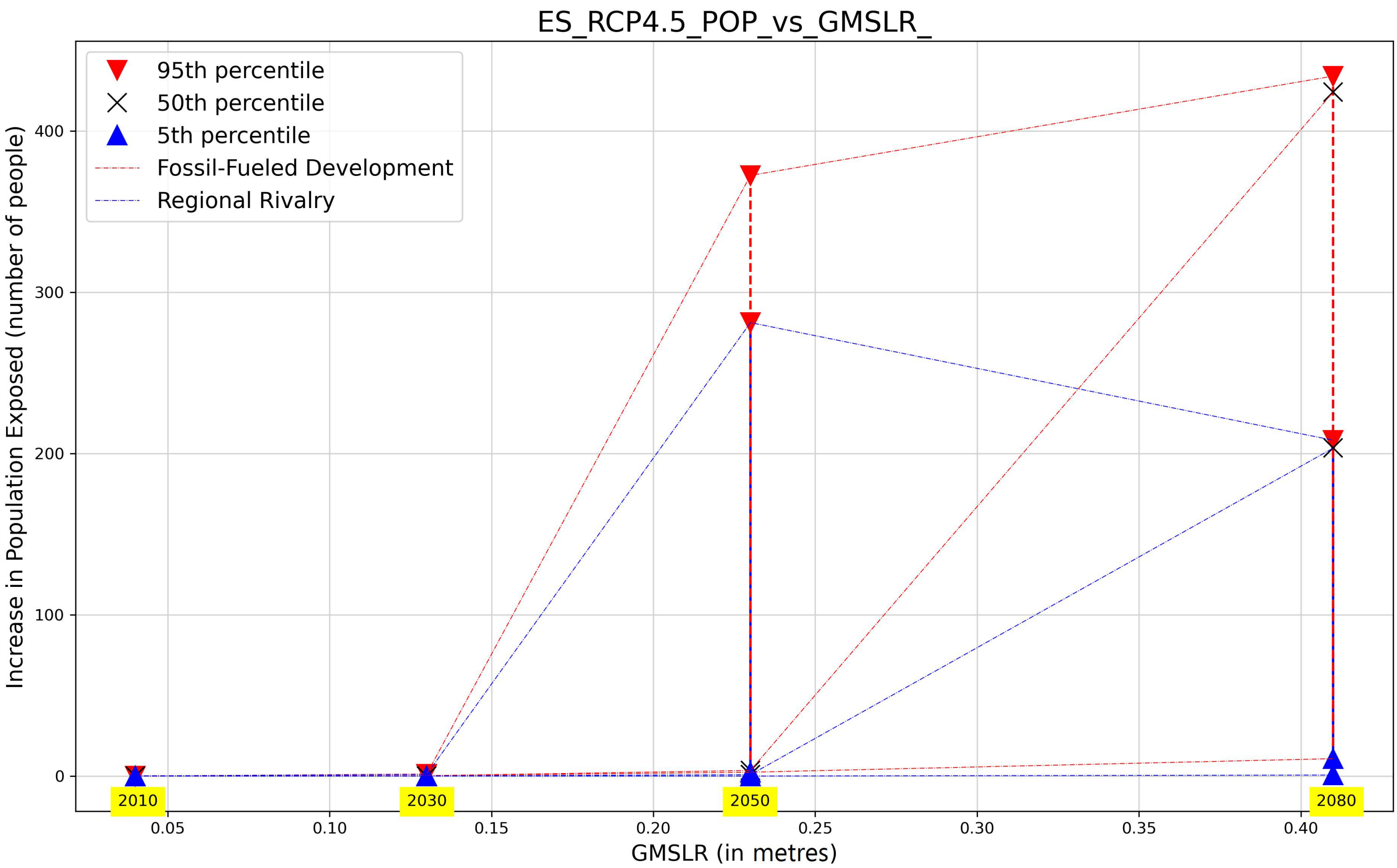



Figure C.3: Graph of ES_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.4: Overview of ES_POP_RCP4.5_vs_GMSLR values.

| **Estonia - Population (number of people) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 0 | 0 | 1 | 0 | 0 | 1 |
| **2050** | 0 | 1 | 281 | 2 | 3 | 372 |
| **2080** | 1 | 203 | 208 | 11 | 424 | 434 |

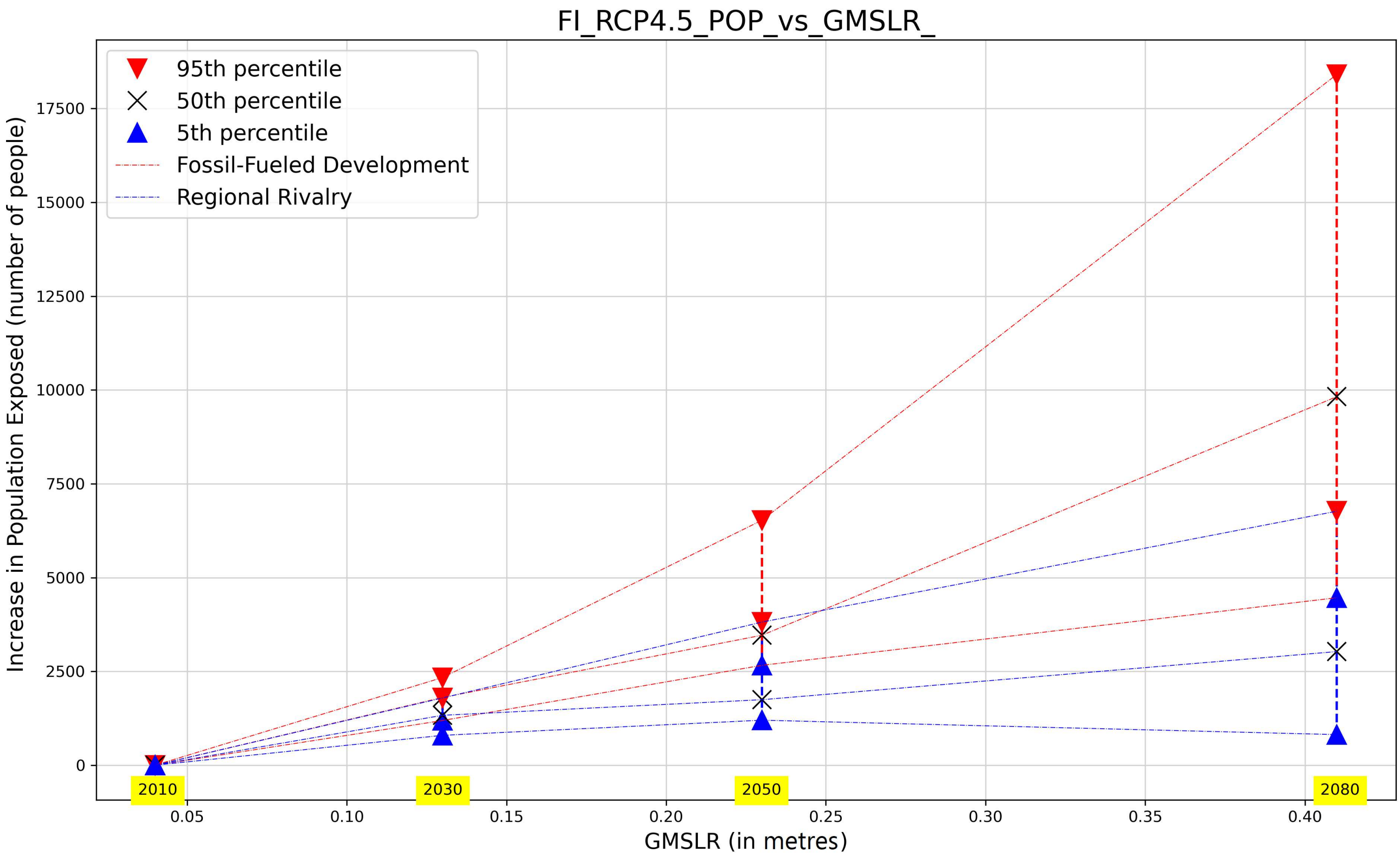



Figure C.4: Graph of FI_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.5: Overview of FI_POP_RCP4.5_vs_GMSLR values.

| Finland - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 796 | 1,330 | 1,792 | 1,191 | 1,805 | 2,337 |
| **2050** | 1,199 | 1,745 | 3,813 | 2,661 | 3,463 | 6,527 |
| **2080** | 815 | 3,028 | 6,768 | 4,462 | 9,822 | 18,409 |

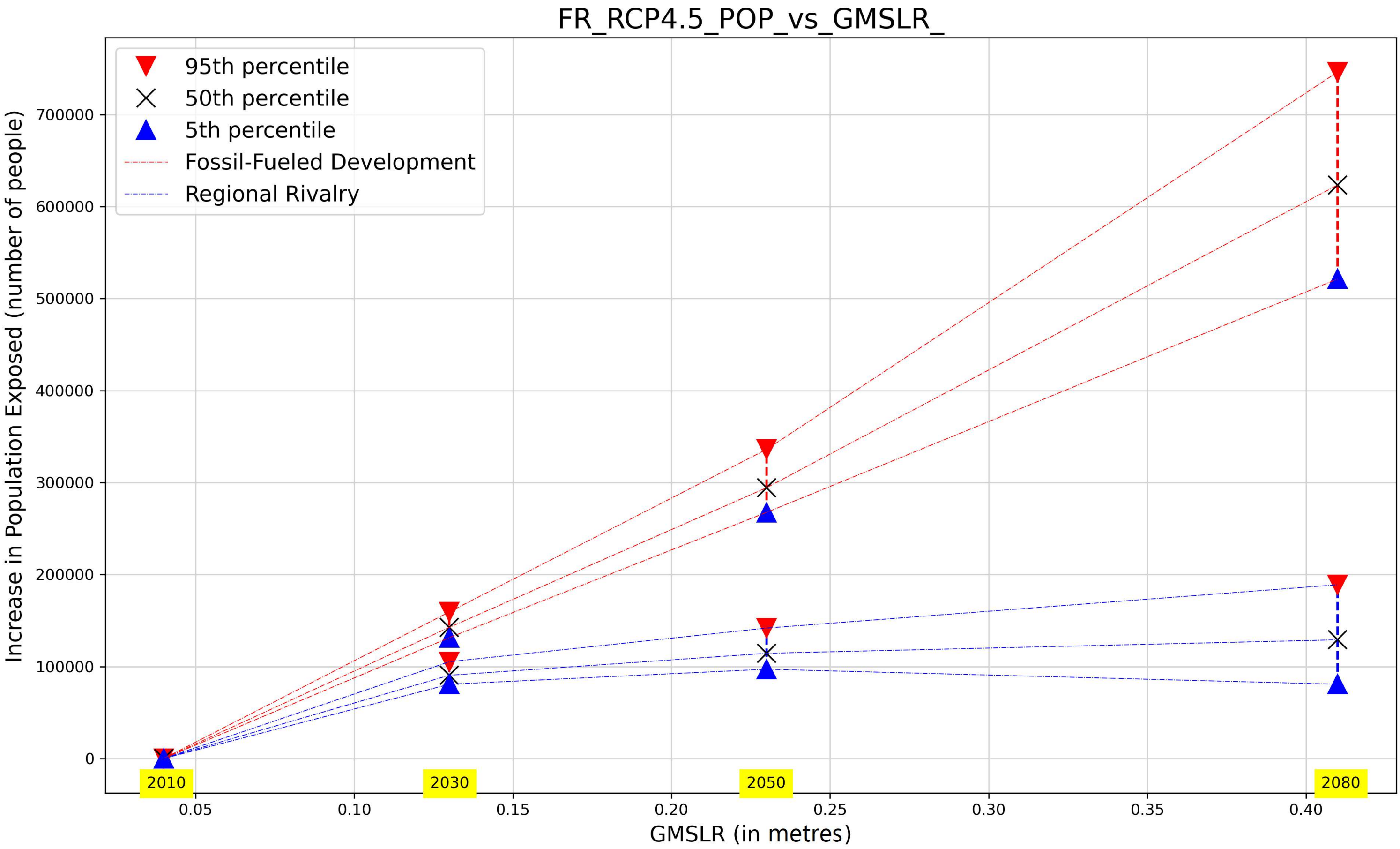



Figure C.5: Graph of FR_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.6: Overview of FR_POP_RCP4.5_vs_GMSLR values.

| France - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 80,745 | 90,496 | 105,196 | 131,397 | 142,566 | 159,362 |
| **2050** | 97,081 | 114,365 | 141,785 | 267,566 | 294,392 | 336,077 |
| **2080** | 80,768 | 129,051 | 188,884 | 521,369 | 623,506 | 746,393 |

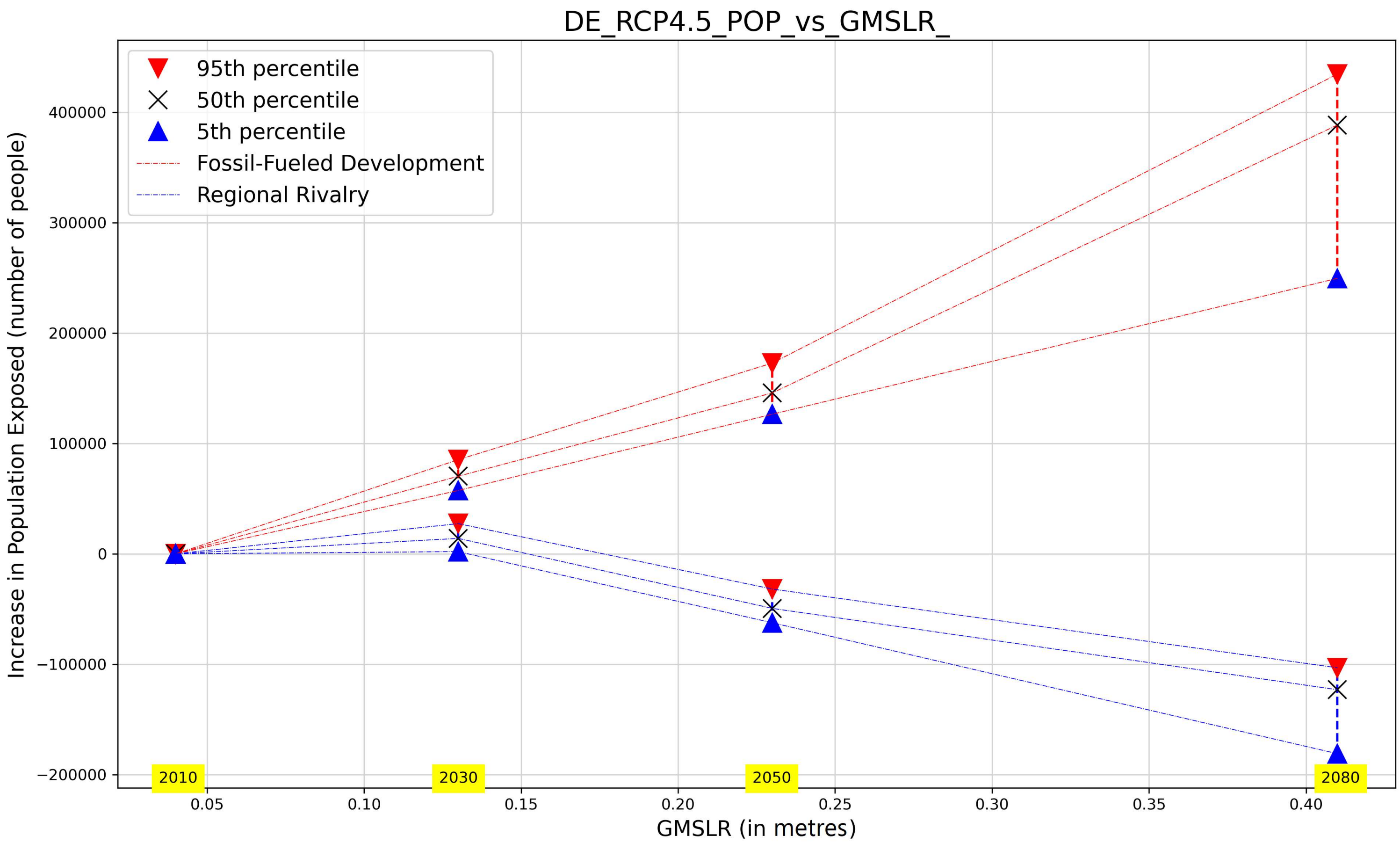



Figure C.6: Graph of DE_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.7: Overview of DE_POP_RCP4.5_vs_GMSLR values.

| Germany - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | -11.339 | 648 | 14,025 | 57,392 | 70,294 | 86,257 |
| **2050** | -75.763 | -62,767 | -45,256 | 126,461 | 145,763 | 172,798 |
| **2080** | -194,416 | -136,452 | -116,569 | 249,582 | 388,518 | 434,657 |

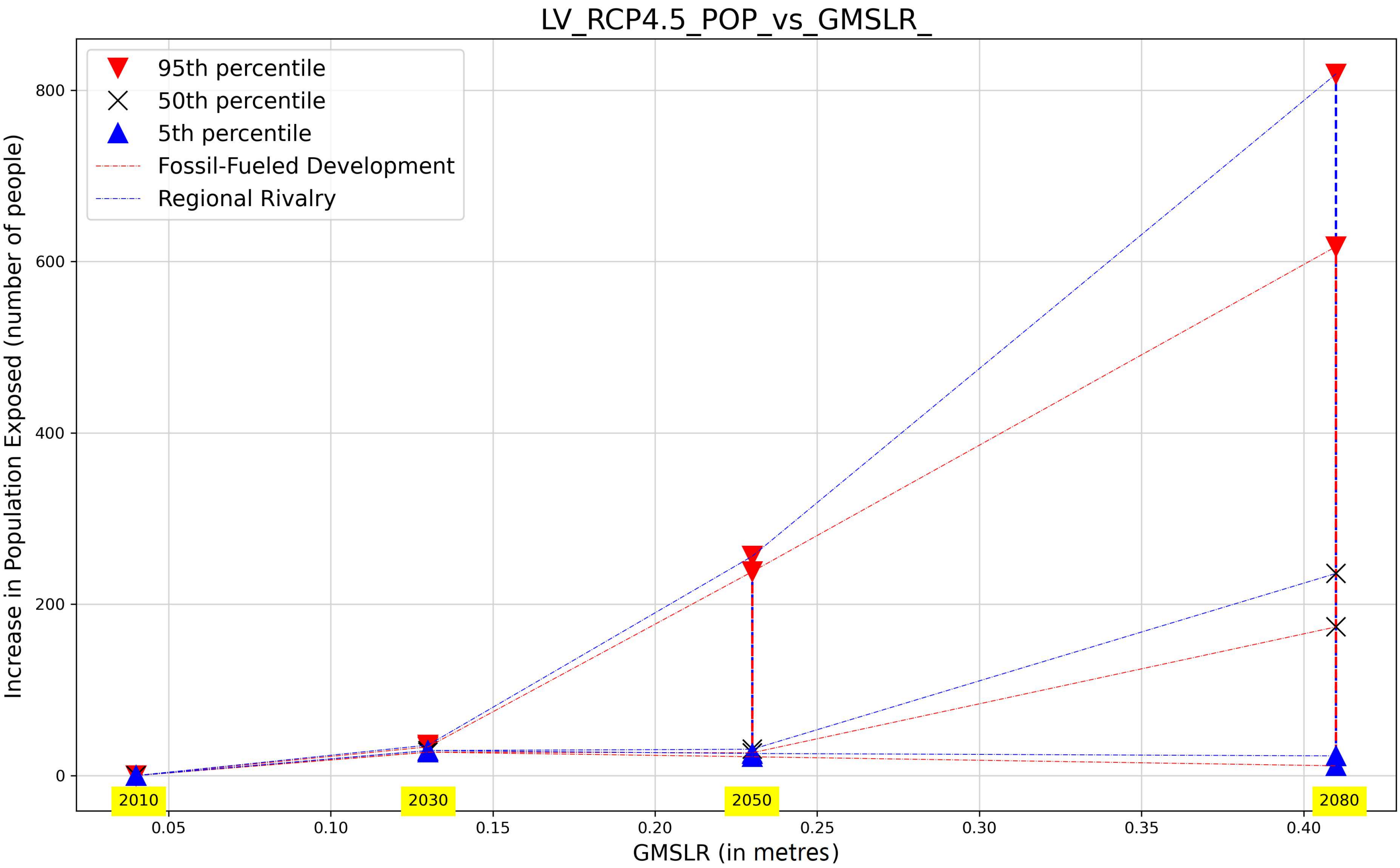



Figure C.7: Graph of LV_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.8: Overview of LV_POP_RCP4.5_vs_GMSLR values.

| Latvia - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 29 | 29 | 36 | 27 | 27 | 34 |
| **2050** | 26 | 31 | 256 | 22 | 27 | 238 |
| **2080** | 23 | 236 | 819 | 11 | 174 | 618 |

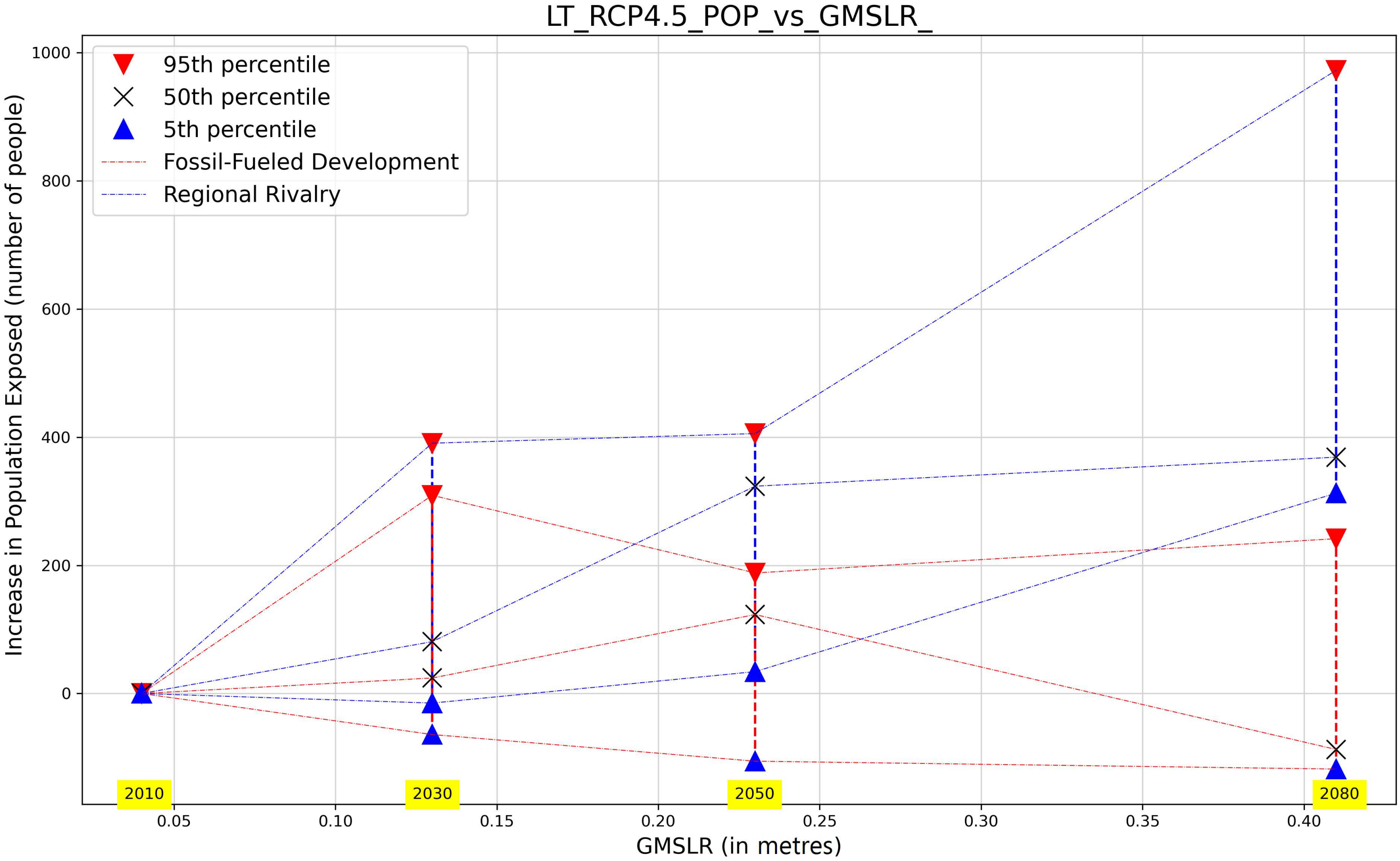



Figure C.8: Graph of LT_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.9: Overview of LT_POP_RCP4.5_vs_GMSLR values.

| **Lithuania - Population (number of people) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | -15 | 81 | 391 | -64 | 24 | 309 |
| **2050** | 34 | 324 | 406 | -106 | 123 | 188 |
| **2080** | 313 | 369 | 973 | -118 | -87 | 242 |

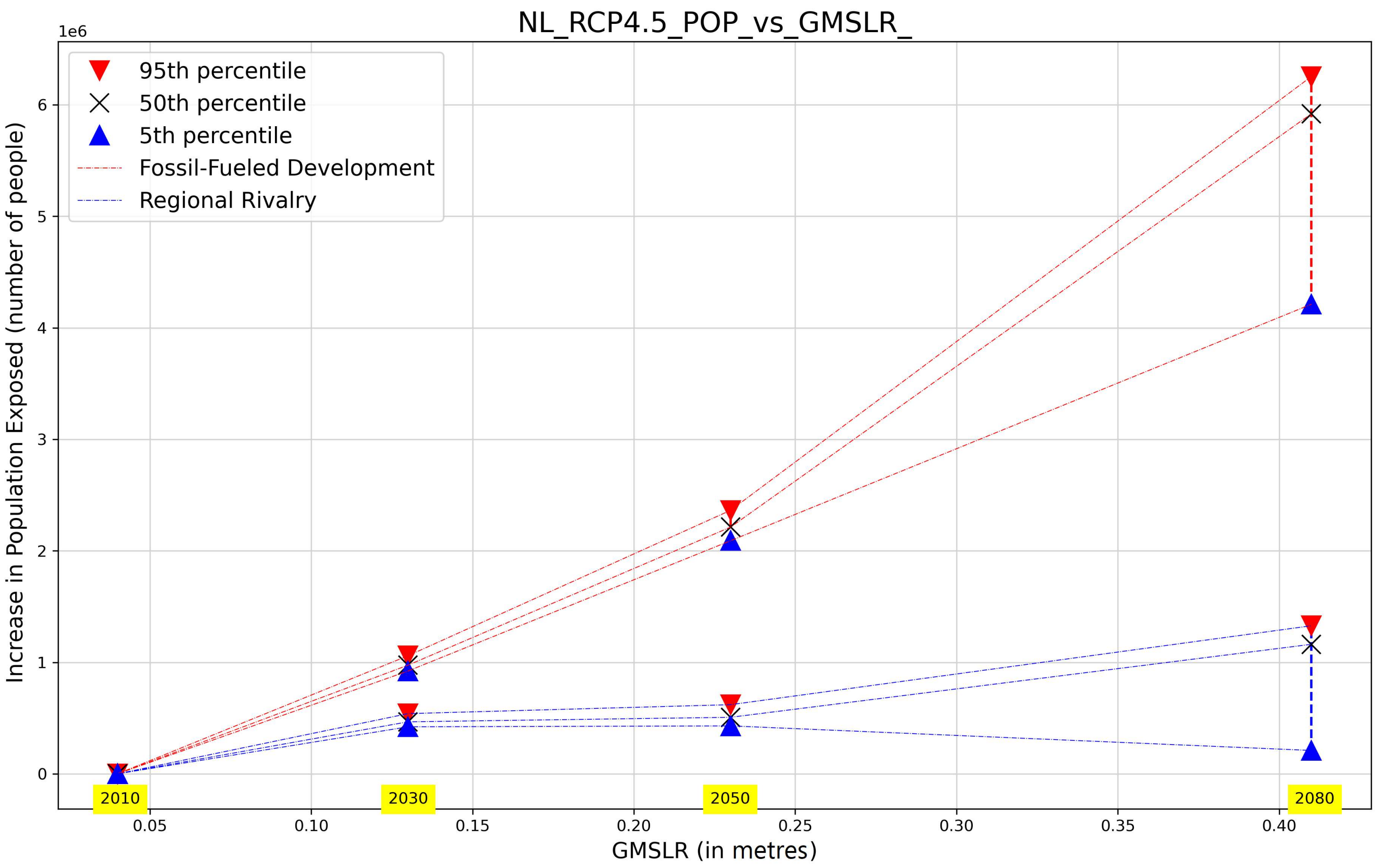



Figure C.9: Graph of NL_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.10: Overview of NL_POP_RCP4.5_vs_GMSLR values.

| the Netherlands - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 421,432 | 466,222 | 539,685 | 921,875 | 974,120 | 1,058,699 |
| **2050** | 429,667 | 506,870 | 620,100 | 2,090,728 | 2,212,910 | 2,363,523 |
| **2080** | 209,388 | 1,161,556 | 1,327,905 | 4,211,612 | 5,920,312 | 6,254,522 |

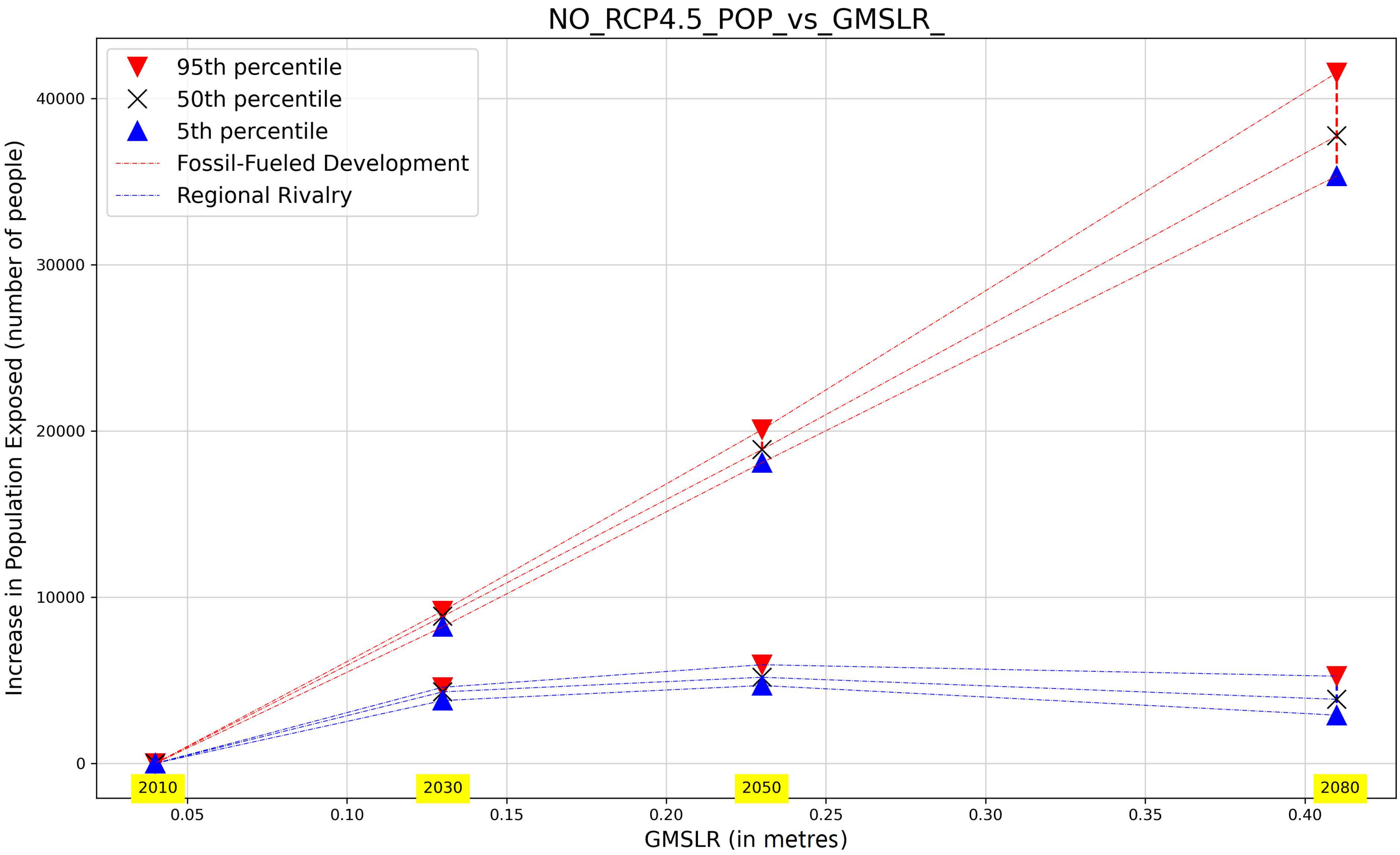



Figure C.10: Graph of NO_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.11: Overview of NO_POP_RCP4.5_vs_GMSLR values.

| Norway - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 3,780 | 4,300 | 4,576 | 8,217 | 8,843 | 9,174 |
| **2050** | 4,682 | 5,179 | 5,933 | 18,091 | 18,881 | 20,079 |
| **2080** | 2,899 | 3,850 | 5,242 | 35,336 | 37,751 | 41,548 |

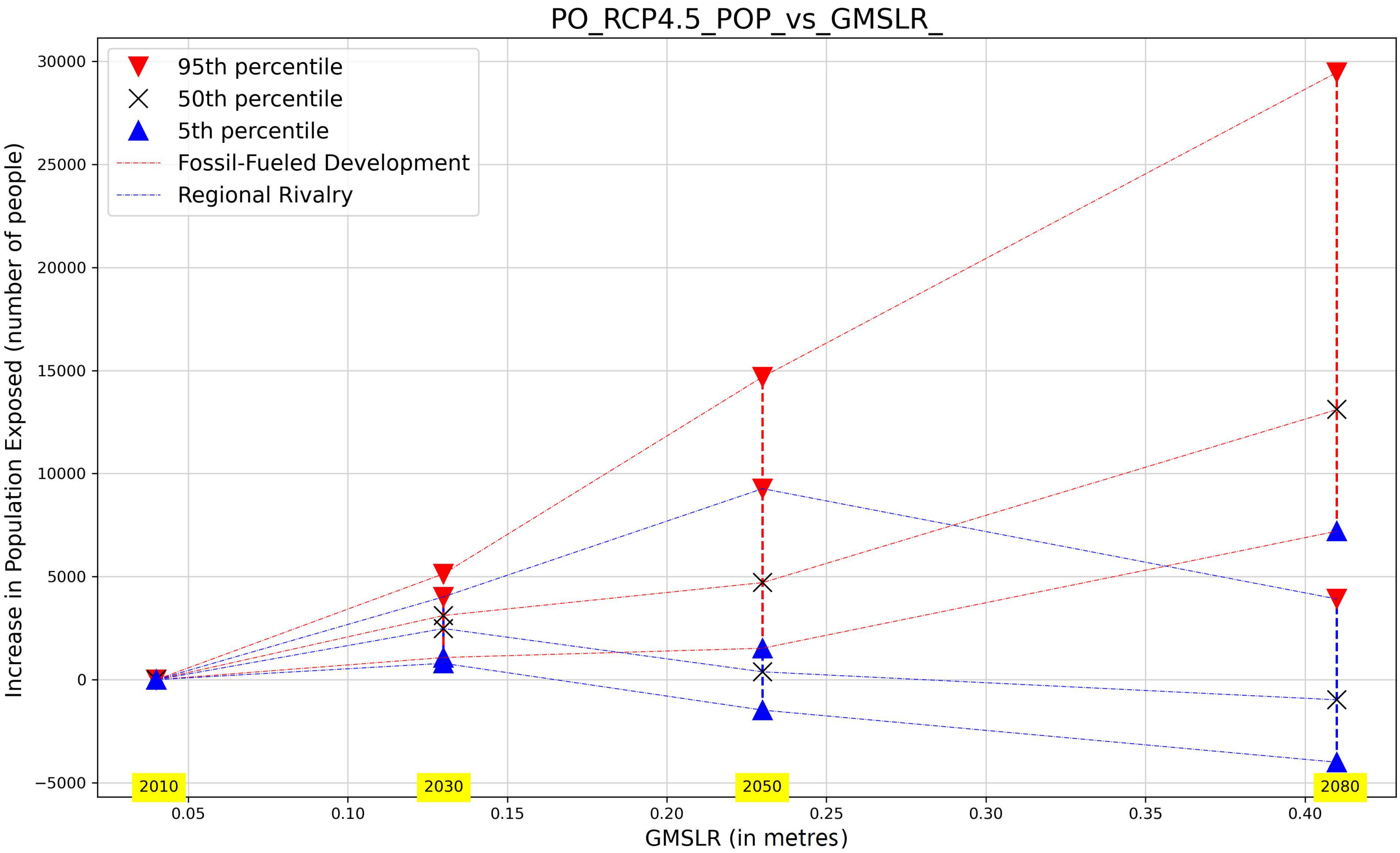



Figure C.11: Graph of PO_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.12: Overview of PO_POP_RCP4.5_vs_GMSLR values.

| Poland - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 795 | 2,482 | 4,018 | 1,076 | 3,114 | 5,135 |
| **2050** | -1,477 | 380 | 9,268 | 1,525 | 4,709 | 14,691 |
| **2080** | -4,006 | -977 | 3,915 | 7,207 | 13,108 | 29,469 |

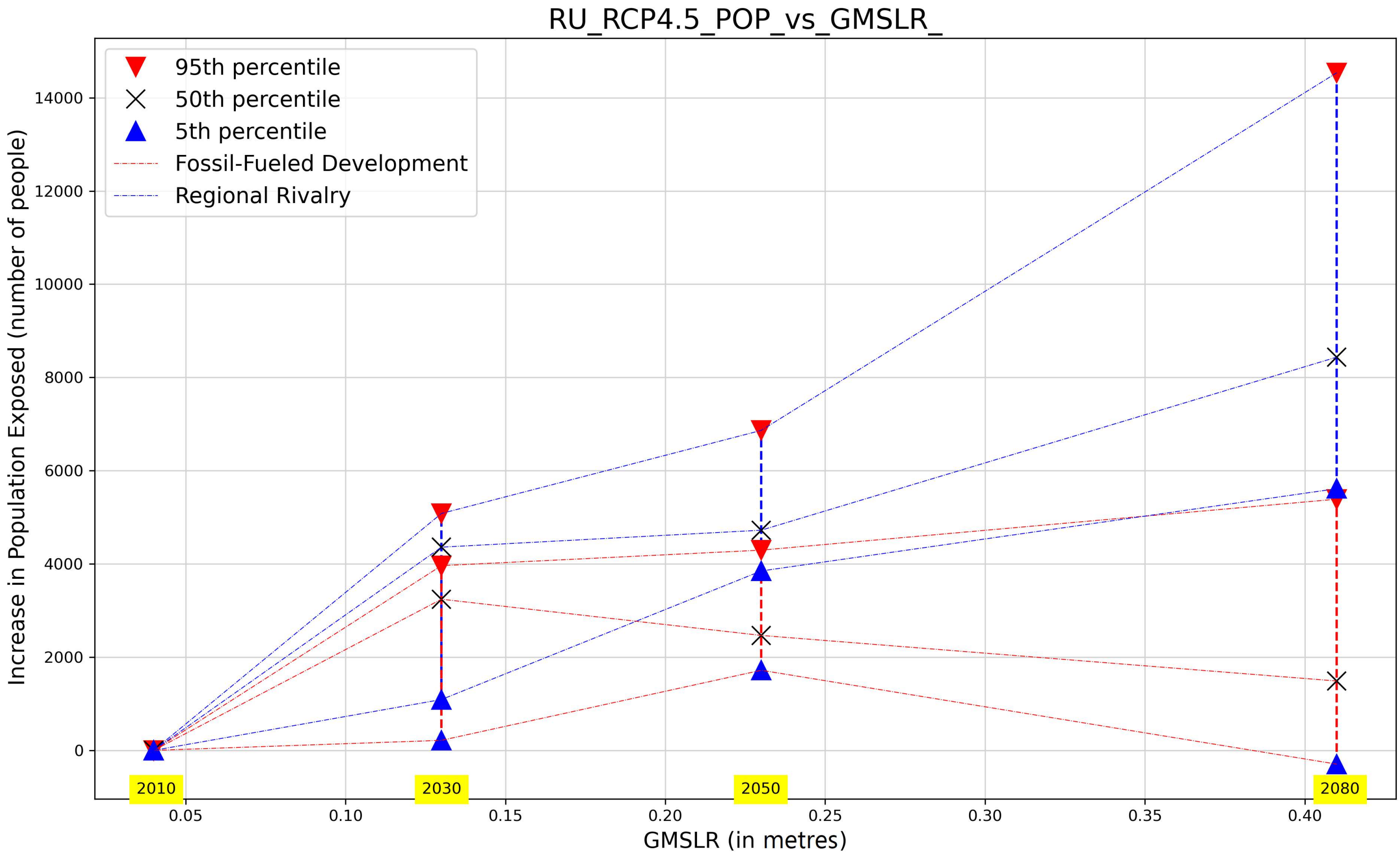



Figure C.12: Graph of RU_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.13: Overview of RU_POP_RCP4.5_vs_GMSLR values.

| **Russia - Population (number of people) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 1,091 | 4,359 | 5,082 | 215 | 3,243 | 3,963 |
| **2050** | 3,849 | 4,723 | 6,864 | 1,718 | 2,466 | 4,295 |
| **2080** | 5,614 | 8,436 | 14,536 | -296 | 1,488 | 5,389 |

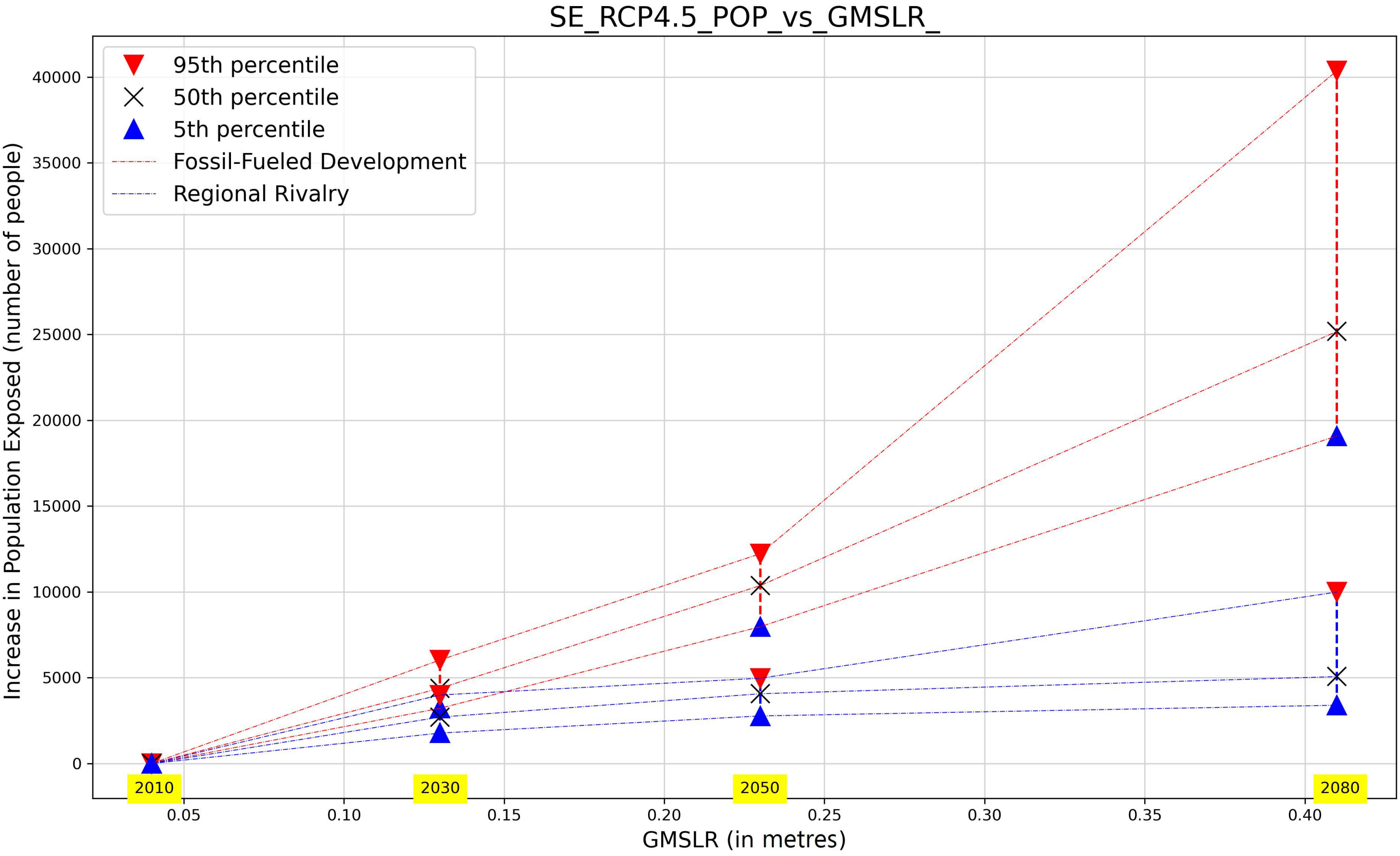



Figure C.13: Graph of SE_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.14: Overview of SE_POP_RCP4.5_vs_GMSLR values.

| Sweden - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 1,773 | 2,705 | 3,994 | 3,217 | 4,383 | 6,031 |
| **2050** | 2,772 | 4,064 | 4,969 | 7,971 | 10,369 | 12,229 |
| **2080** | 3,396 | 5,065 | 9,993 | 19,091 | 25,181 | 40,378 |

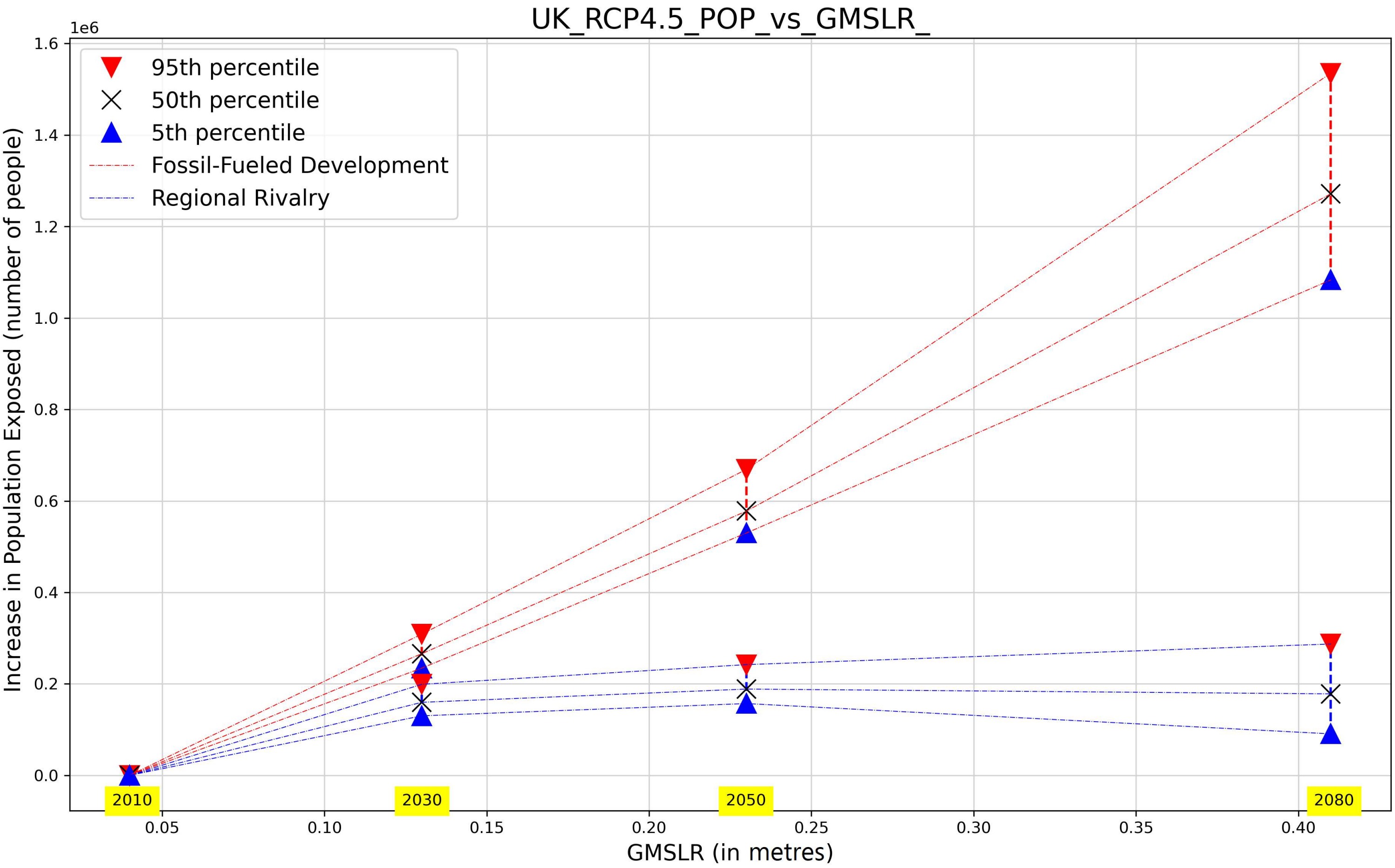



Figure C.14: Graph of UK_RCP4.5_RP1000_POP_vs_GMSLR.

Table C.15: Overview of UK_POP_RCP4.5_vs_GMSLR values.

| the United Kingdom - Population (number of people) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 130,199 | 159,702 | 199,111 | 234,361 | 265,930 | 308,750 |
| **2050** | 156,959 | 188,683 | 242,116 | 529,847 | 577,814 | 669,030 |
| **2080** | 90,723 | 178,162 | 287,166 | 1,083,213 | 1,271,468 | 1,535,199 |

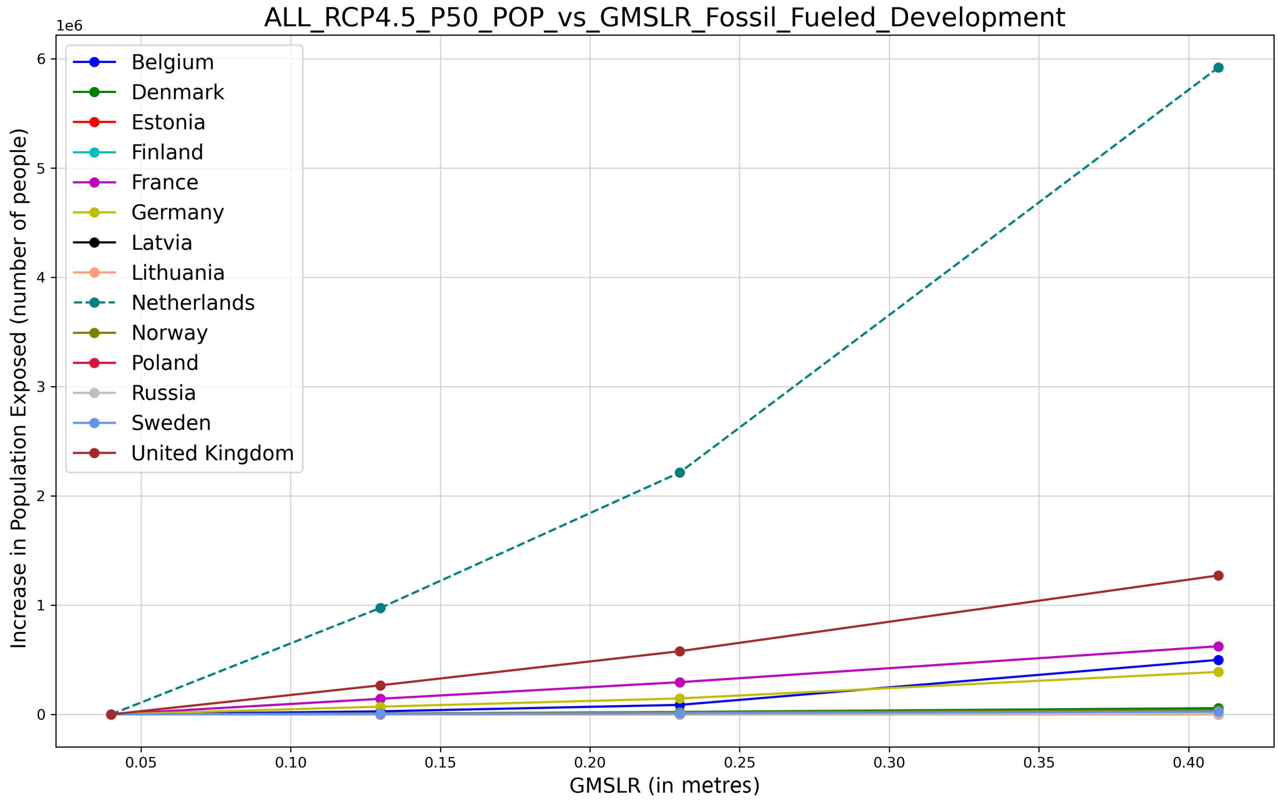



Figure C.15: Graph of ALL_RCP4.5_RP1000_POP_vs_GMSLR.

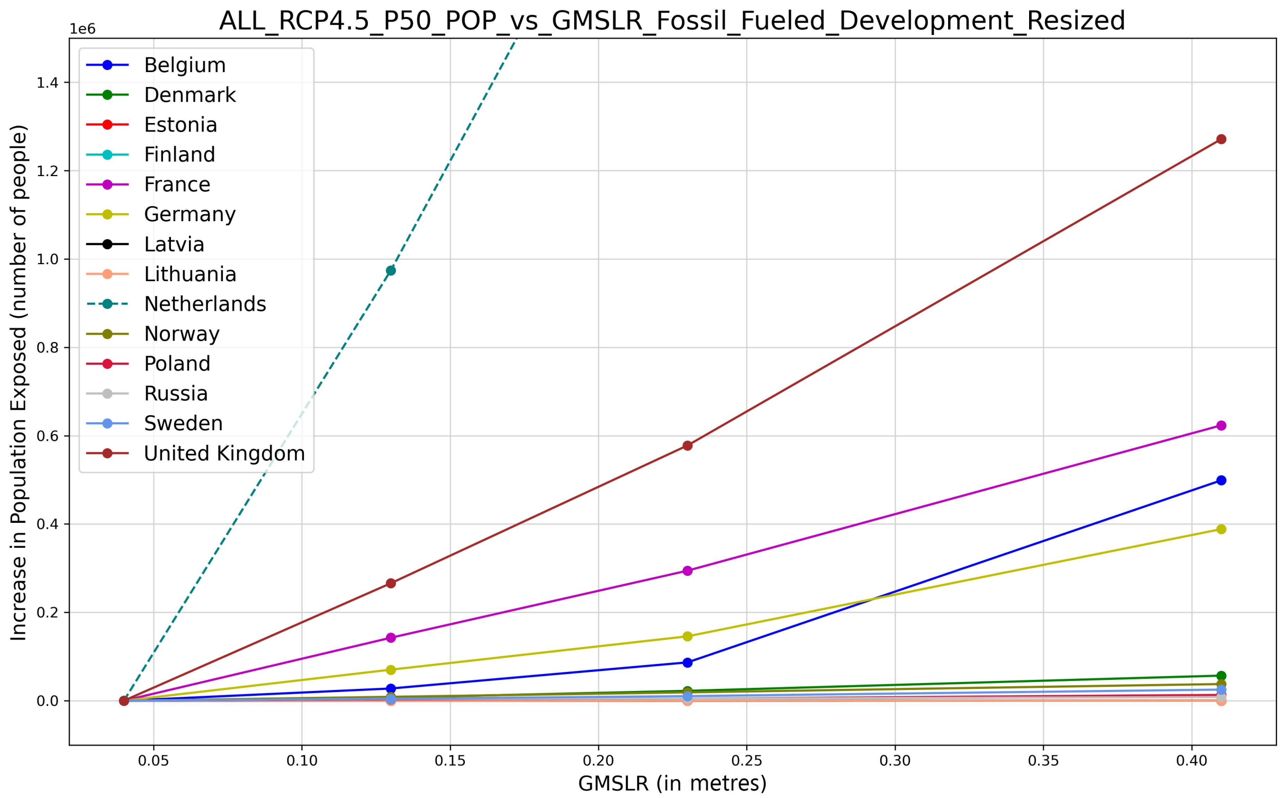



Figure C.16: Graph of ALL_RCP4.5_RP1000_POP_vs_GMSLR_Resized.

## C.3. Population - RCP8.5

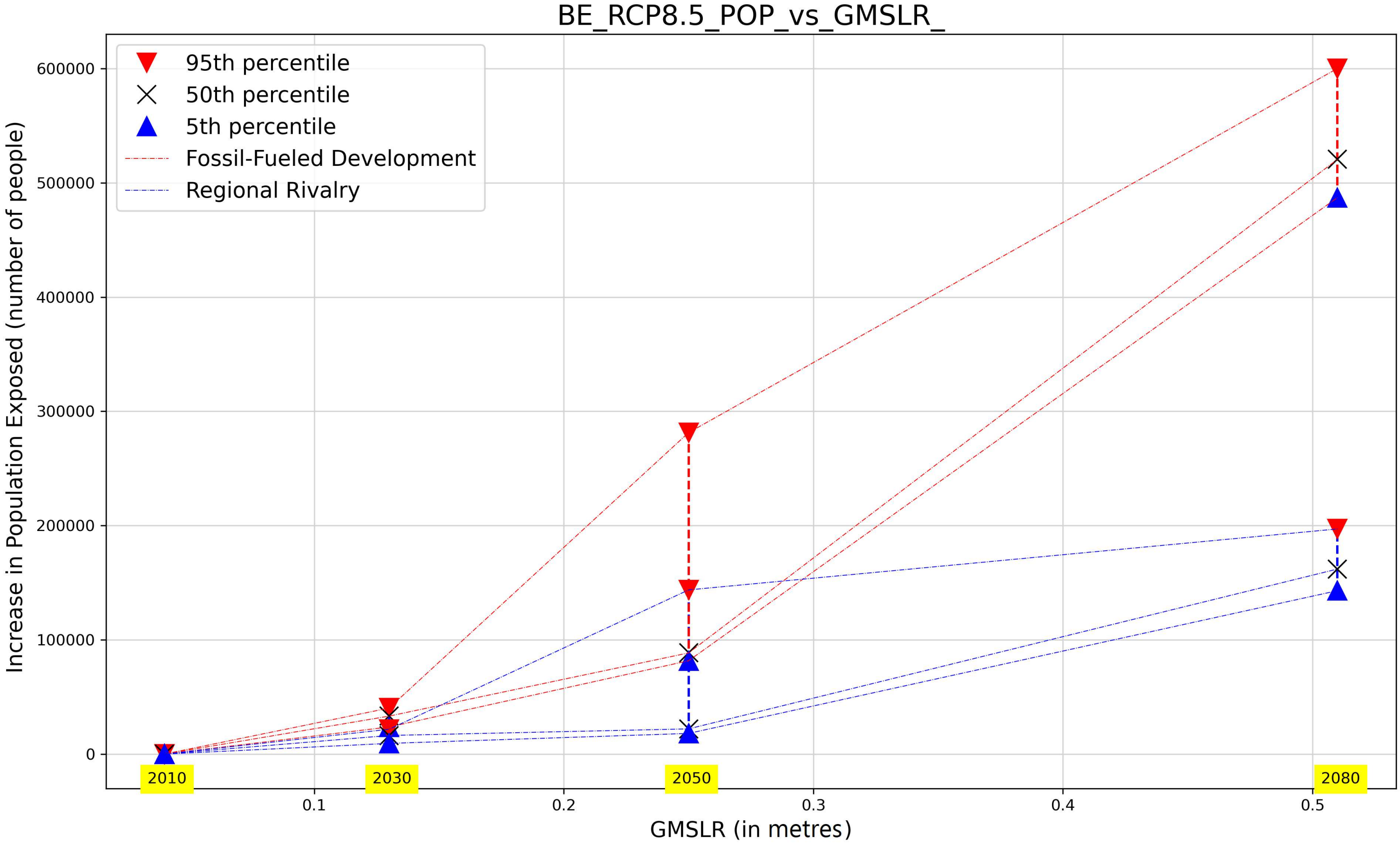



Figure C.17: Graph of BE_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.16: Overview of BE_POP_RCP8.5_vs_GMSLR values.

| Belgium - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 9,332 | 16,279 | 21,727 | 23,707 | 33,226 | 40,283 |
| **2050** | 18,061 | 22,044 | 143,689 | 81,683 | 88,521 | 281,344 |
| **2080** | 143,027 | 161.951 | 197,037 | 487,045 | 520,525 | 600,095 |

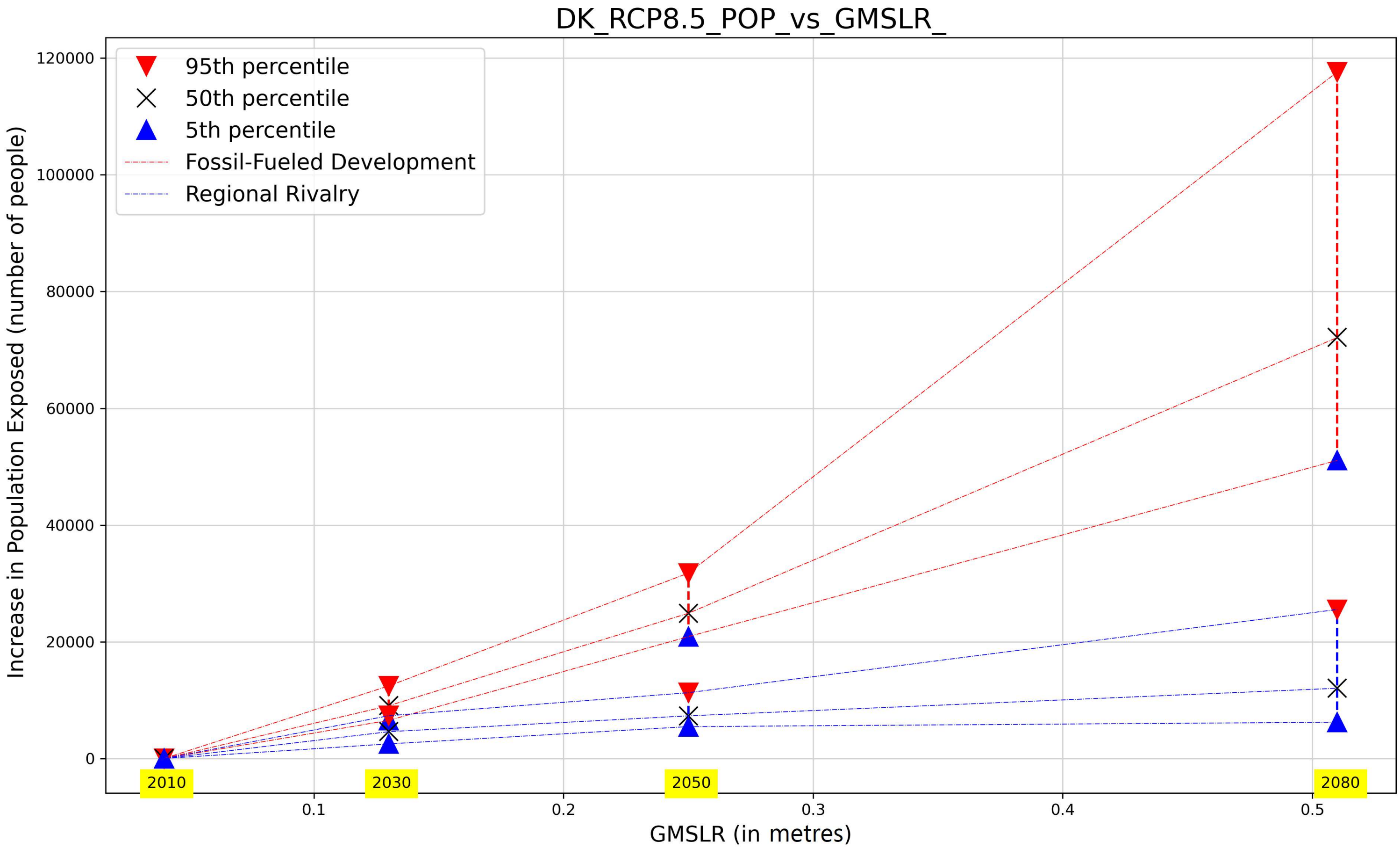



Figure C.18: Graph of DK_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.17: Overview of DK_POP_RCP8.5_vs_GMSLR values.

| Denmark - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 2,503 | 4,596 | 7,326 | 6,536 | 9,042 | 12,441 |
| **2050** | 5,462 | 7,306 | 11,271 | 20,879 | 24,880 | 31,750 |
| **2080** | 6,217 | 12,037 | 25,536 | 51,081 | 72,125 | 117,620 |

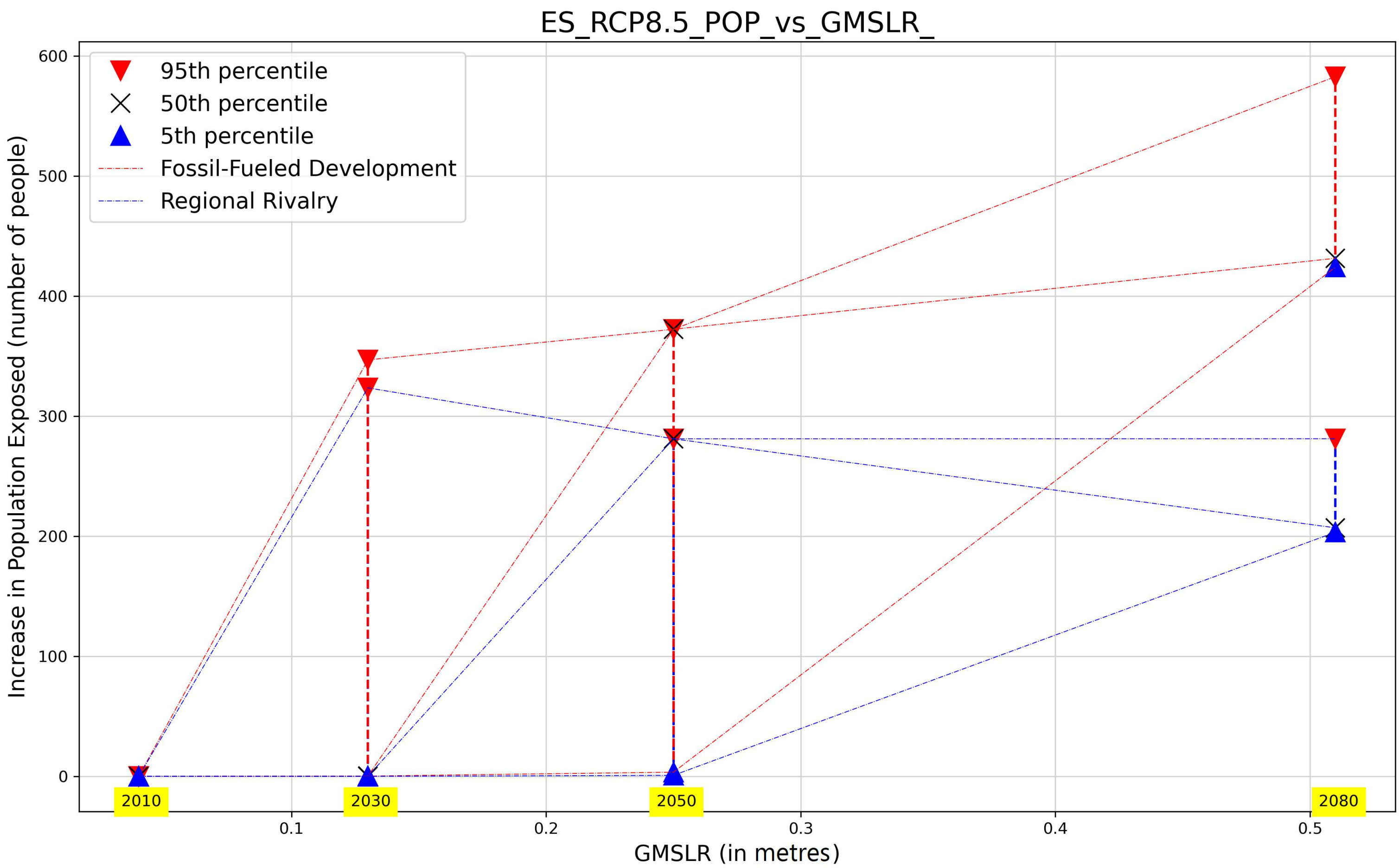



Figure C.19: Graph of ES_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.18: Overview of ES_POP_RCP8.5_vs_GMSLR values.

| Estonia - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 0 | 0 | 323 | 0 | 0 | 346 |
| **2050** | 0 | 281 | 281 | 0 | 372 | 372 |
| **2080** | 203 | 207 | 281 | 424 | 431 | 582 |

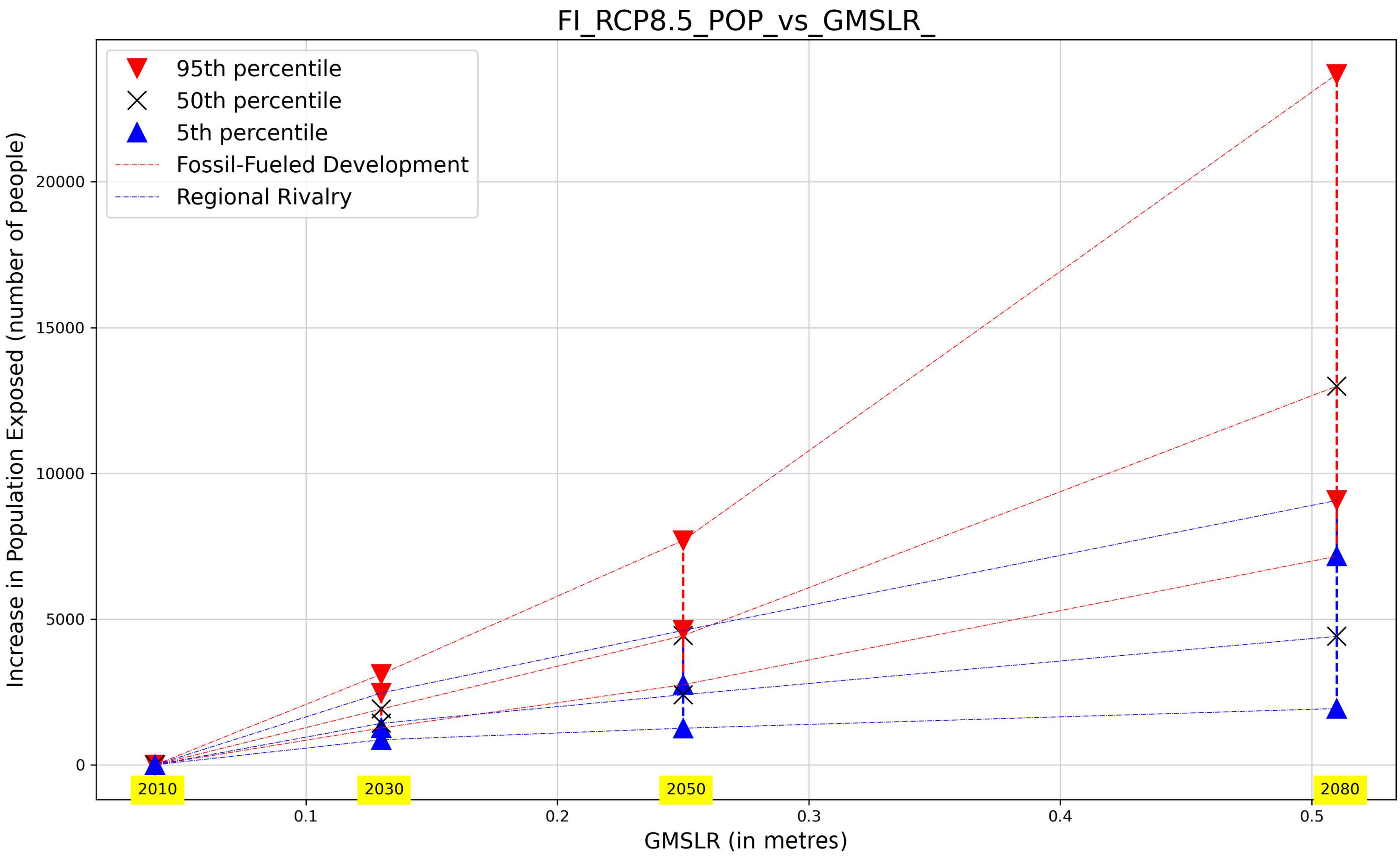



Figure C.20: Graph of FI_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.19: Overview of FI_POP_RCP8.5_vs_GMSLR values.

| Finland - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 860 | 1,424 | 2,464 | 1,265 | 1,912 | 3,110 |
| **2050** | 1,257 | 2,404 | 4,609 | 2,746 | 4,430 | 7,695 |
| **2080** | 1,931 | 4,408 | 9,071 | 7,156 | 12,988 | 23,692 |

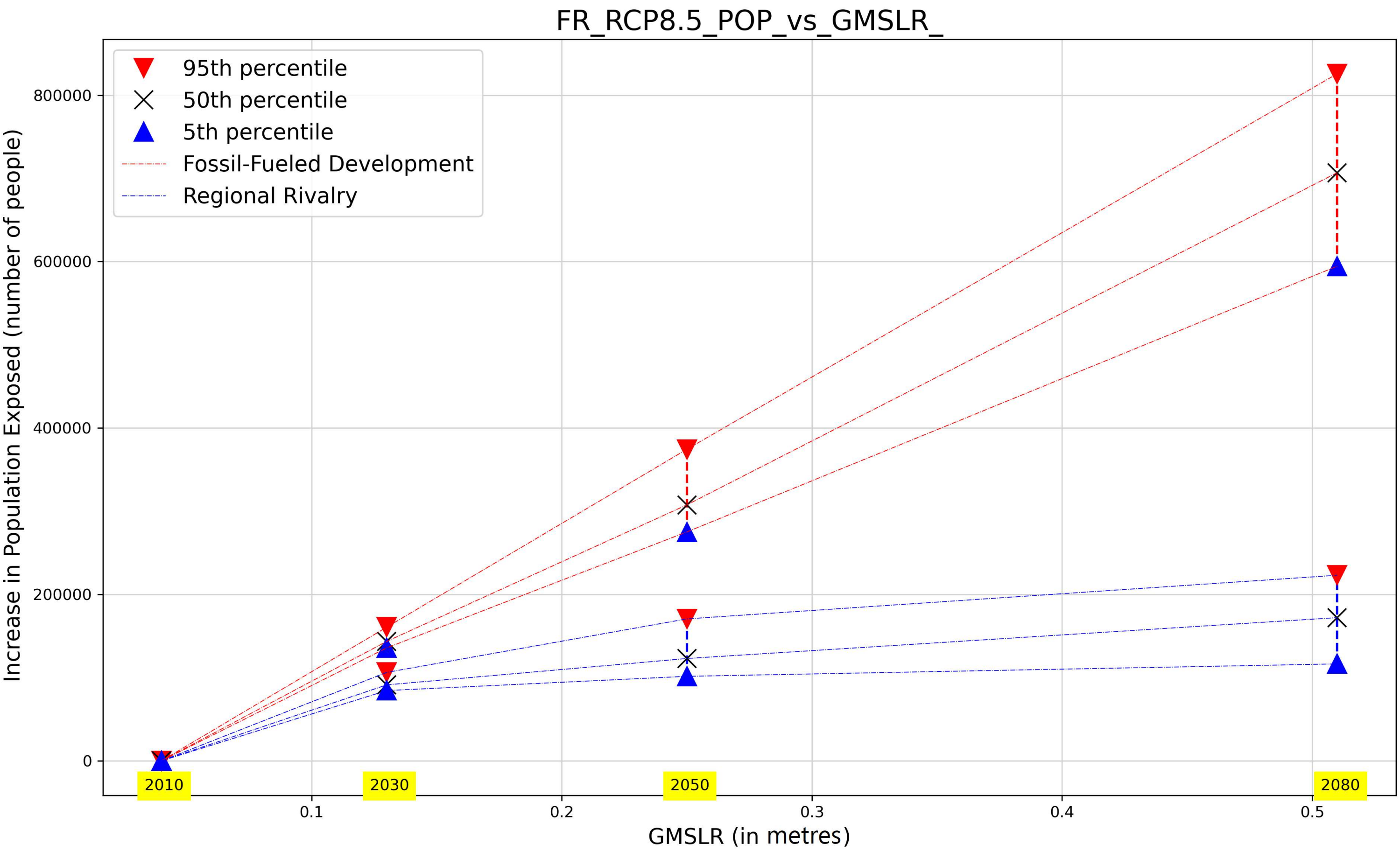



Figure C.21: Graph of FR_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.20: Overview of FR_POP_RCP8.5_vs_GMSLR values.

| France - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 84,405 | 91,250 | 106,239 | 135,680 | 143,492 | 160,601 |
| **2050** | 101,535 | 122,948 | 170,580 | 275,095 | 307,623 | 374,448 |
| **2080** | 116,470 | 172,104 | 223,030 | 594,552 | 706,929 | 825,844 |

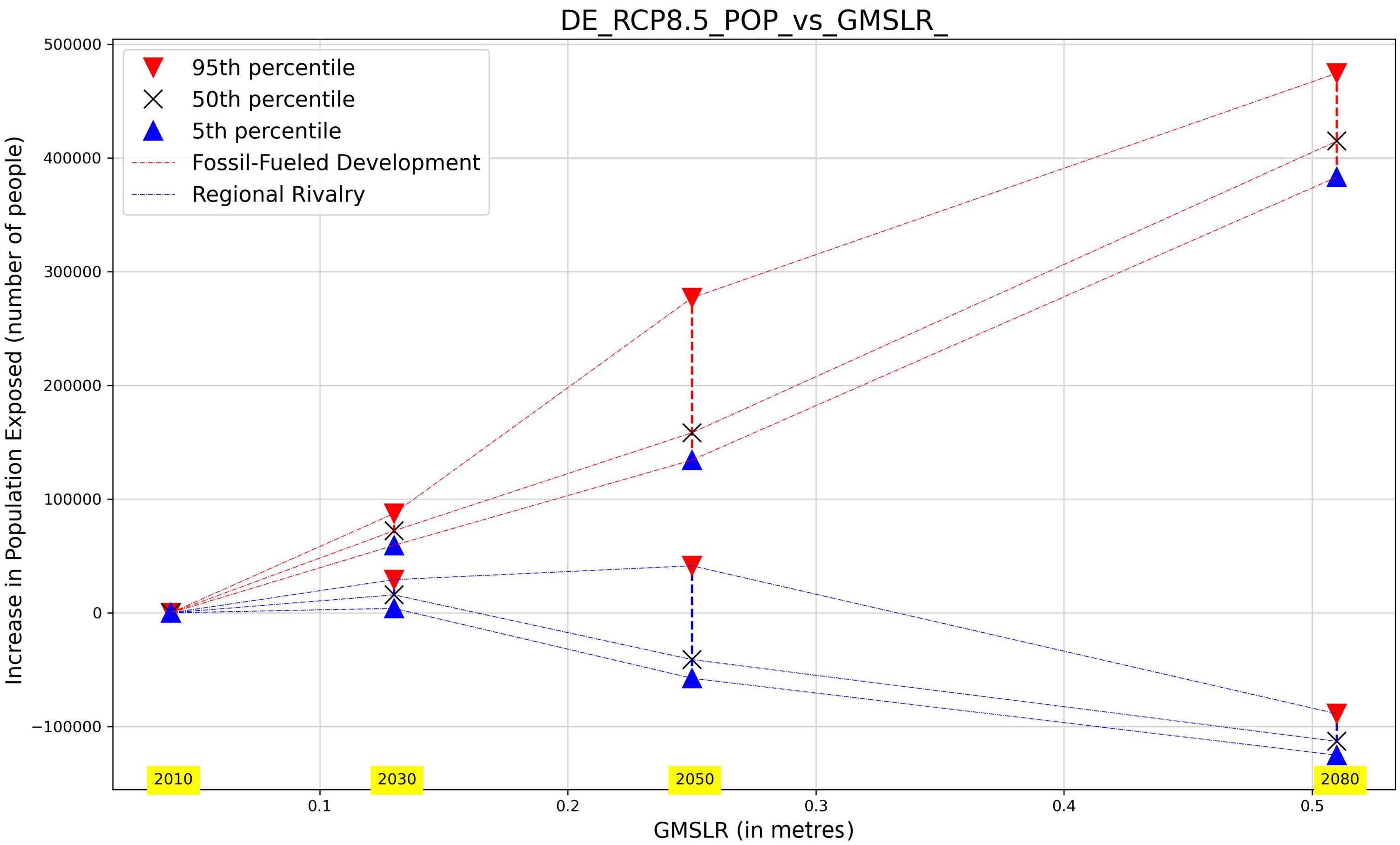



Figure C.22: Graph of DE_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.21: Overview of DE_POP_RCP8.5_vs_GMSLR values.

| Germany - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 3,904 | 15,772 | 29,171 | 59,384 | 72,216 | 87,426 |
| **2050** | -57,516 | -41,108 | 41,371 | 134,325 | 158,339 | 276,966 |
| **2080** | -125,191 | -112,970 | -88,761 | 383,205 | 414,814 | 474,548 |

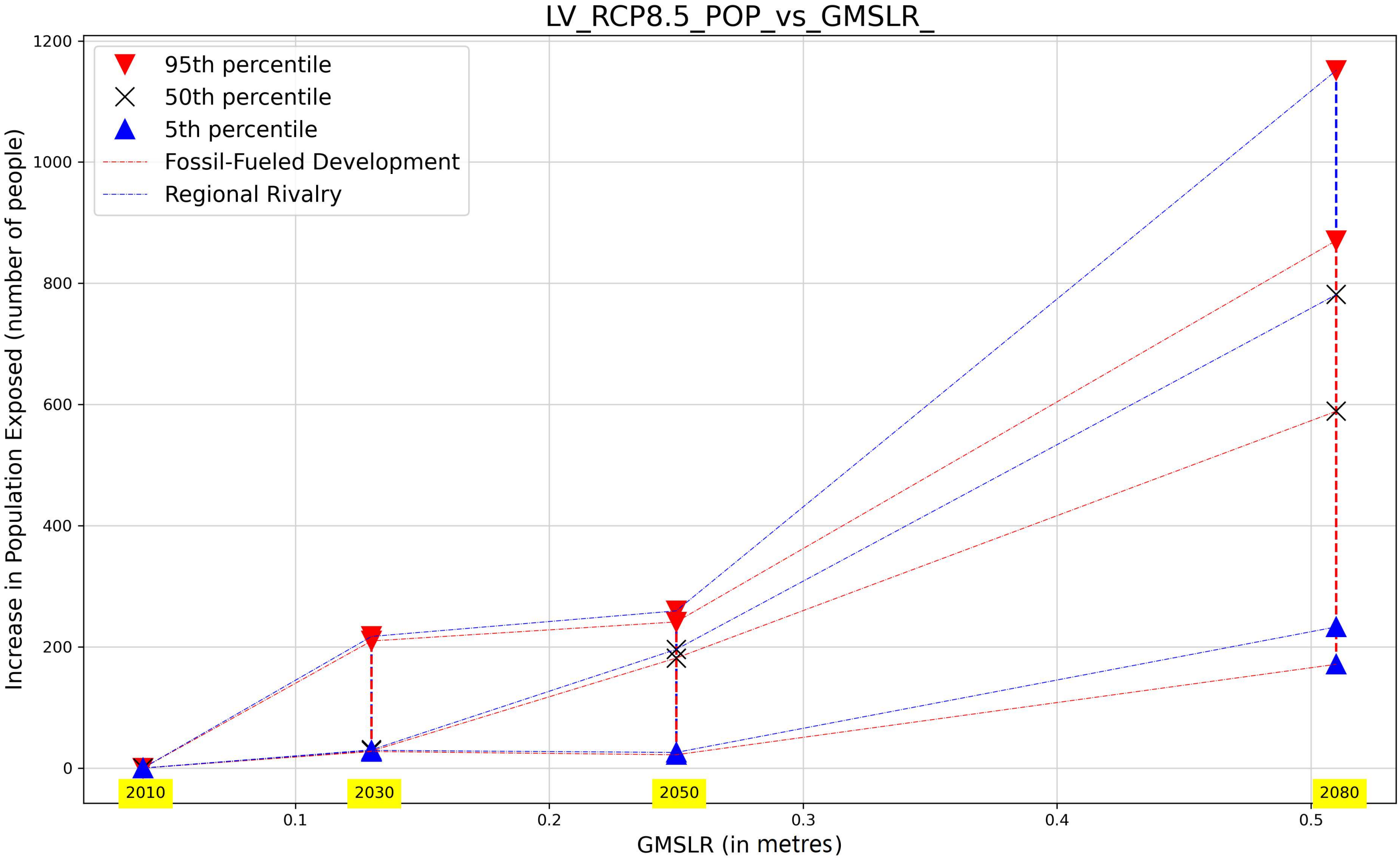



Figure C.23: Graph of LV_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.22: Overview of LV_POP_RCP8.5_vs_GMSLR values.

| Latvia - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 29 | 30 | 217 | 27 | 28 | 210 |
| **2050** | 26 | 195 | 259 | 21 | 181 | 241 |
| **2080** | 232 | 781 | 1.151 | 171 | 589 | 871 |

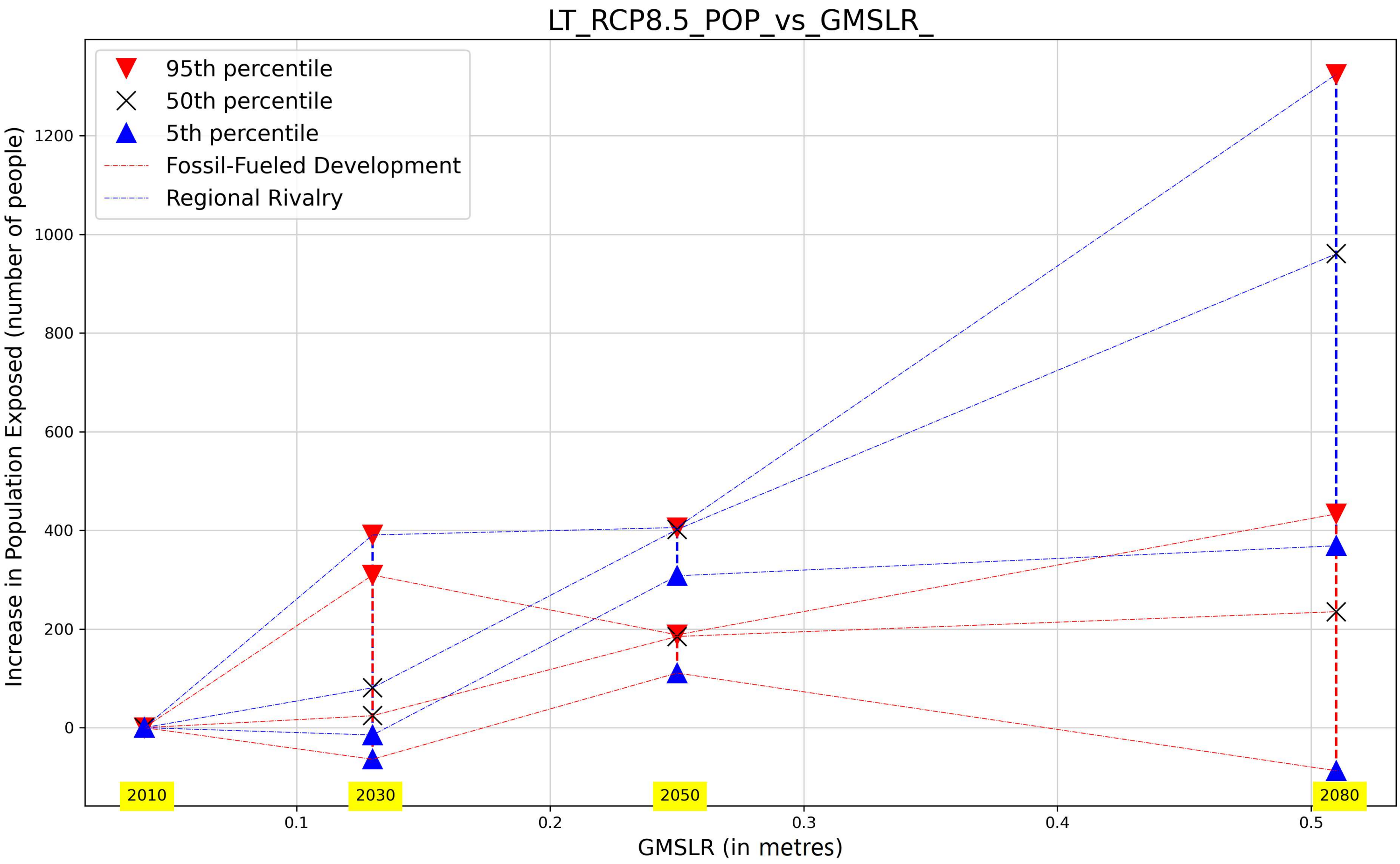



Figure C.24: Graph of LT_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.23: Overview of LT_POP_RCP8.5_vs_GMSLR values.

| Lithuania - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | -15 | 81 | 391 | -64 | 24 | 309 |
| **2050** | 308 | 401 | 406 | 111 | 185 | 188 |
| **2080** | 369 | 961 | 1,325 | -87 | 235 | 433 |

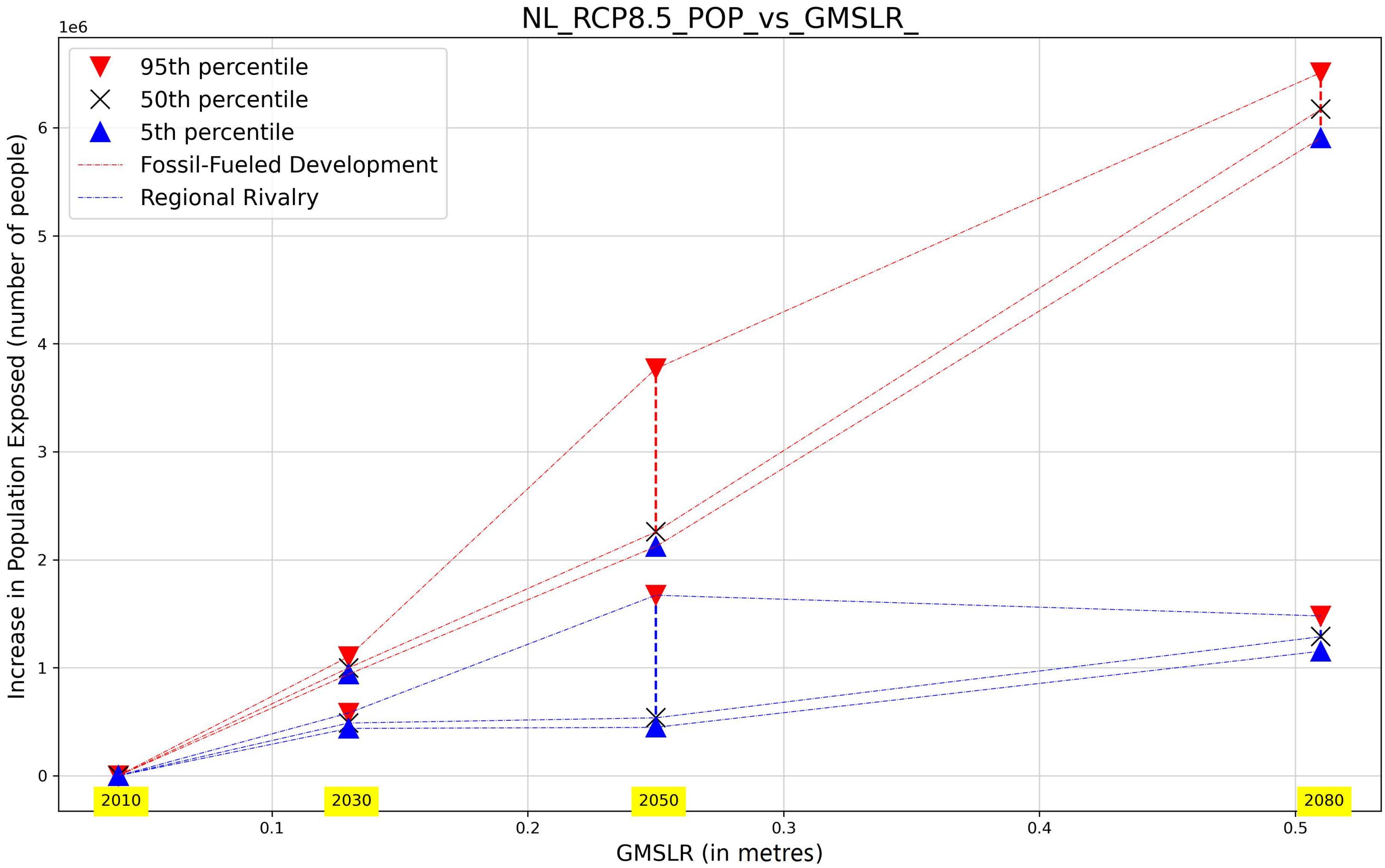



Figure C.25: Graph of NL_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.24: Overview of NL_POP_RCP8.5_vs_GMSLR values.

| the Netherlands - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 437,510 | 487,740 | 580,522 | 939,497 | 998,563 | 1,102,706 |
| **2050** | 447,445 | 535,649 | 1,671,082 | 2,120,814 | 2,257,329 | 3,768,765 |
| **2080** | 1,152,707 | 1,287,378 | 1,479,451 | 5,904,914 | 6,171,640 | 6,511,482 |

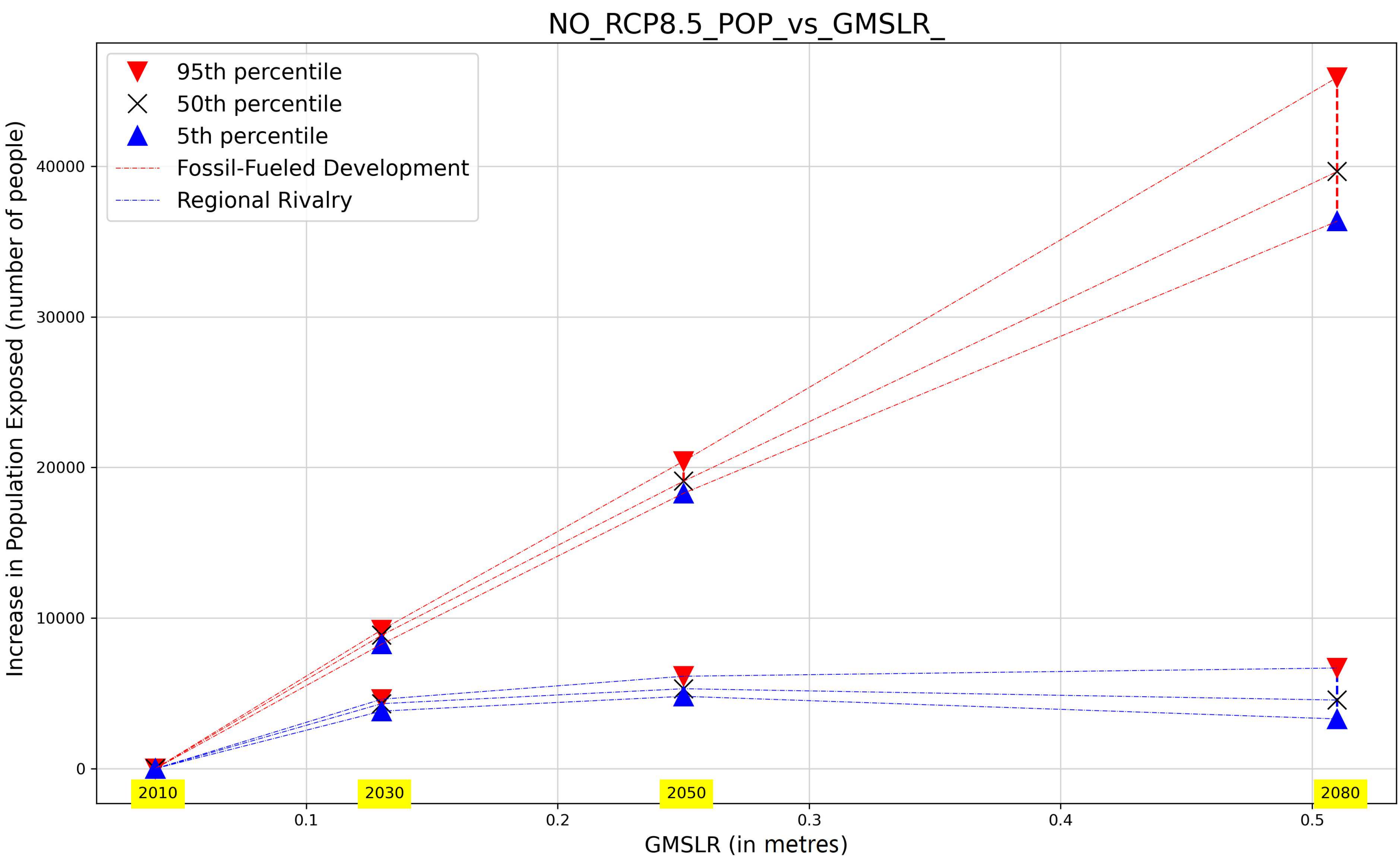



Figure C.26: Graph of NO_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.25: Overview of NO_POP_RCP8.5_vs_GMSLR values.

| Norway - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 3,821 | 4,314 | 4,609 | 8,267 | 8,861 | 9,215 |
| **2050** | 4,803 | 5,306 | 6,135 | 18,283 | 19,083 | 20,413 |
| **2080** | 3,301 | 4,553 | 6,681 | 36,356 | 39,655 | 45,907 |

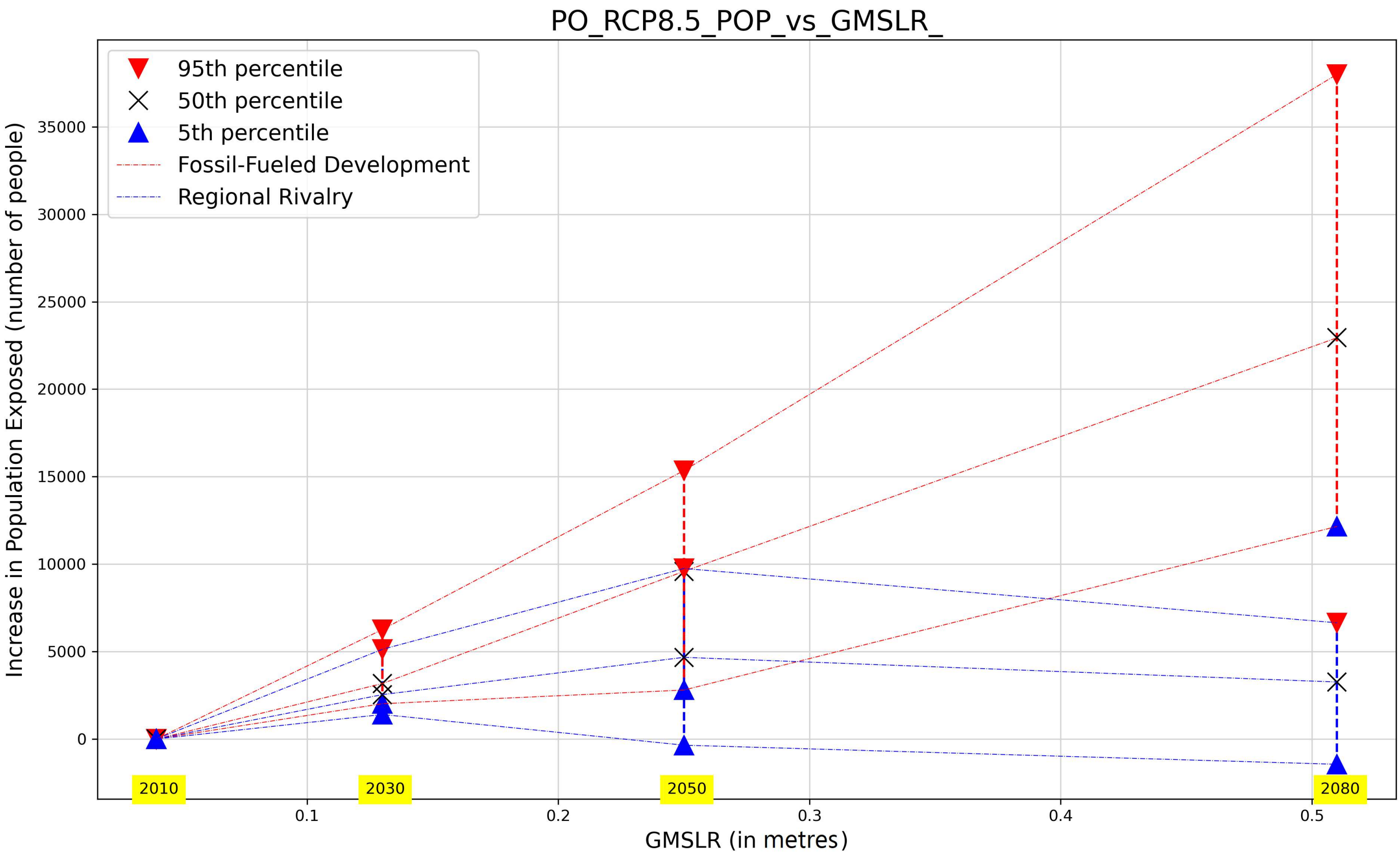



Figure C.27: Graph of PO_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.26: Overview of PO_POP_RCP8.5_vs_GMSLR values.

| Poland - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 1,403 | 2,538 | 5,128 | 2,019 | 3,171 | 6,261 |
| **2050** | -353 | 4,669 | 9,748 | 2,799 | 9,584 | 15,344 |
| **2080** | -1,445 | 3,258 | 6,644 | 12,154 | 22,941 | 38,006 |

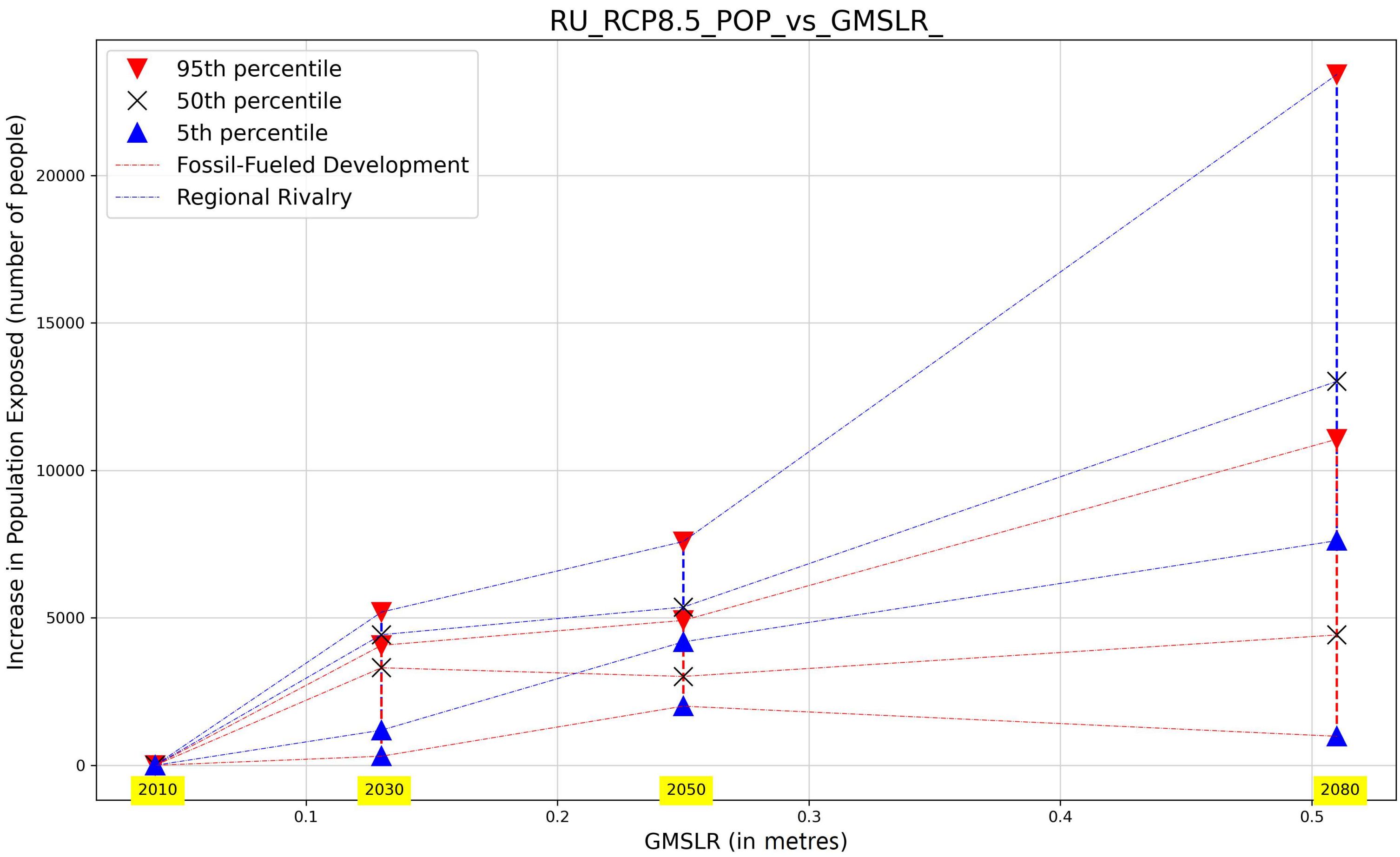



Figure C.28: Graph of RU_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.27: Overview of RU_POP_RCP8.5_vs_GMSLR values.

| Russia - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 1,191 | 4,429 | 5,195 | 308 | 3,307 | 4,068 |
| **2050** | 4,184 | 5,364 | 7,586 | 2,006 | 3,013 | 4,912 |
| **2080** | 7,620 | 13,023 | 23,430 | 983 | 4,420 | 11,059 |

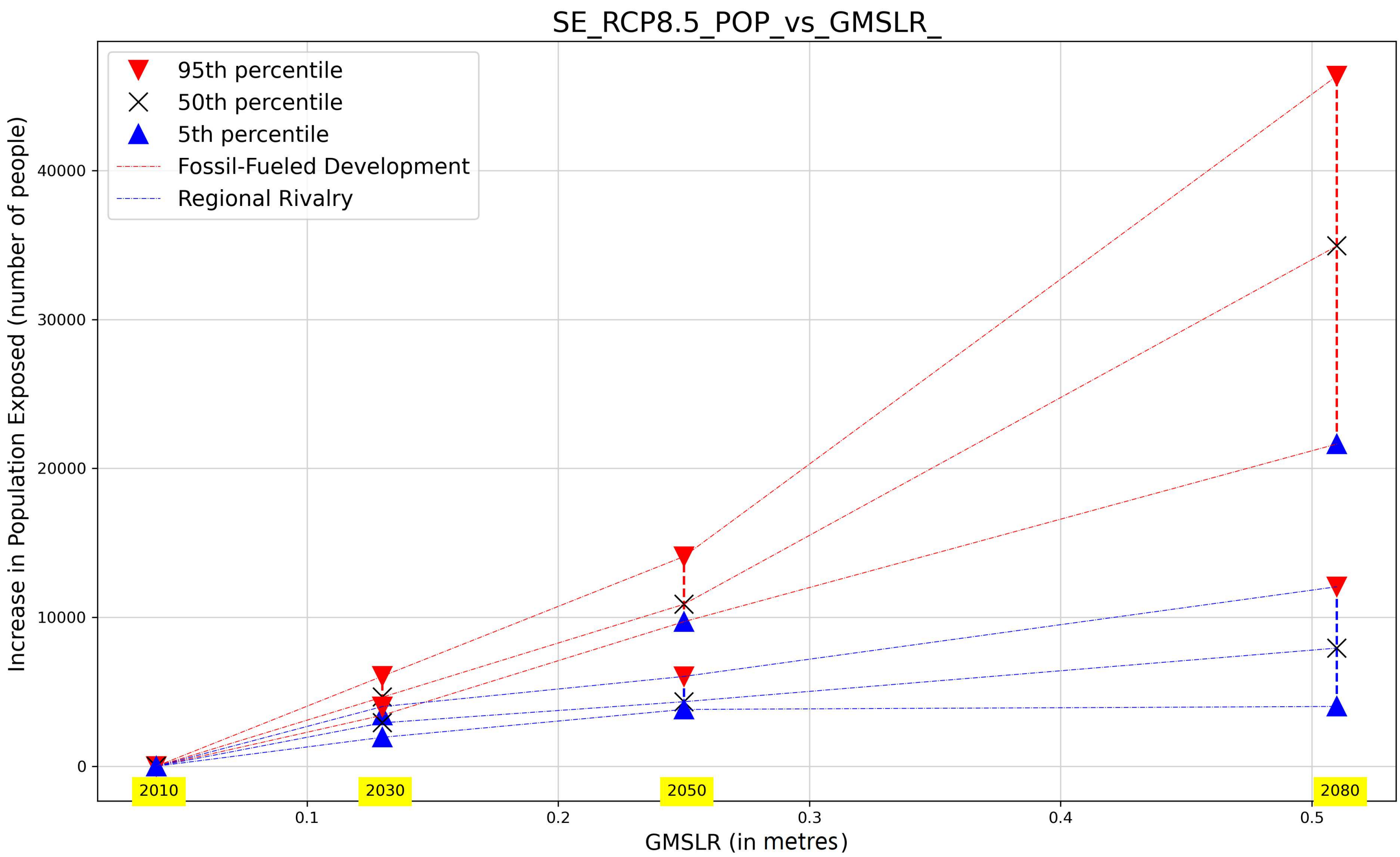



Figure C.29: Graph of SE_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.28: Overview of SE_POP_RCP8.5_vs_GMSLR values.

| Sweden - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 1,941 | 2,916 | 4,007 | 3,422 | 4,638 | 6,046 |
| **2050** | 3,814 | 4,332 | 6,028 | 9,702 | 10,872 | 14,078 |
| **2080** | 4,014 | 7,935 | 12,054 | 21,638 | 34,935 | 46,358 |

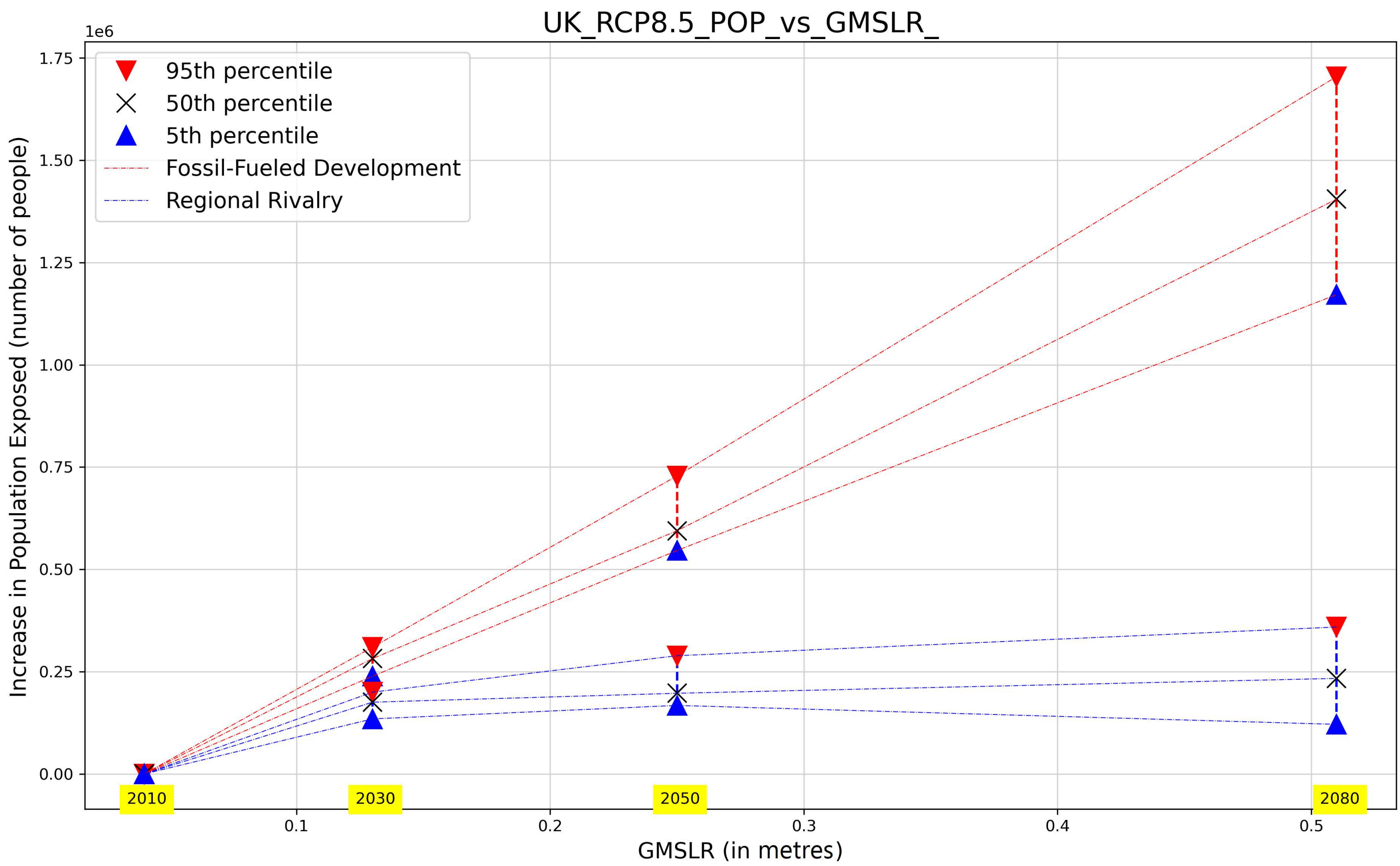



Figure C.30: Graph of UK_RCP8.5_RP1000_POP_vs_GMSLR.

Table C.29: Overview of UK_POP_RCP8.5_vs_GMSLR values.

| the United Kingdom - Population (number of people) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 138,579 | 175,459 | 199,945 | 238,922 | 281,977 | 309,851 |
| **2050** | 167,502 | 197,224 | 288,998 | 546,237 | 594,476 | 728,347 |
| **2080** | 121,261 | 233,551 | 359,106 | 1,171,620 | 1,405,090 | 1,704,542 |

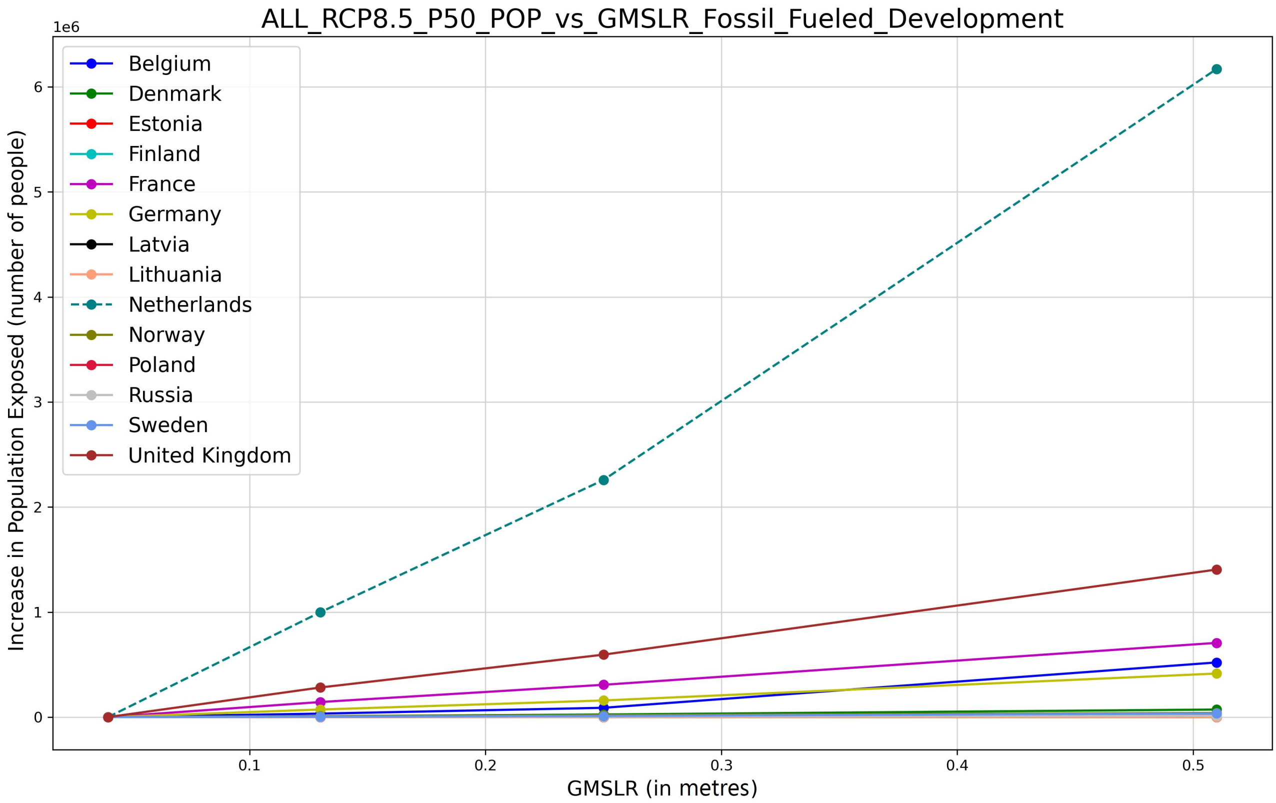



Figure C.31: Graph of ALL_RCP8.5_RP1000_POP_vs_GMSLR.

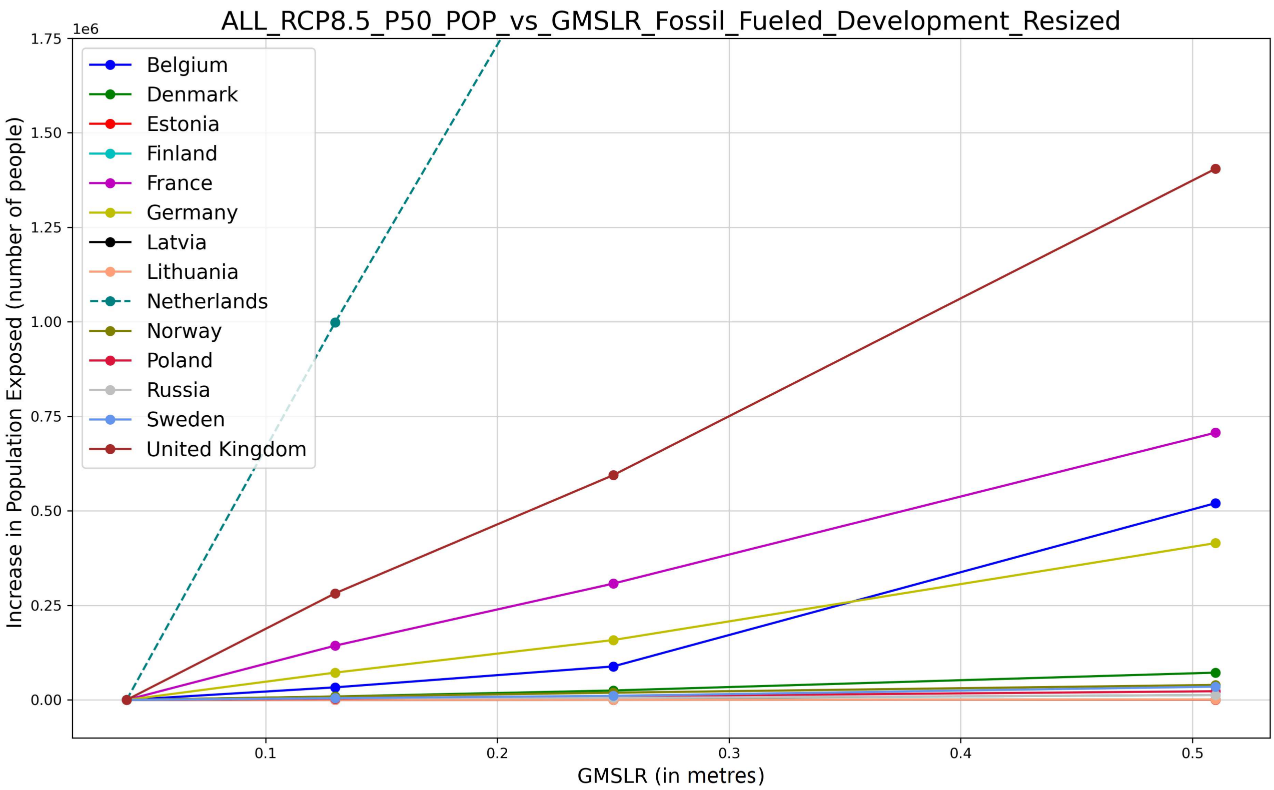



Figure C.32: Graph of ALL_RCP8.5_RP1000_POP_vs_GMSLR_Resized.

## C.4. Economic Damages - Base Values

Table C.30: Overview of the base values for indicator Economic Damages (in US$) for all countries.

| Country | FP Standard RP | Base Value |
|---|---|---|
| Belgium | 1000 | 3,460,581,680 US$ |
| Denmark | 500 | 1,275,368,243 US$ |
| Estonia | 100 | 13,129,504 US$ |
| Finland | 100 | 45,071,451 US$ |
| France | 100 | 4,551,408,678 US$ |
| Germany | 100 | 16,736,100,728 US$ |
| Latvia | 100 | 1,666,499 US$ |
| Lithuania | 100 | 8,268,557 US$ |
| the Netherlands | 1000 | 89,491,607,392 US$ |
| Norway | 100 | 244,225,941 US$ |
| Poland | 100 | 618,857,628 US$ |
| Russia | 500 | 325,196,224 US$ |
| Sweden | 100 | 194,225,745 US$ |
| the United Kingdom | 500 | 11,422,121,900 US$ |

## C.5. Economic Damages - RCP4.5

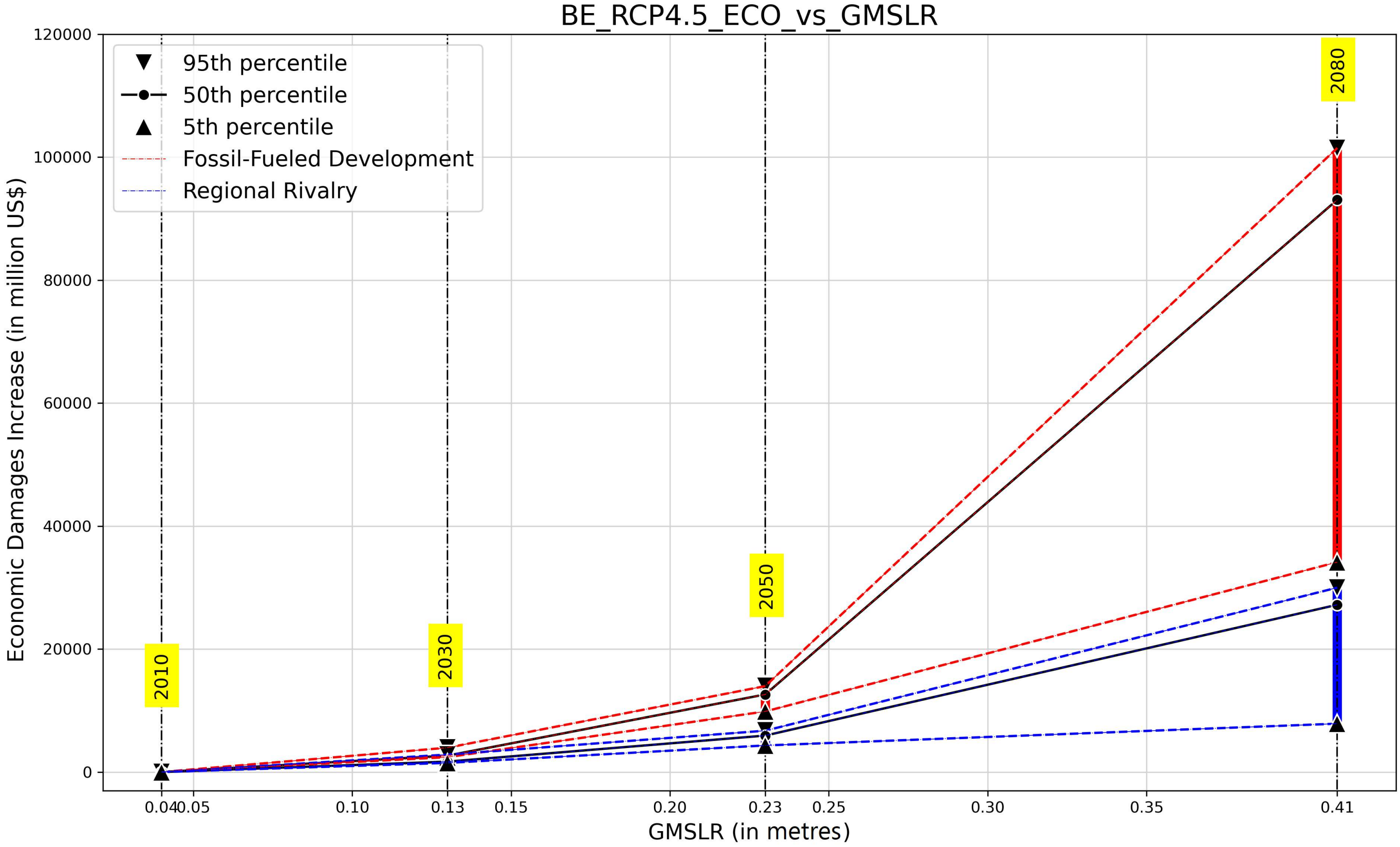



Figure C.33: Graph of BE_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.31: Overview of BE_ECO_RCP4.5_vs_GMSLR values.

| Belgium - Economic Damages (million US$) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 1,489.5 | 1,697.1 | 2,839.4 | 2,424.6 | 2,671.3 | 3,963.0 |
| **2050** | 4,326.7 | 5,929.6 | 6,724.0 | 9,856.3 | 12,621.2 | 13,978.3 |
| **2080** | 7,869.3 | 27,206.8 | 29,991.2 | 34,147.4 | 93,071.2 | 101,494.3 |

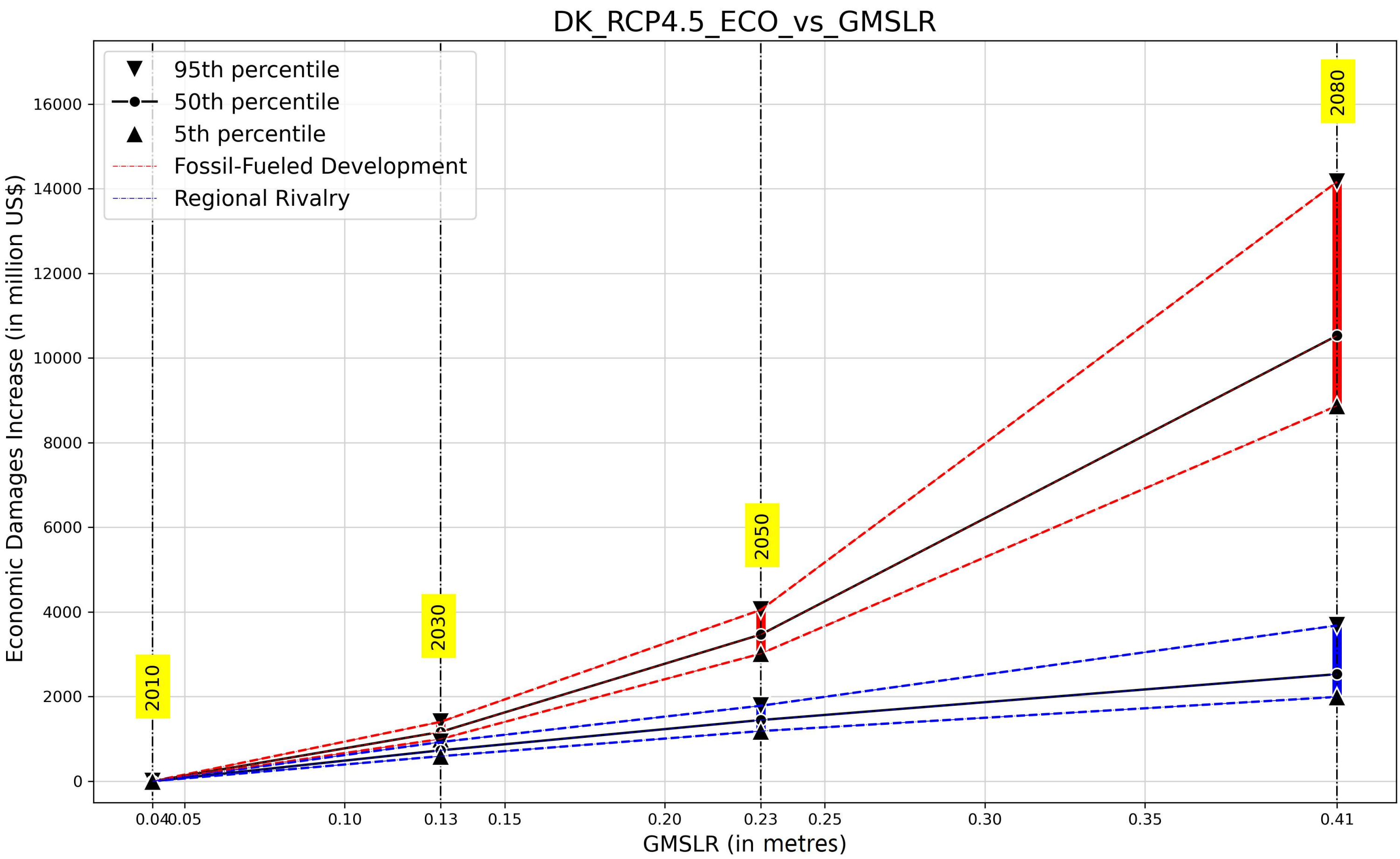



Figure C.34: Graph of DK_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.32: Overview of DK_ECO_RCP4.5_vs_GMSLR values.

| **Denmark - Economic Damages (million US$) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 591.8 | 729.7 | 925.9 | 997.5 | 1,165.4 | 1,403.4 |
| **2050** | 1,185.1 | 1,445.6 | 1,783.6 | 3,014.7 | 3,465.9 | 4,049.4 |
| **2080** | 1,992.8 | 2,530.0 | 3,679.9 | 8,872.6 | 10,530.3 | 14,166.0 |

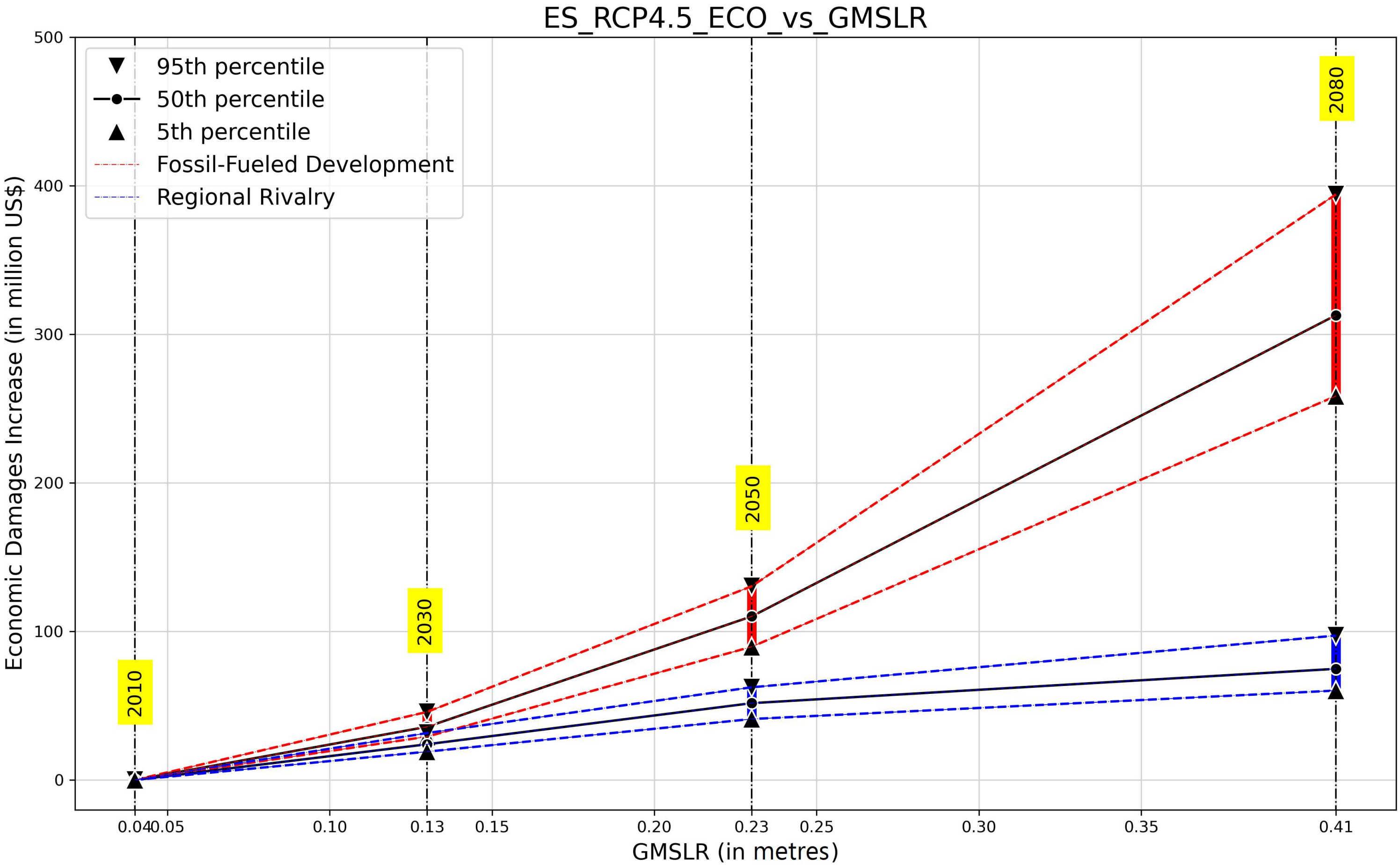



Figure C.35: Graph of ES_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.33: Overview of DK_ECO_RCP4.5_vs_GMSLR values.

| **Estonia - Economic Damages (million US$) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 19.1 | 24.0 | 31.6 | 29.2 | 35.8 | 45.9 |
| **2050** | 41.0 | 51.7 | 62.4 | 89.7 | 110.1 | 130.4 |
| **2080** | 60.2 | 74.8 | 97.2 | 258.5 | 321.9 | 394.2 |

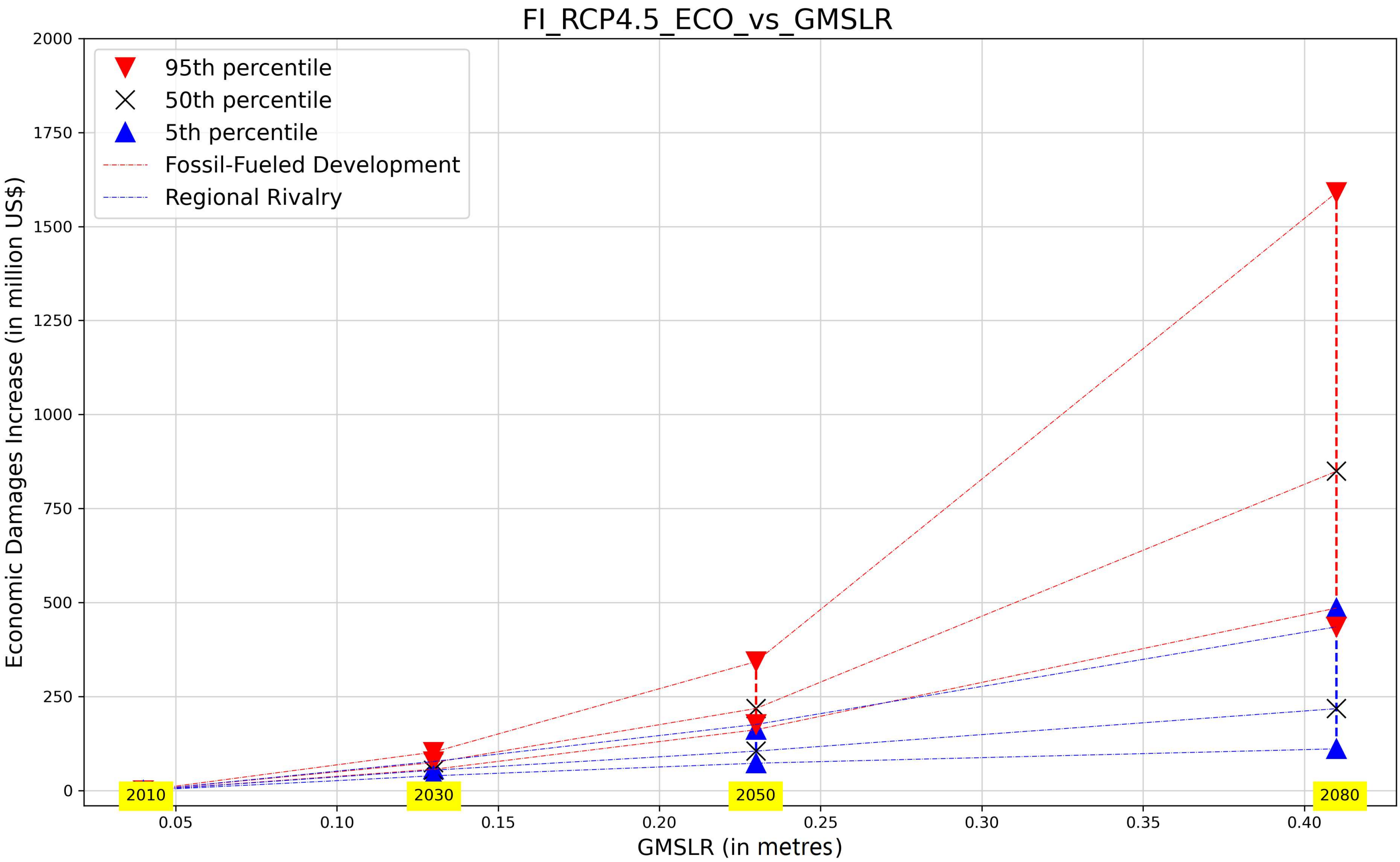



Figure C.36: Graph of FI_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.34: Overview of FI_ECO_RCP4.5_vs_GMSLR values.

| **Finland - Economic Damages (million US$) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 38.9 | 53.8 | 77.0 | 56.1 | 74.1 | 102.0 |
| **2050** | 72.3 | 104.5 | 175.5 | 161.3 | 218.0 | 342.7 |
| **2080** | 110.6 | 217.5 | 435.2 | 485.1 | 849.2 | 1,590.7 |

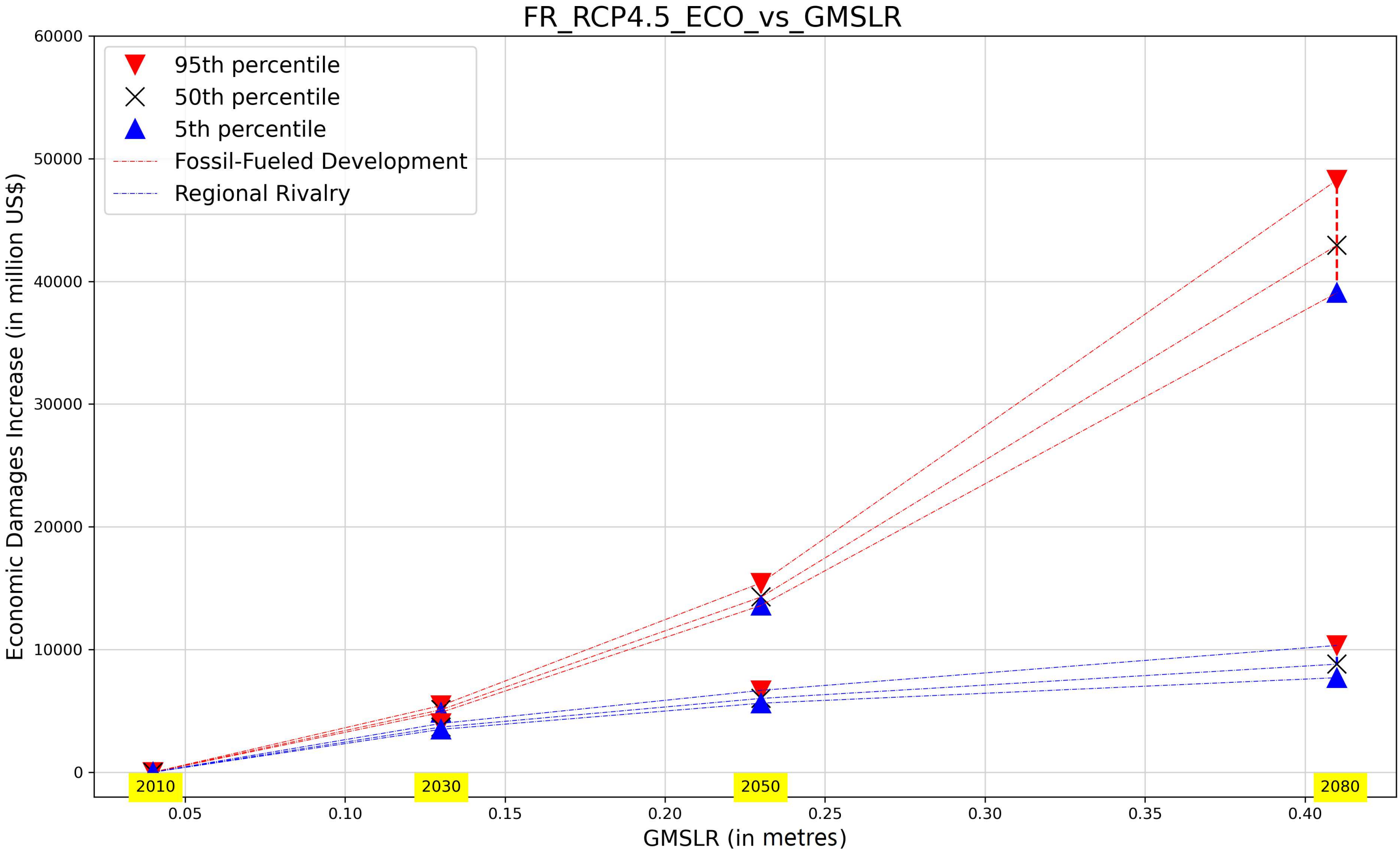



Figure C.37: Graph of FR_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.35: Overview of FR_ECO_RCP4.5_vs_GMSLR values.

| France - Economic Damages (million US$) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 3,490.8 | 3,678.8 | 3,971.6 | 4,870.4 | 5,089.2 | 5,429.8 |
| **2050** | 5,622.1 | 6,013.3 | 6,666.6 | 13,586.9 | 14,273.3 | 15,426.0 |
| **2080** | 7,701.9 | 8,804.2 | 10,329.8 | 39,076.8 | 42,949.1 | 48,272.3 |

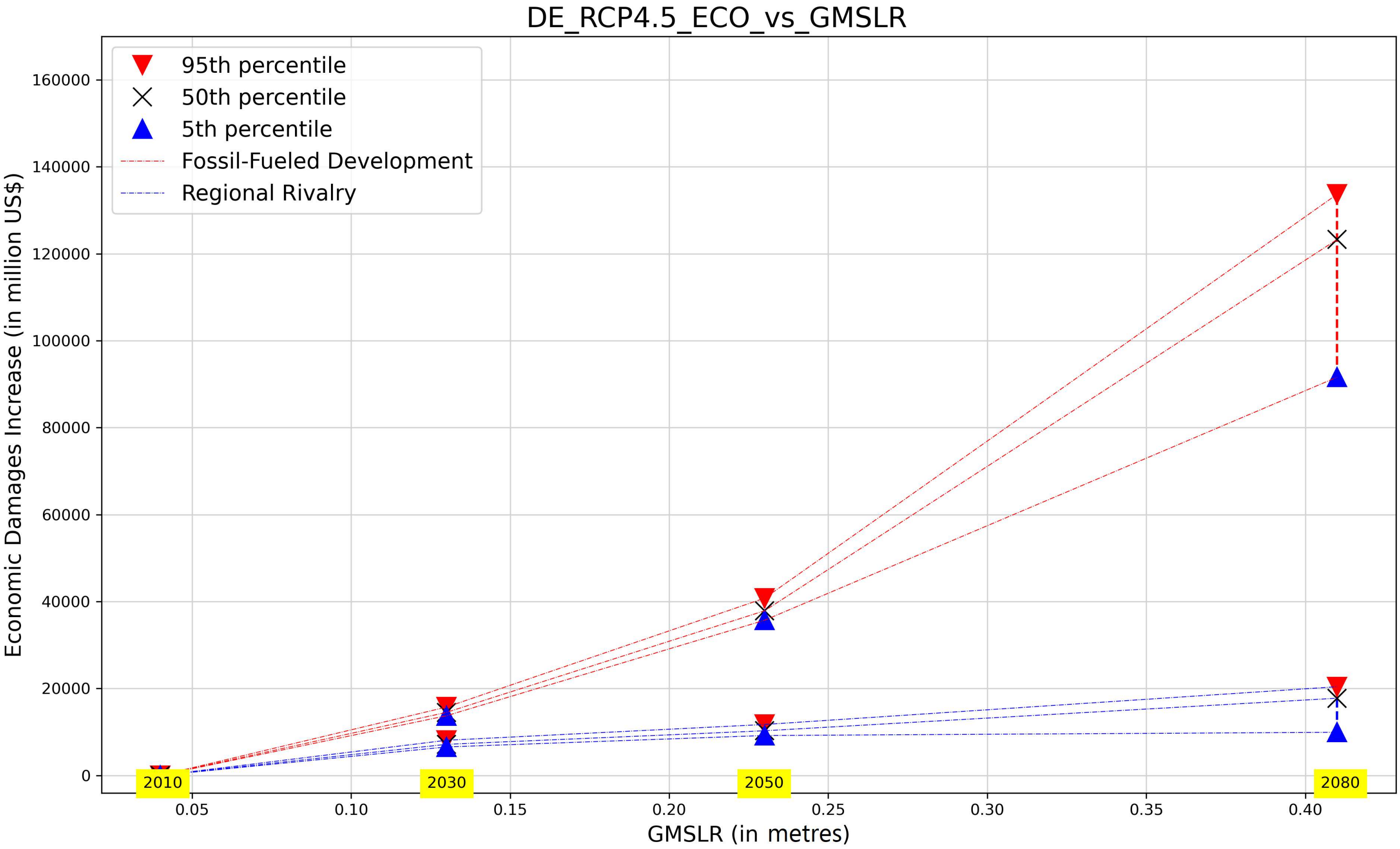



Figure C.38: Graph of DE_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.36: Overview of DE_ECO_RCP4.5_vs_GMSLR values.

| **Germany - Economic Damages (million US$) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 6,553.8 | 7,150.6 | 8,085.5 | 13,729.4 | 14,505.5 | 15,720.6 |
| **2050** | 9,181.3 | 10,272.6 | 11,718.1 | 35,697.3 | 37,878.7 | 40,774.6 |
| **2080** | 9,921.1 | 17,764.3 | 20,408.5 | 91,617.5 | 123,291.3 | 133,710.9 |

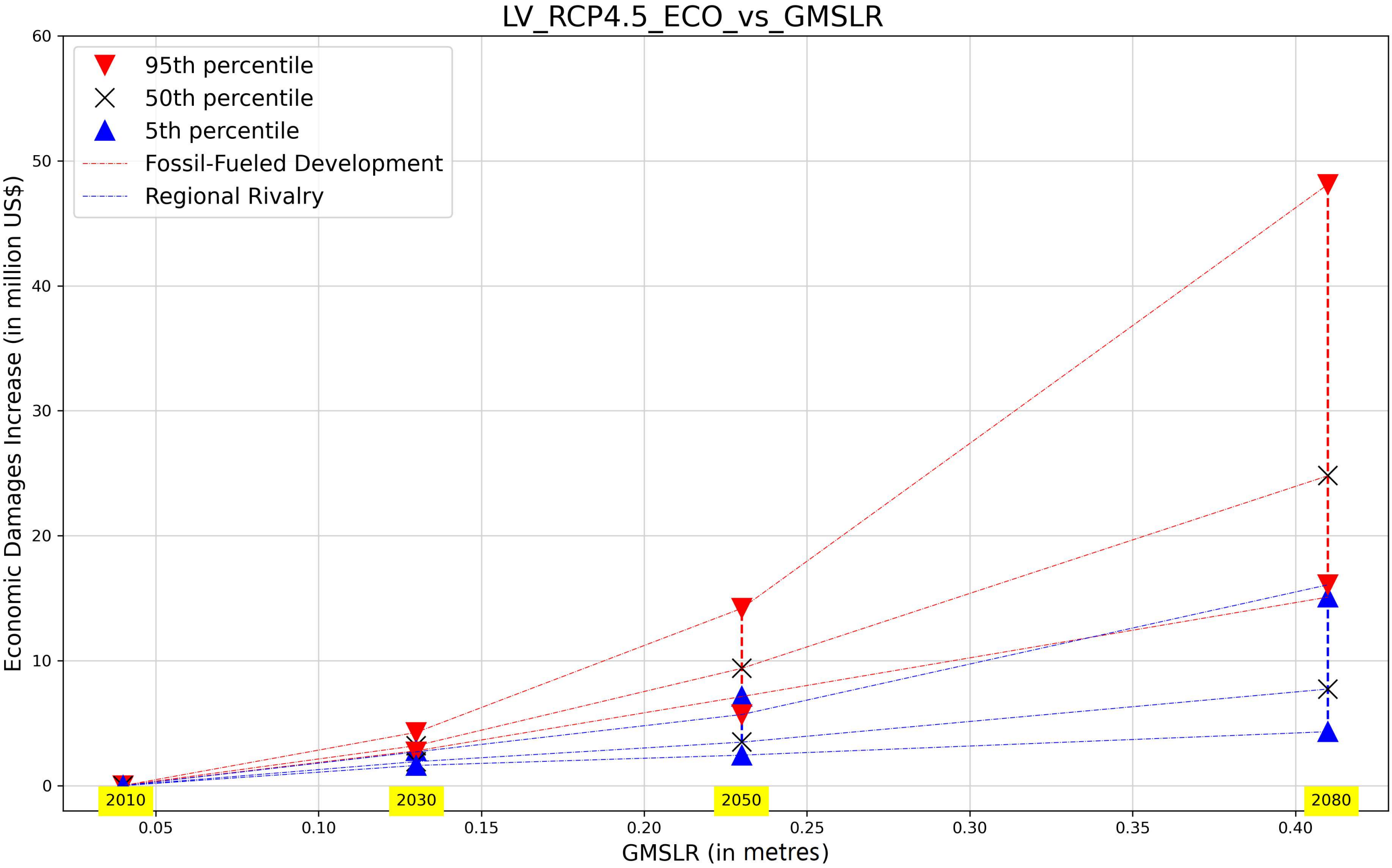



Figure C.39: Graph of LV_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.37: Overview of LV_ECO_RCP4.5_vs_GMSLR values.

| Latvia - Economic Damages (million US$) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 1.6 | 1.9 | 2.7 | 2.8 | 3.2 | 4.3 |
| **2050** | 2.4 | 3.4 | 5.7 | 7.1 | 9.4 | 14.2 |
| **2080** | 4.3 | 7.7 | 16.1 | 15.1 | 24.8 | 48.1 |

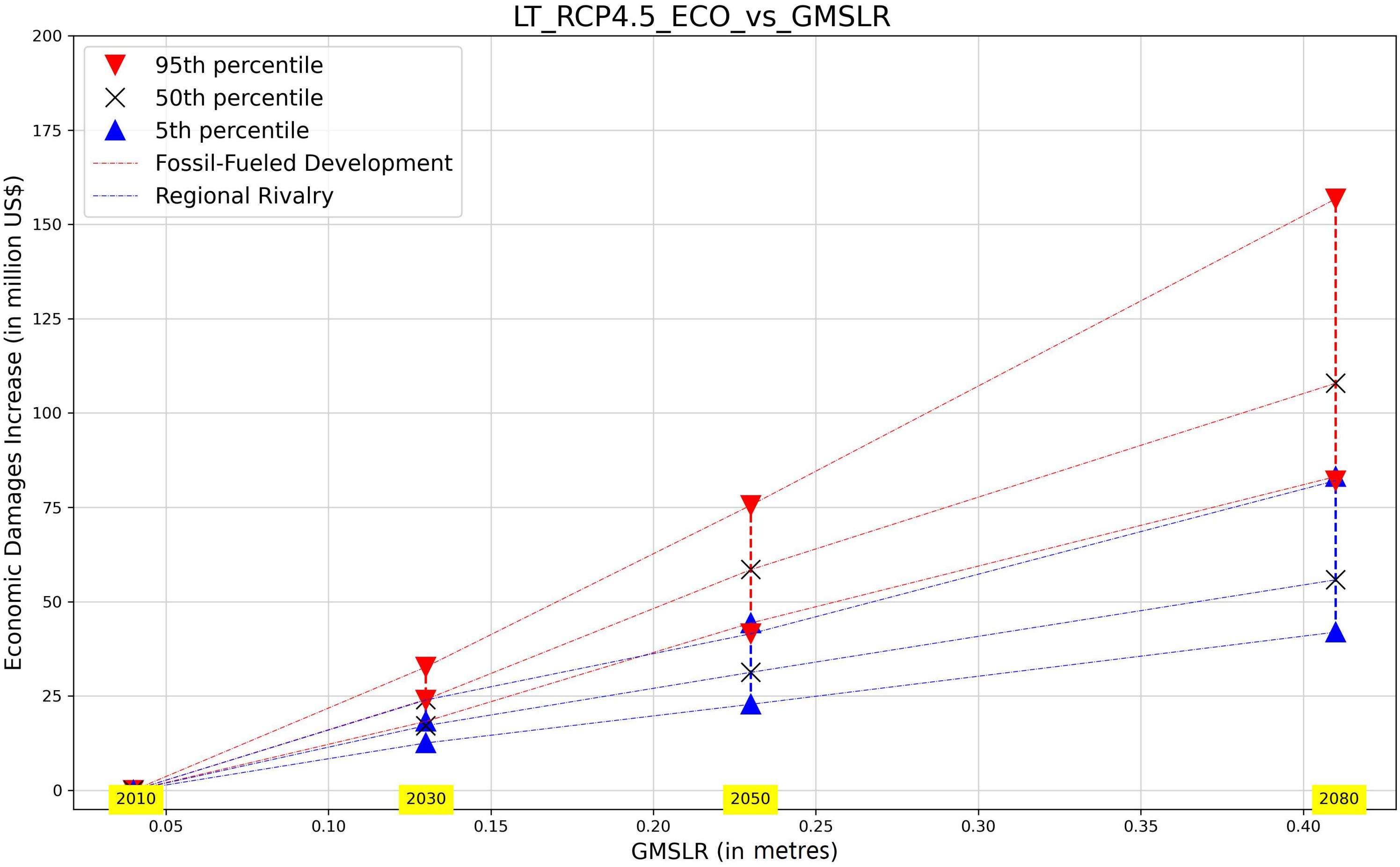



Figure C.40: Graph of LT_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.38: Overview of LT_ECO_RCP4.5_vs_GMSLR values.

| **Lithuania - Economic Damages (million US$) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 12.5 | 17.1 | 23.9 | 18.3 | 24.1 | 32.7 |
| **2050** | 22.8 | 31.3 | 41.5 | 44.3 | 58.5 | 75.6 |
| **2080** | 41.9 | 55.8 | 82.1 | 83.1 | 107.9 | 156.8 |

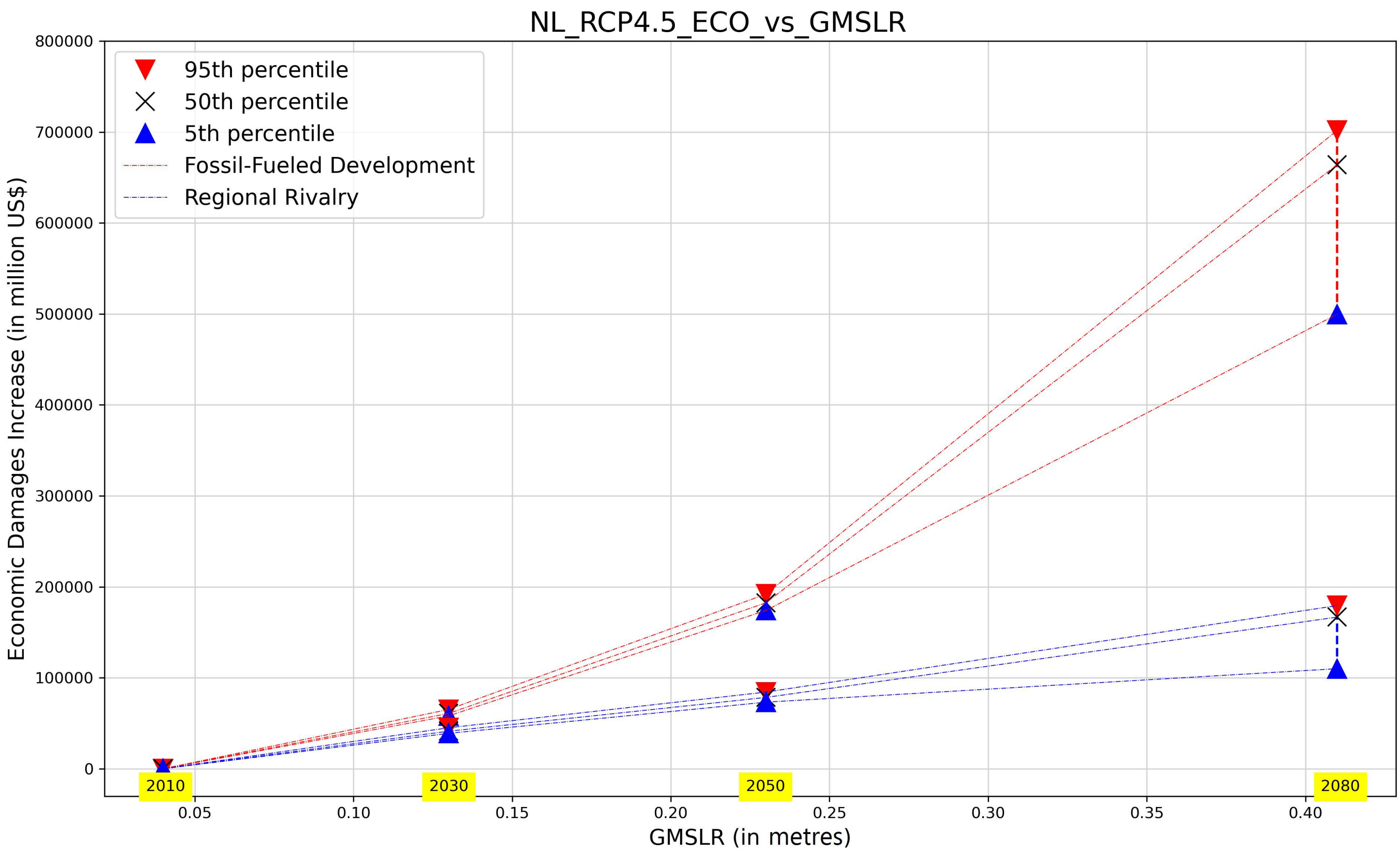



Figure C.41: Graph of NO_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.39: Overview of NL_ECO_RCP4.5_vs_GMSLR values.

| the Netherlands - Economic Damages (million US$) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 38,928.8 | 41,278.6 | 45,053.6 | 58,124.0 | 60,828.0 | 65,182.7 |
| **2050** | 73,199.8 | 78,416.4 | 84,293.9 | 174,058.9 | 182,493.3 | 191,994.0 |
| **2080** | 110,005.0 | 166,723.7 | 179,381.4 | 499,695.7 | 664,051.6 | 701,874.5 |

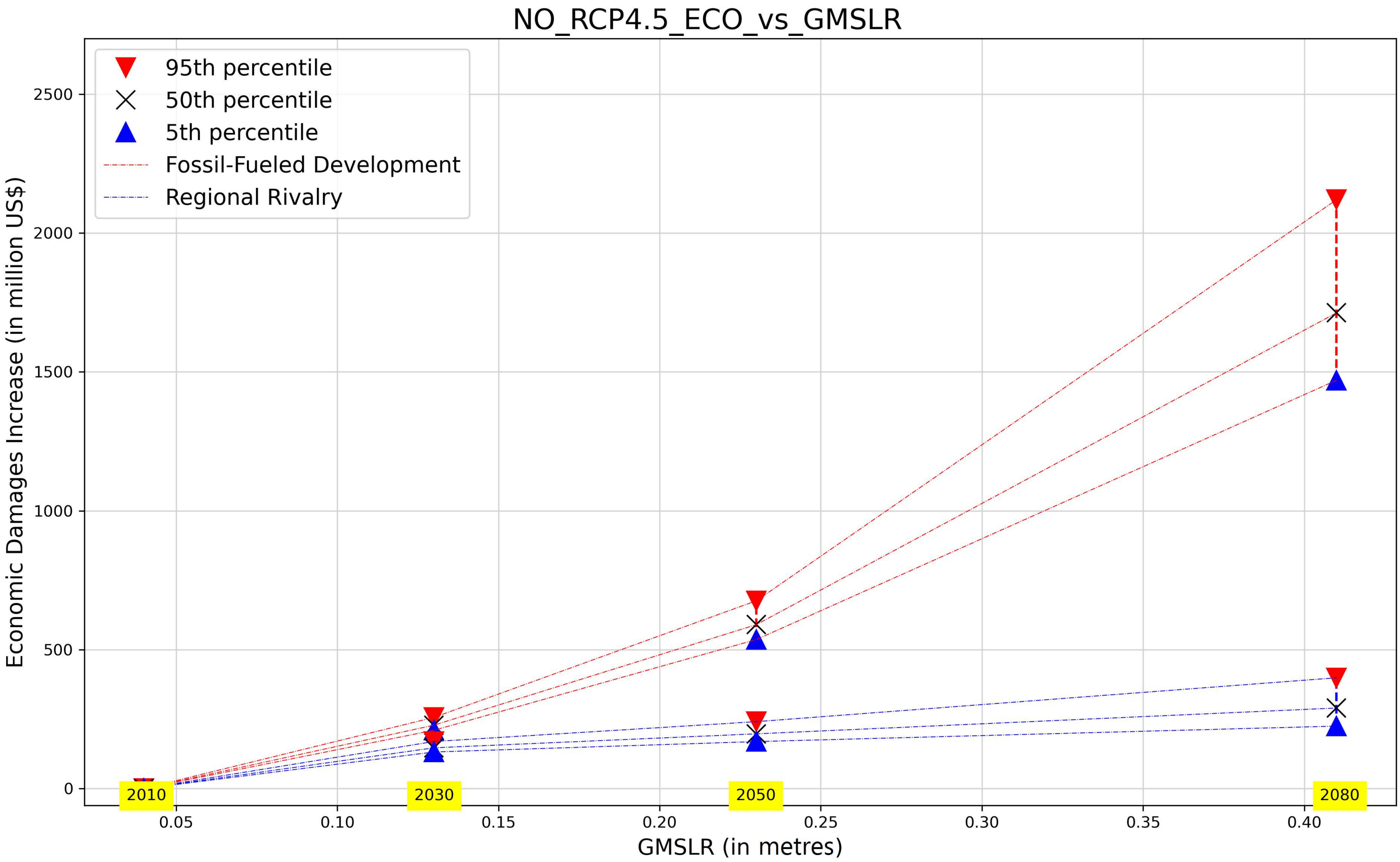



Figure C.42: Graph of NO_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.40: Overview of NO_ECO_RCP4.5_vs_GMSLR values.

| Norway - Economic Damages (million US$) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 131.7 | 146.7 | 169.4 | 209.9 | 228.2 | 256.1 |
| **2050** | 169.1 | 197.0 | 240.8 | 536.4 | 590.0 | 676.0 |
| **2080** | 224.8 | 290.0 | 398.8 | 1,469.8 | 1,712.4 | 2,119.9 |

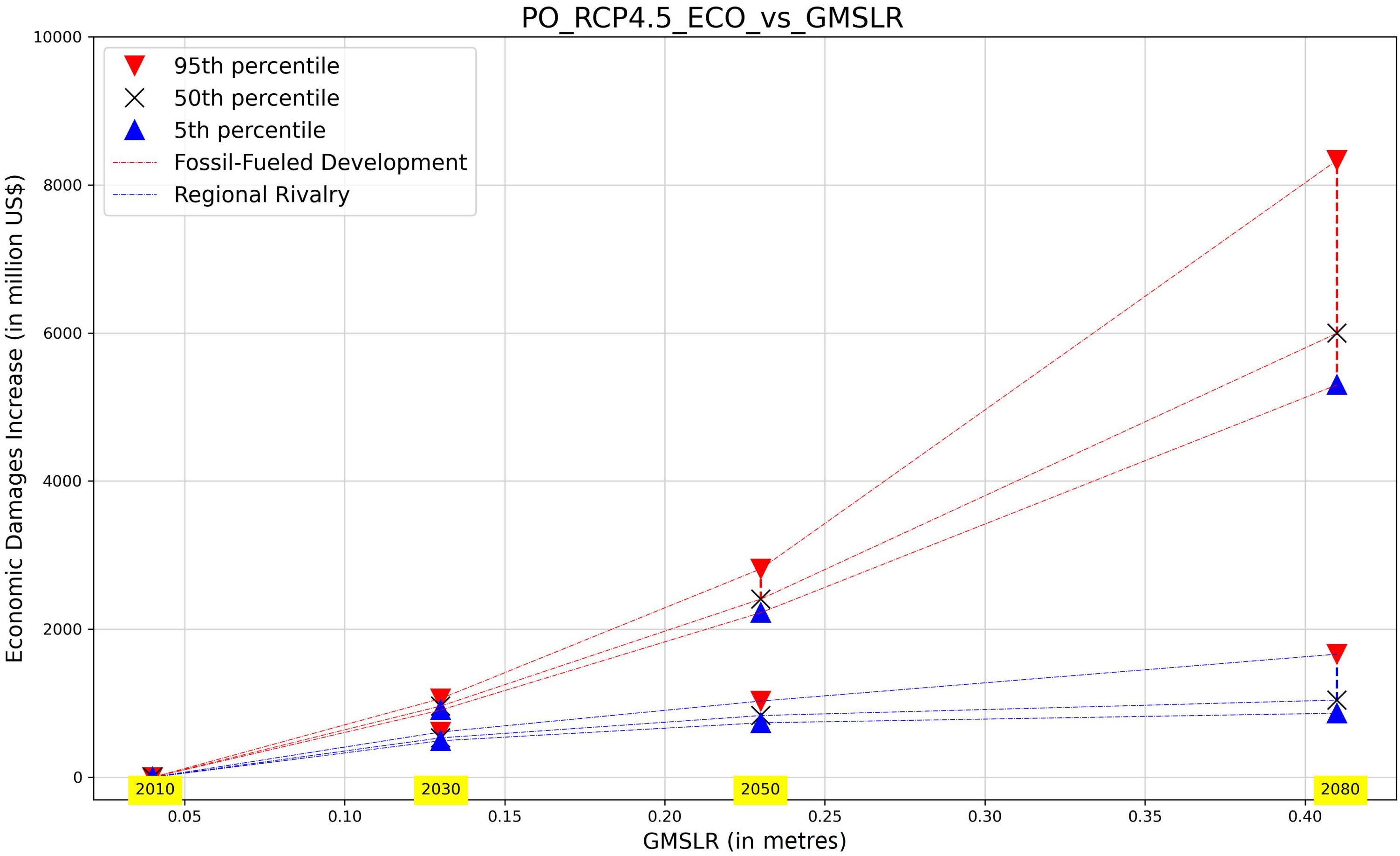



Figure C.43: Graph of PO_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.41: Overview of PO_ECO_RCP4.5_vs_GMSLR values.

| **Poland - Economic Damages (million US$) - RCP4.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 493.1 | 532.1 | 611.2 | 907.7 | 961.1 | 1,061.7 |
| **2050** | 735.4 | 833.3 | 1,029.2 | 2,223.2 | 2,406.4 | 2,814.1 |
| **2080** | 865.1 | 1,042.5 | 1,662.8 | 5,299.9 | 5,997.5 | 8,334.3 |

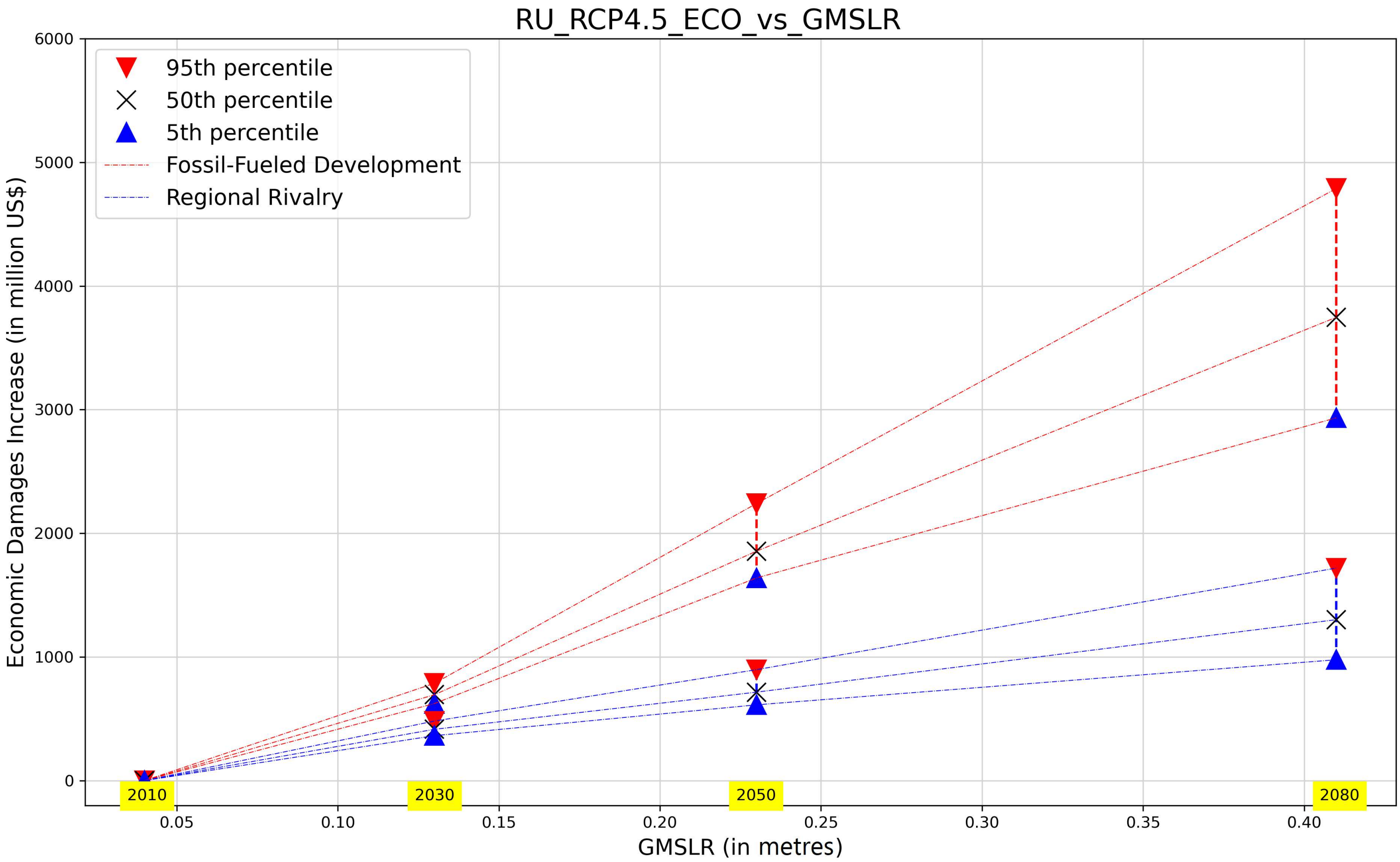



Figure C.44: Graph of RU_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.42: Overview of RU_ECO_RCP4.5_vs_GMSLR values.

| Russia - Economic Damages (million US$) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 363.2 | 414.6 | 481.3 | 622.9 | 694.2 | 786.5 |
| **2050** | 612.6 | 715.2 | 897.1 | 1,638.8 | 1,855.6 | 2,241.0 |
| **2080** | 977.2 | 1,301.4 | 1,718.8 | 2,923.4 | 3,746.9 | 4,788.9 |

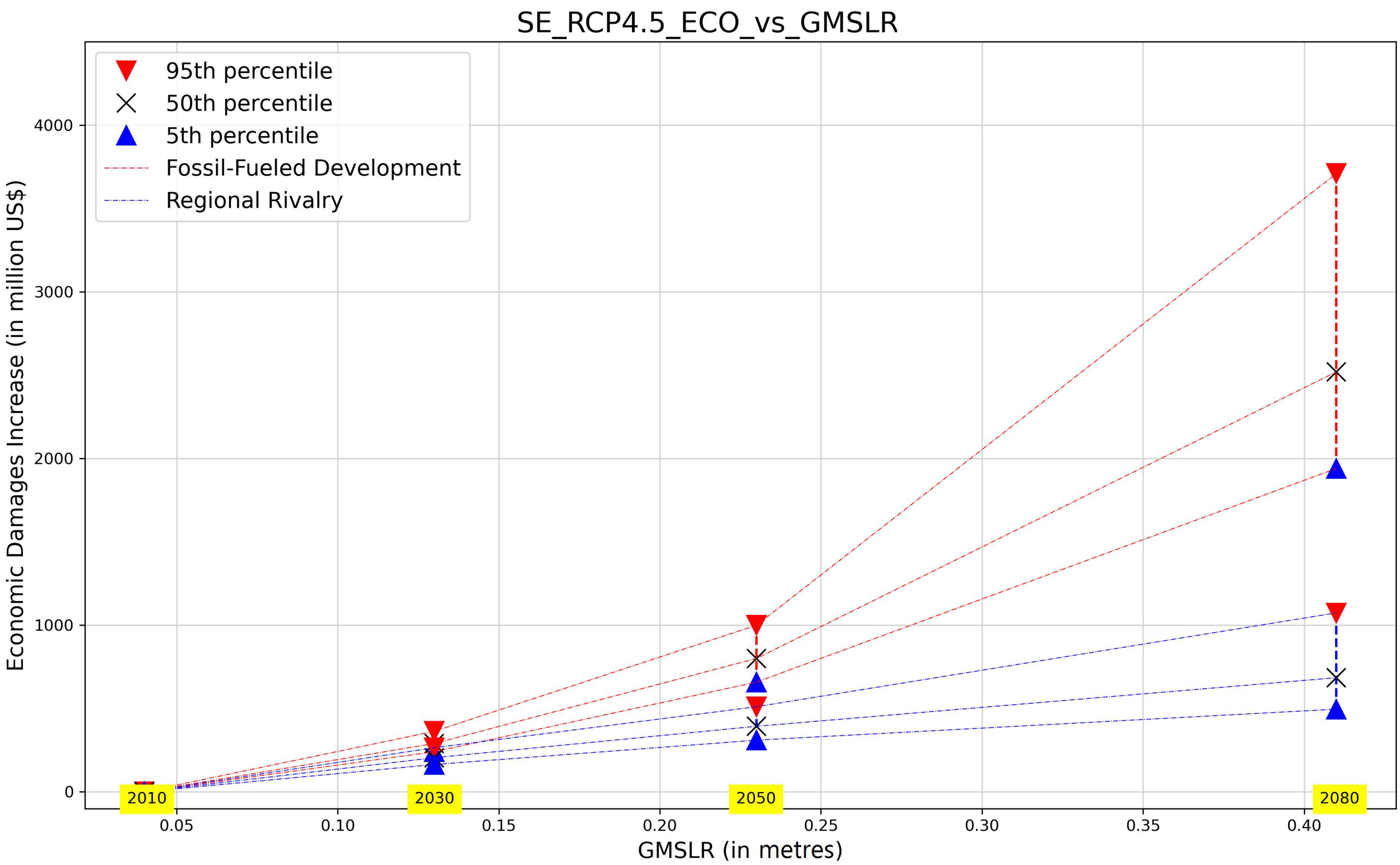



Figure C.45: Graph of SE_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.43: Overview of SE_ECO_RCP4.5_vs_GMSLR values.

| Sweden - Economic Damages (million US$) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 163.7 | 204.4 | 264.5 | 240.2 | 289.7 | 362.7 |
| **2050** | 309.8 | 393.0 | 510.3 | 657.8 | 799.9 | 999.4 |
| **2080** | 495.6 | 684.5 | 1,073.4 | 1,939.7 | 2,519.5 | 3,709.2 |

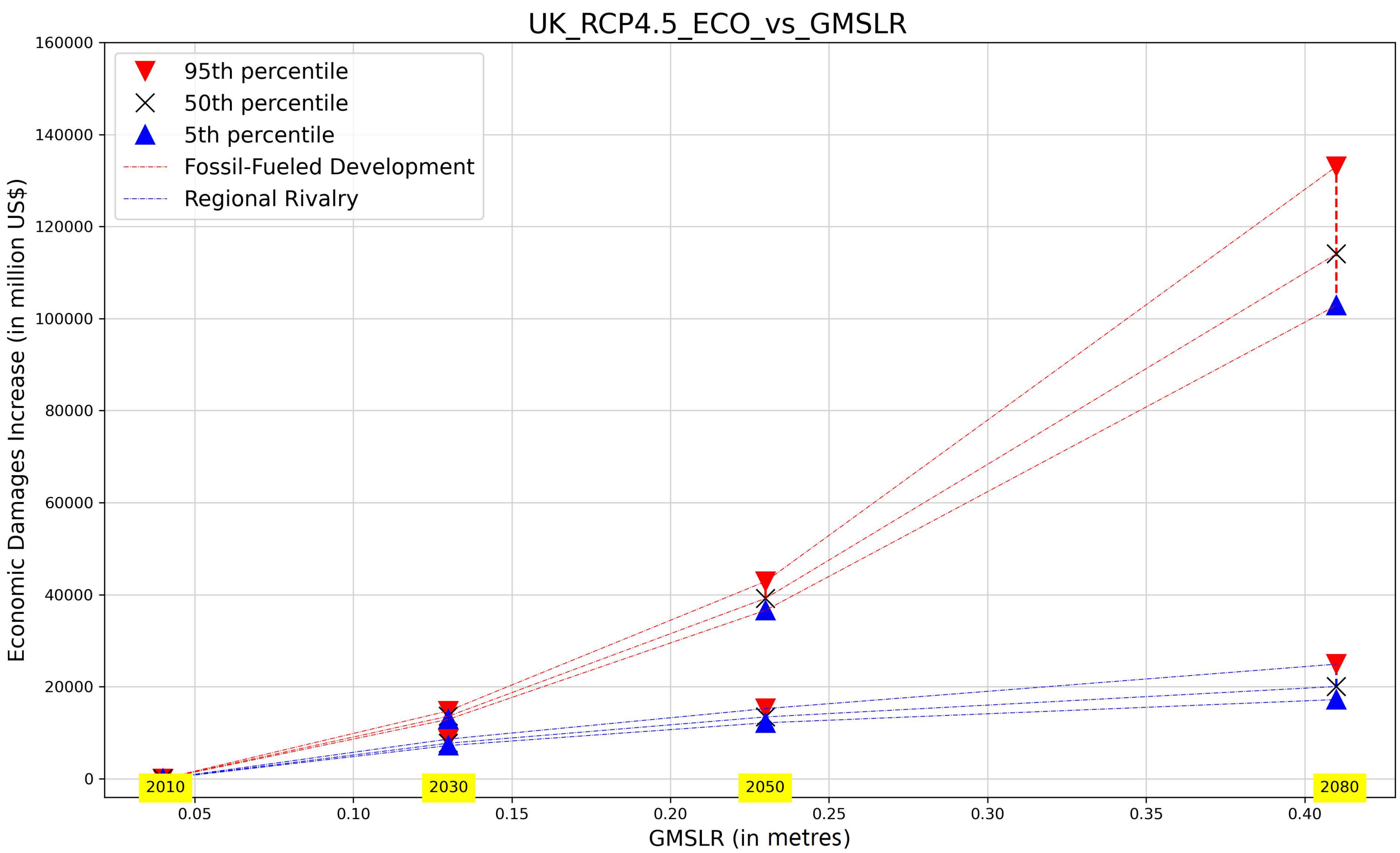



Figure C.46: Graph of UK_RCP4.5_RP1000_ECO_vs_GMSLR.

Table C.44: Overview of UK_ECO_RCP4.5_vs_GMSLR values.

| the United Kingdom - Economic Damages (million US$) - RCP4.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 7,207.1 | 7,717.1 | 8,605.8 | 12,914.1 | 13,580.1 | 14,741.8 |
| **2050** | 12,148.7 | 13,421.4 | 15,229.0 | 36,601.7 | 39,196.5 | 42,870.3 |
| **2080** | 17.197.8 | 20,040.2 | 24,896.9 | 102,884.3 | 114,081.4 | 133,067.1 |

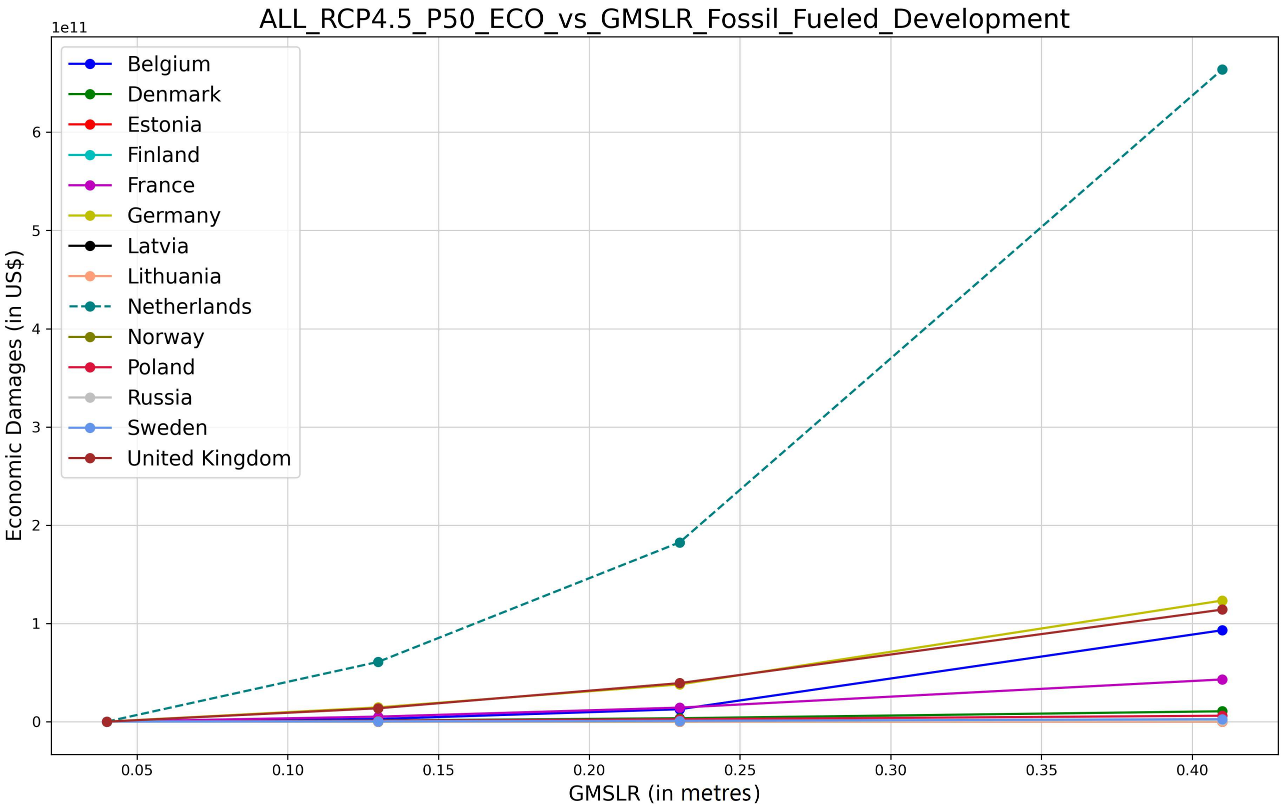



Figure C.47: Graph of ALL_RCP4.5_RP1000_ECO_vs_GMSLR.

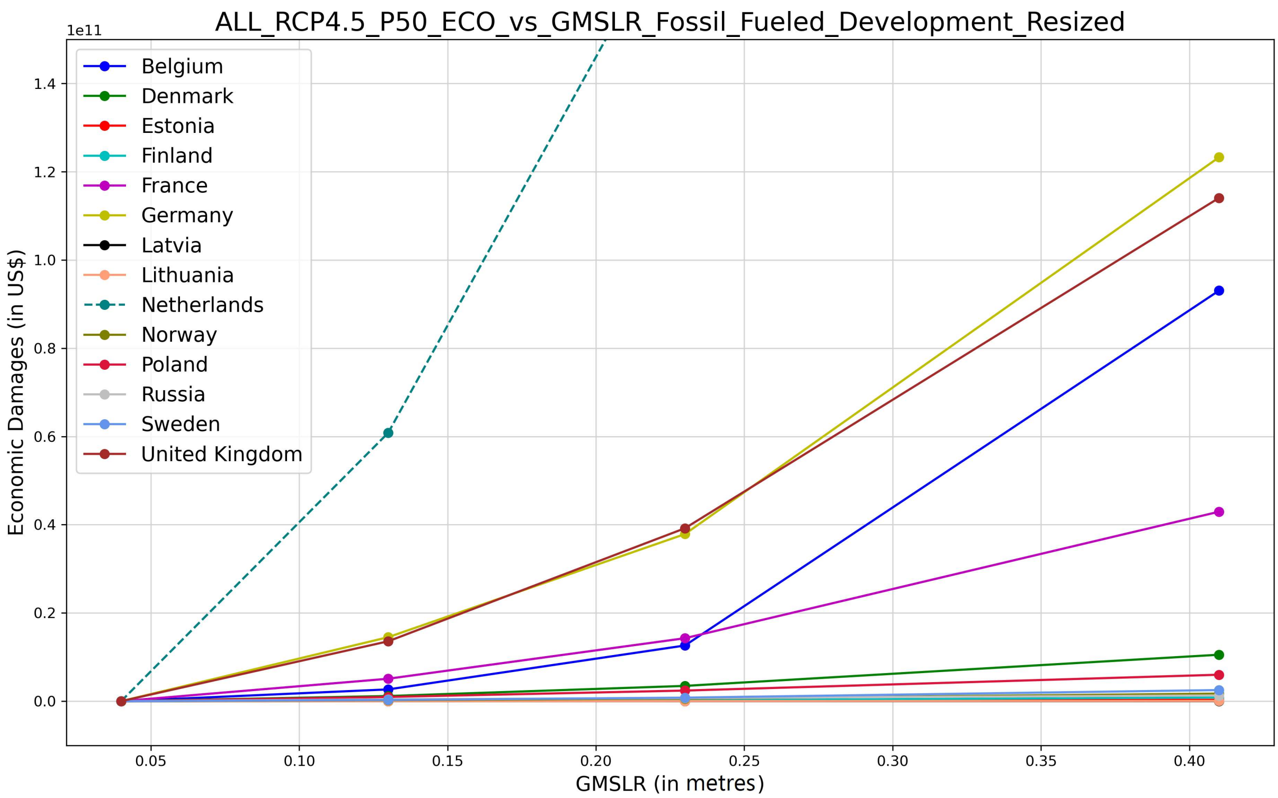



Figure C.48: Graph of ALL_RCP4.5_RP1000_ECO_vs_GMSLR_Resized.

## C.6. Economic Damages - RCP8.5

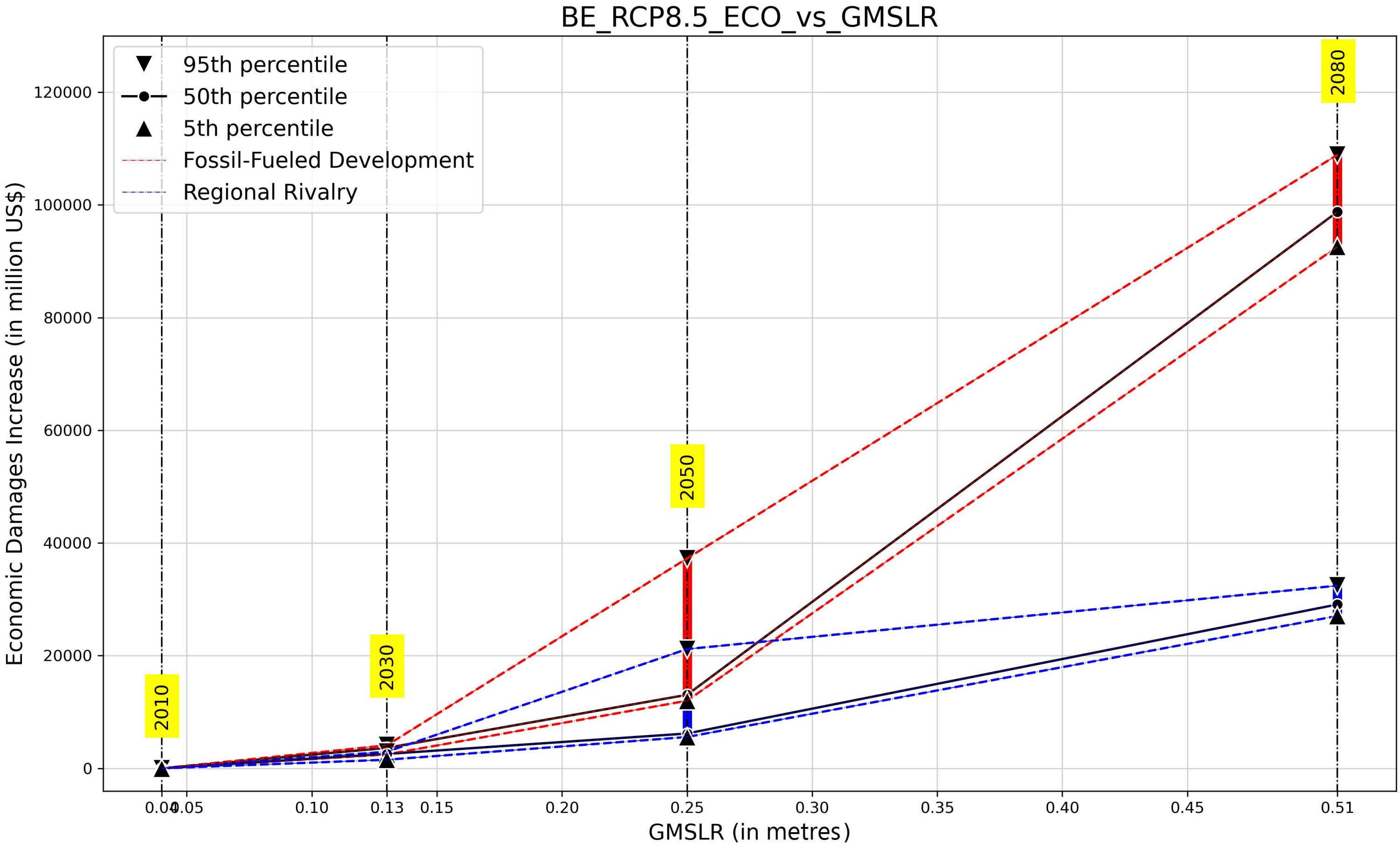



Figure C.49: Graph of BE_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.45: Overview of BE_ECO_RCP8.5_vs_GMSLR values.

| Belgium - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 1,529.6 | 2,556.7 | 2,950.0 | 2,472.2 | 3,632.1 | 4,092.6 |
| **2050** | 5,564.5 | 6,183.7 | 21,172.0 | 11,999.4 | 13,054.4 | 37,257.1 |
| **2080** | 27.048.1 | 29,094.3 | 32,421.0 | 92,591.0 | 98,778.8 | 108,904.6 |

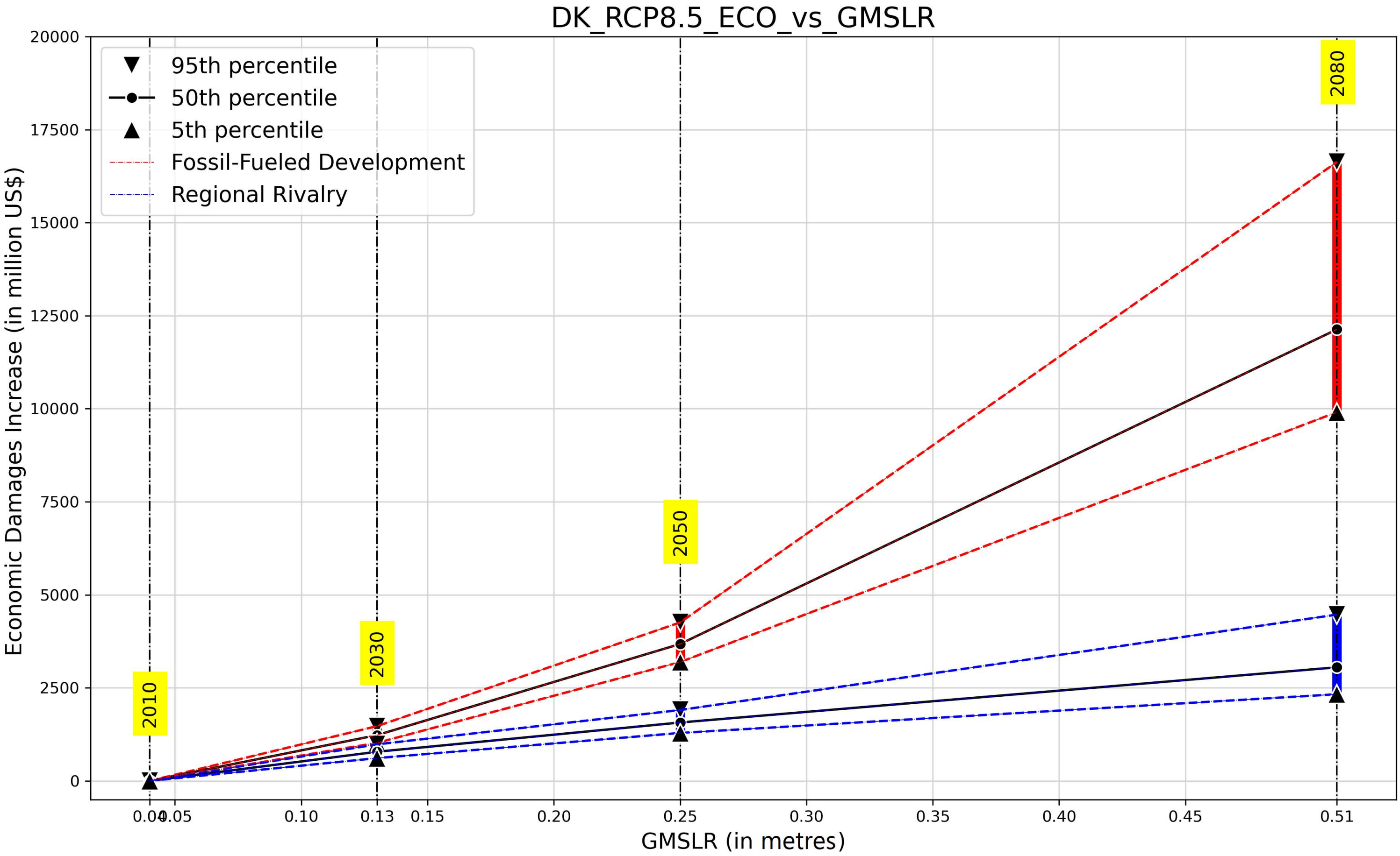



Figure C.50: Graph of DK_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.46: Overview of DK_ECO_RCP8.5_vs_GMSLR values.

| **Denmark - Economic Damages (million US$) - RCP8.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 611.3 | 782.1 | 981.3 | 1,021.1 | 1,229.1 | 1,470.3 |
| **2050** | 1,287.7 | 1,568.3 | 1,903.7 | 3,192.3 | 3,678.4 | 4,257.0 |
| **2080** | 2,328.0 | 3,051.7 | 4,467.3 | 9,907.8 | 12,133.0 | 16,630.4 |

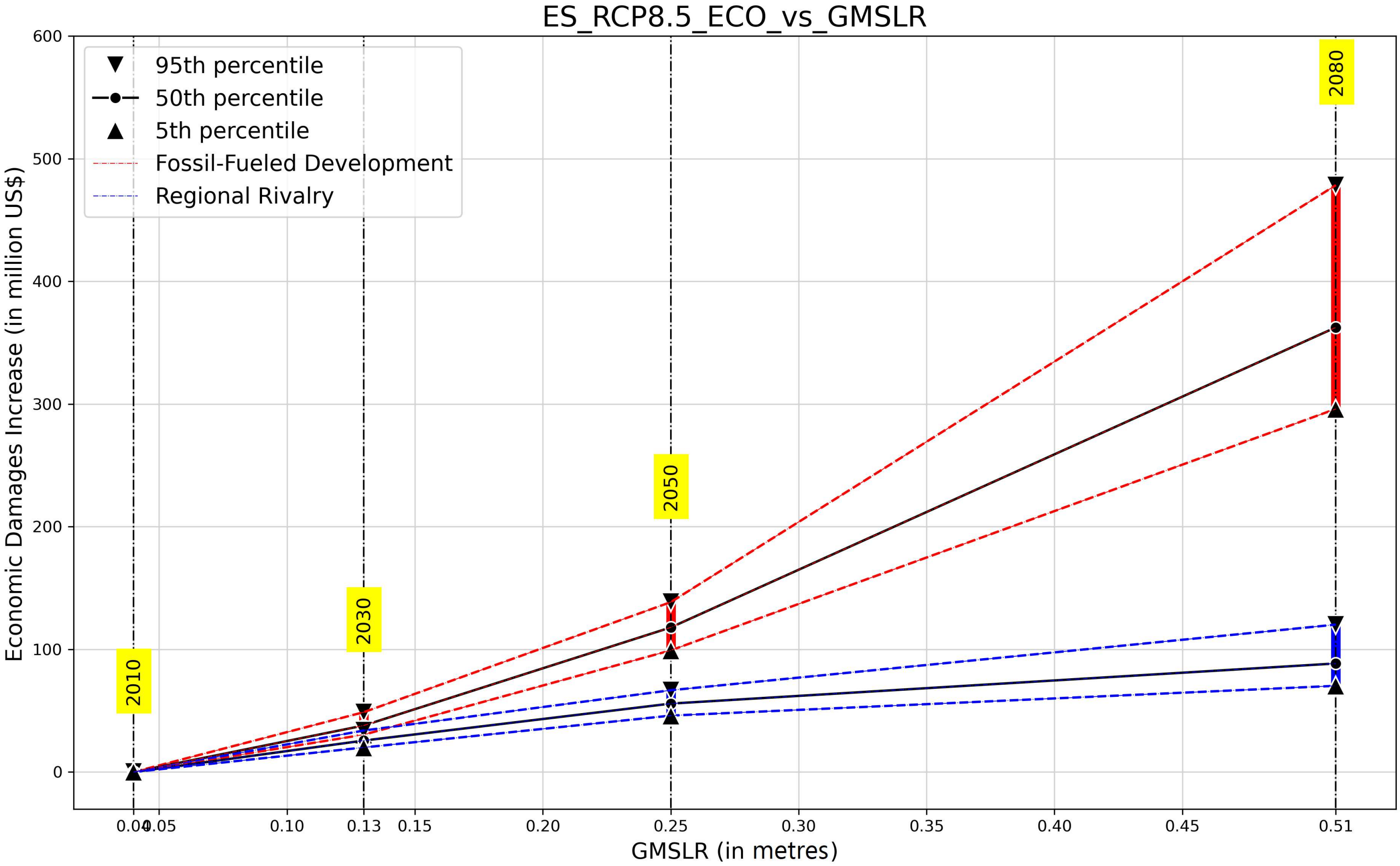



Figure C.51: Graph of ES_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.47: Overview of ES_ECO_RCP8.5_vs_GMSLR values.

| Estonia - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 20.0 | 25.7 | 33.8 | 30.5 | 38.0 | 48.8 |
| **2050** | 46.0 | 55.8 | 66.7 | 99.2 | 117.9 | 138.5 |
| **2080** | 70.3 | 88.5 | 120.2 | 296.0 | 362.4 | 478.4 |

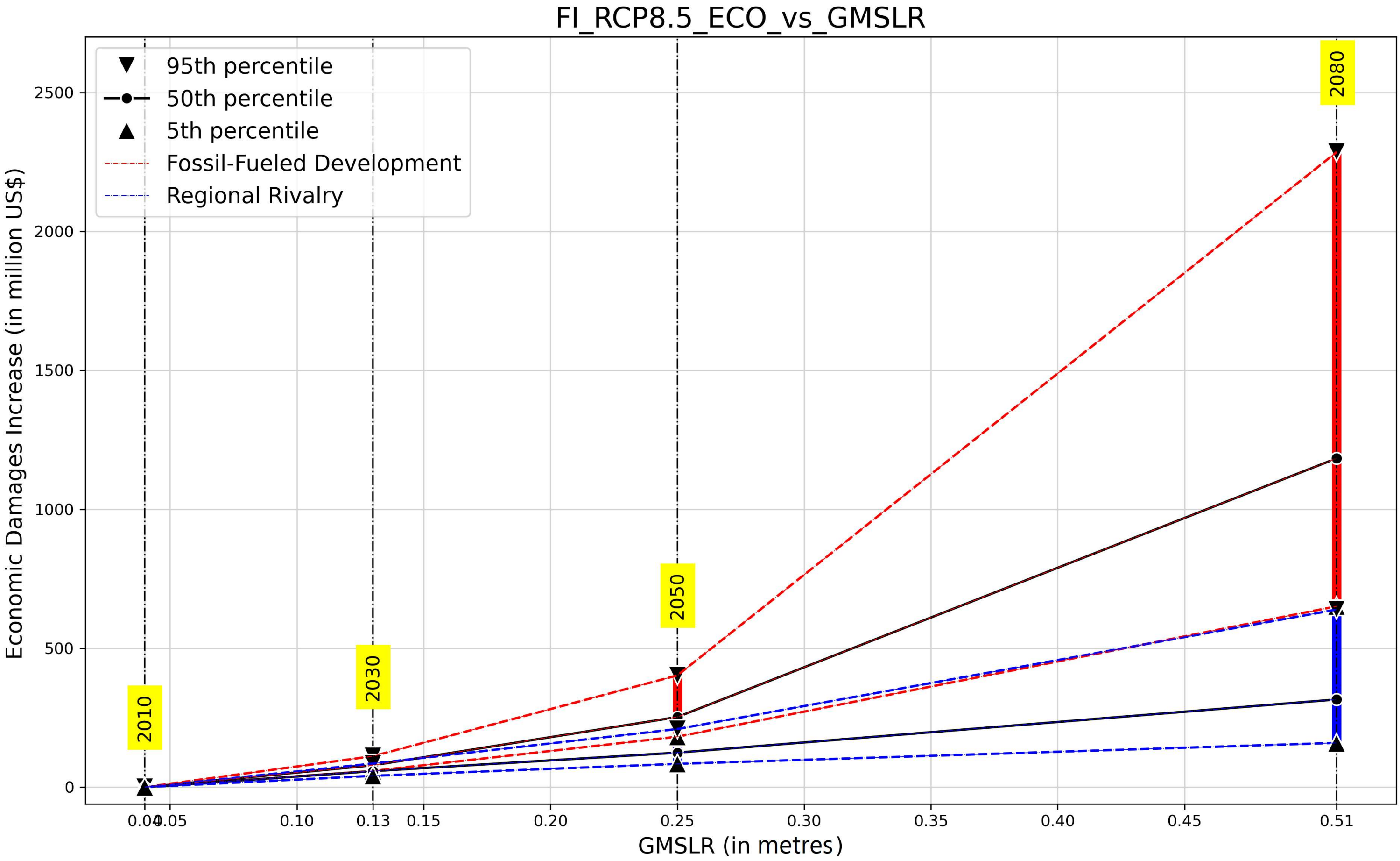



Figure C.52: Graph of FI_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.48: Overview of FI_ECO_RCP8.5_vs_GMSLR values.

| **Finland - Economic Damages (million US$) - RCP8.5 - RP1000** | | | | | | |
|---|---|---|---|---|---|---|
| | **Regional Rivalry** | | | **Fossil-Fueled Development** | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 40.7 | 57.6 | 84.9 | 58.3 | 79.6 | 111.4 |
| **2050** | 83.7 | 124.0 | 209.1 | 181.4 | 252.2 | 402.0 |
| **2080** | 159.3 | 315.6 | 639.1 | 650.9 | 1,183.4 | 2,285.3 |

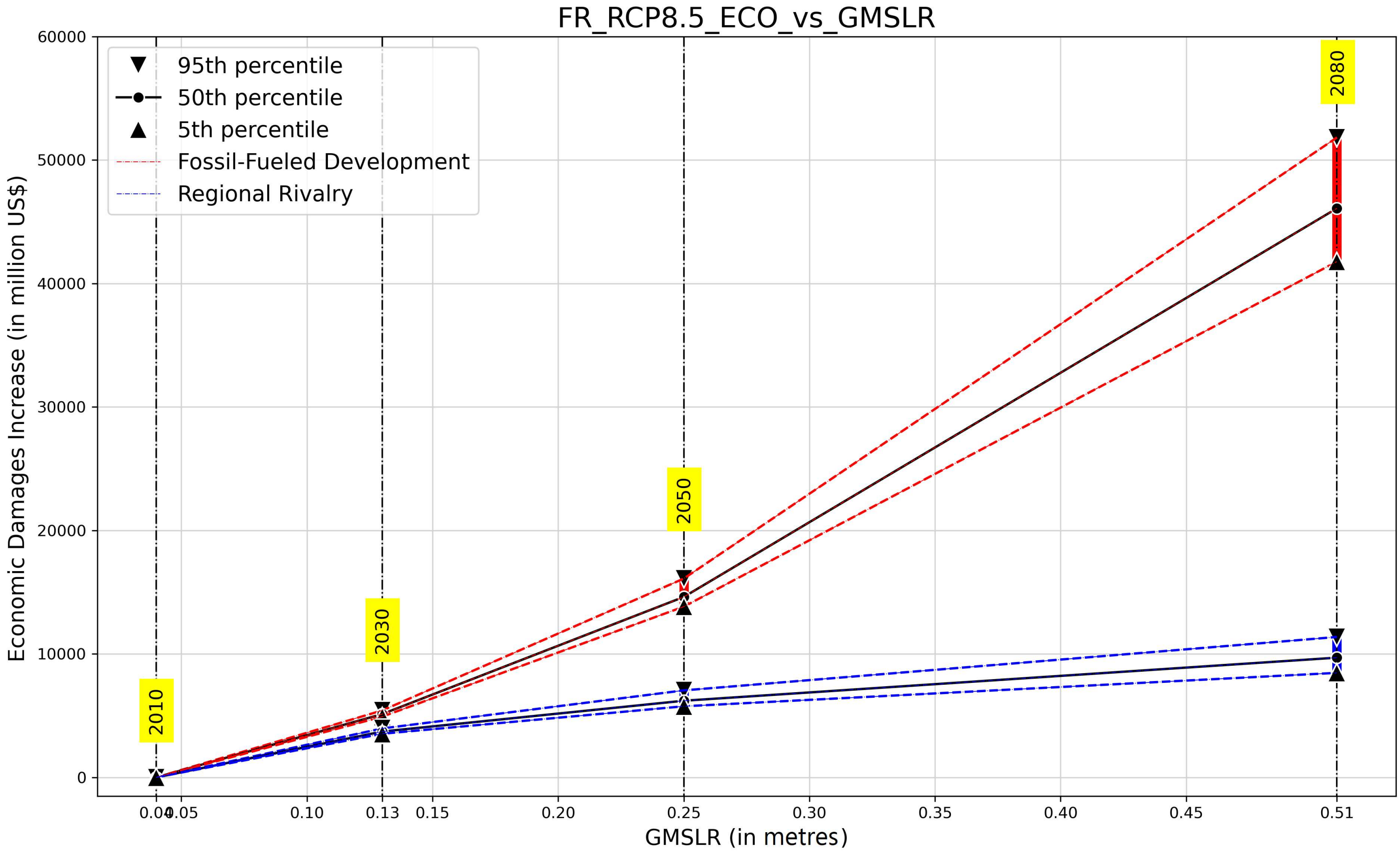



Figure C.53: Graph of FR_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.49: Overview of FR_ECO_RCP8.5_vs_GMSLR values.

| France - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 3,535.9 | 3,714.9 | 3,965.6 | 4,923.0 | 5,131.3 | 5,423.0 |
| **2050** | 5,759.3 | 6,209.2 | 7,047.5 | 13,828.4 | 14,616.2 | 16,102.4 |
| **2080** | 8,467.4 | 9,698.9 | 11,373.9 | 41,778.0 | 46,092.3 | 51,826.2 |

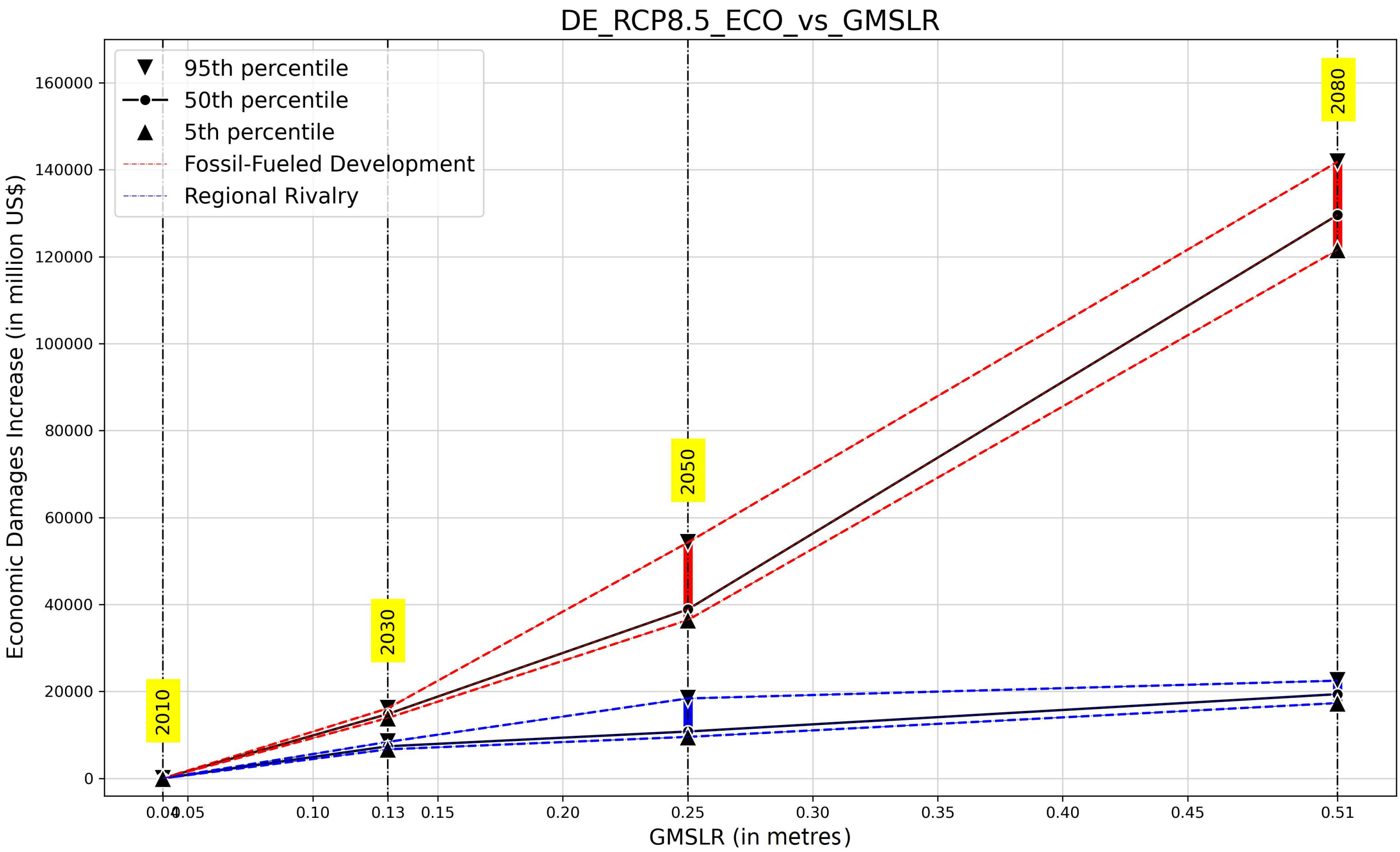



Figure C.54: Graph of DE_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.50: Overview of DE_ECO_RCP8.5_vs_GMSLR values.

| Germany - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 6,675.9 | 7,378.7 | 8,377.6 | 13,888.2 | 14,802.0 | 16,100.2 |
| **2050** | 9,540.2 | 10,769.4 | 18,383.3 | 36,417.0 | 38,874.6 | 54,254.8 |
| **2080** | 17,317.1 | 19,373.2 | 22,471.1 | 121.582.6 | 129,612.7 | 141,841.2 |

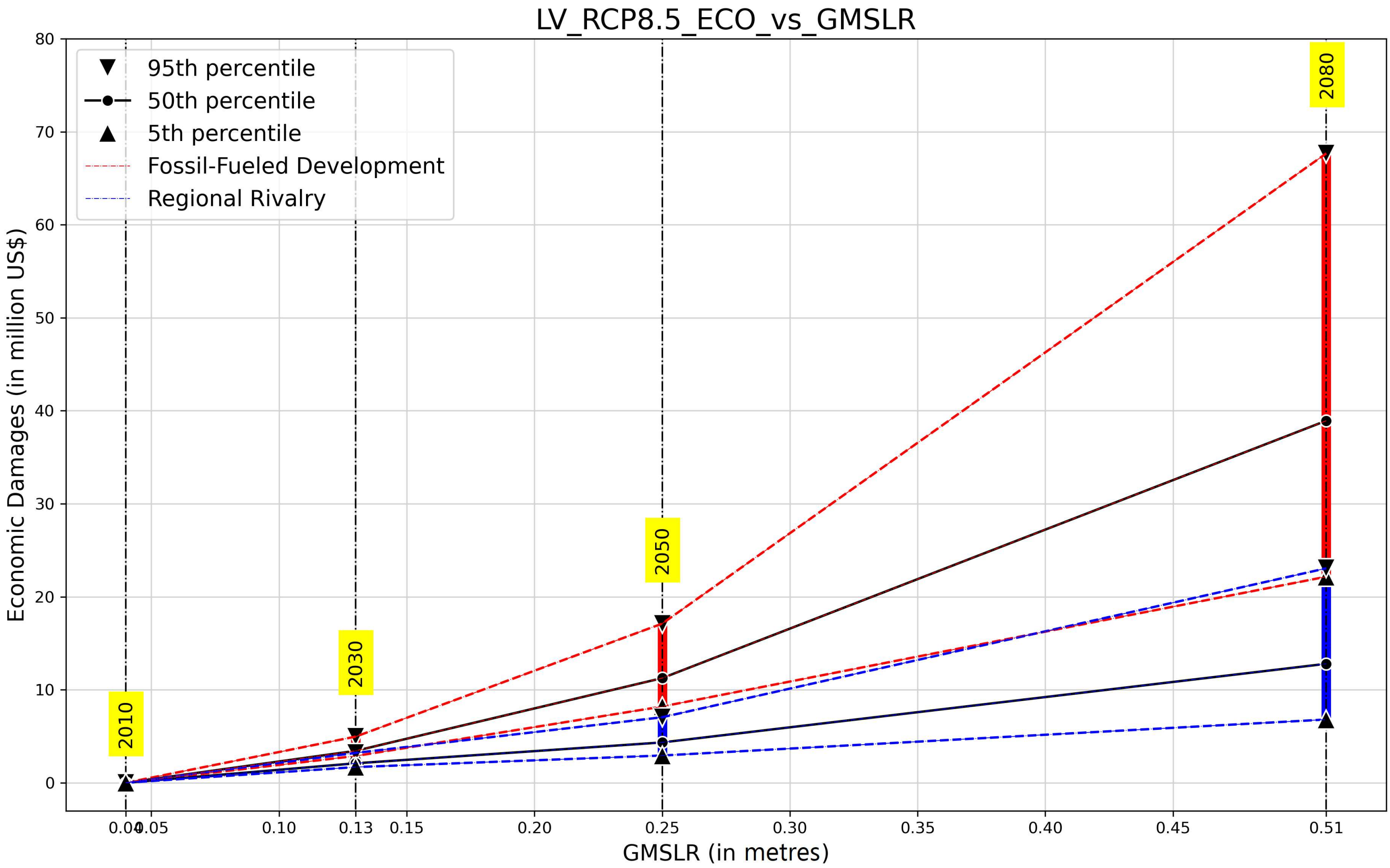



Figure C.55: Graph of LV_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.51: Overview of LV_ECO_RCP8.5_vs_GMSLR values.

| Latvia - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 1.7 | 2.1 | 3.2 | 2.9 | 3.4 | 5.0 |
| **2050** | 2.9 | 4.3 | 7.0 | 8.2 | 11.3 | 17.1 |
| **2080** | 6.8 | 12.8 | 23.1 | 22.2 | 38.9 | 67.7 |

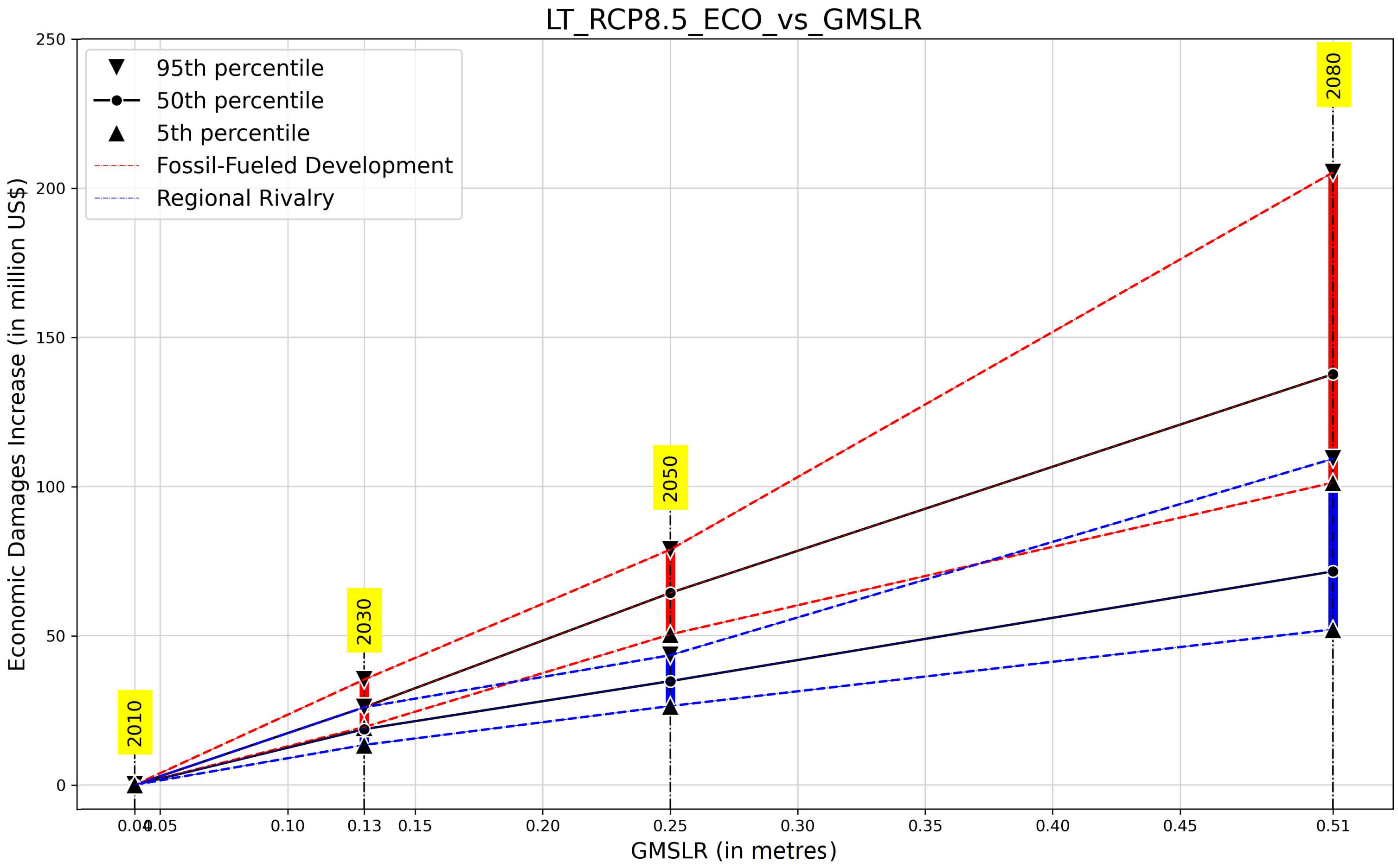



Figure C.56: Graph of LT_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.52: Overview of LT_ECO_RCP8.5_vs_GMSLR values.

| Lithuania - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 13.4 | 18.7 | 26.0 | 19.3 | 26.0 | 35.3 |
| **2050** | 26.4 | 34.8 | 43.4 | 50.4 | 64.3 | 78.8 |
| **2080** | 52.1 | 71.5 | 109.3 | 101.3 | 137.6 | 205.2 |

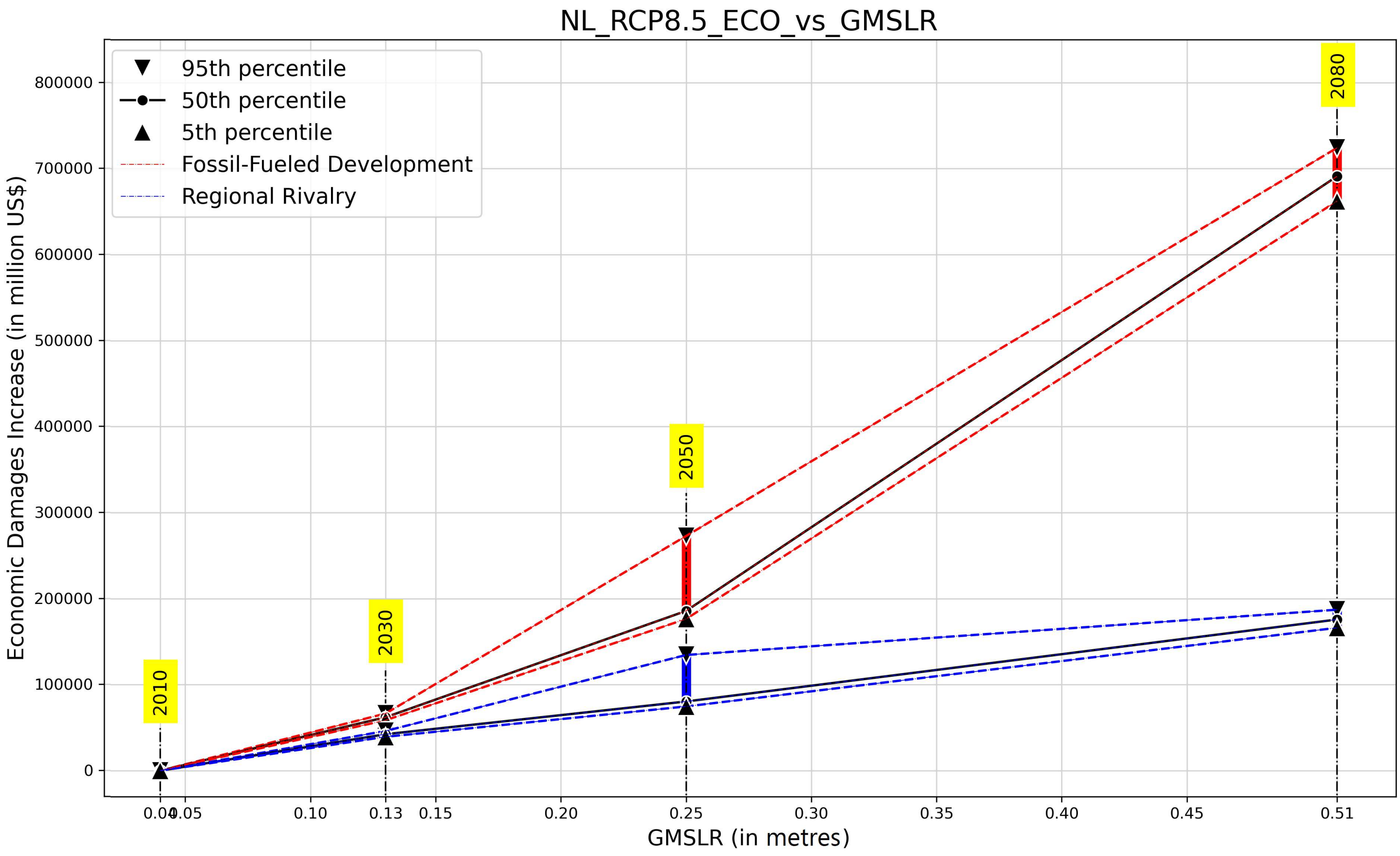



Figure C.57: Graph of NL_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.53: Overview of NL_ECO_RCP8.5_vs_GMSLR values.

| Netherlands - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 39,391.6 | 42,376.3 | 46,142.5 | 58,656.6 | 62,101.7 | 66,435.3 |
| **2050** | 74,655.5 | 80,436.2 | 134,502.9 | 176,413.8 | 185,759.2 | 272,849.6 |
| **2080** | 166,124.4 | 175,759.9 | 187,174.9 | 662,320.7 | 691,219.0 | 724,250.4 |

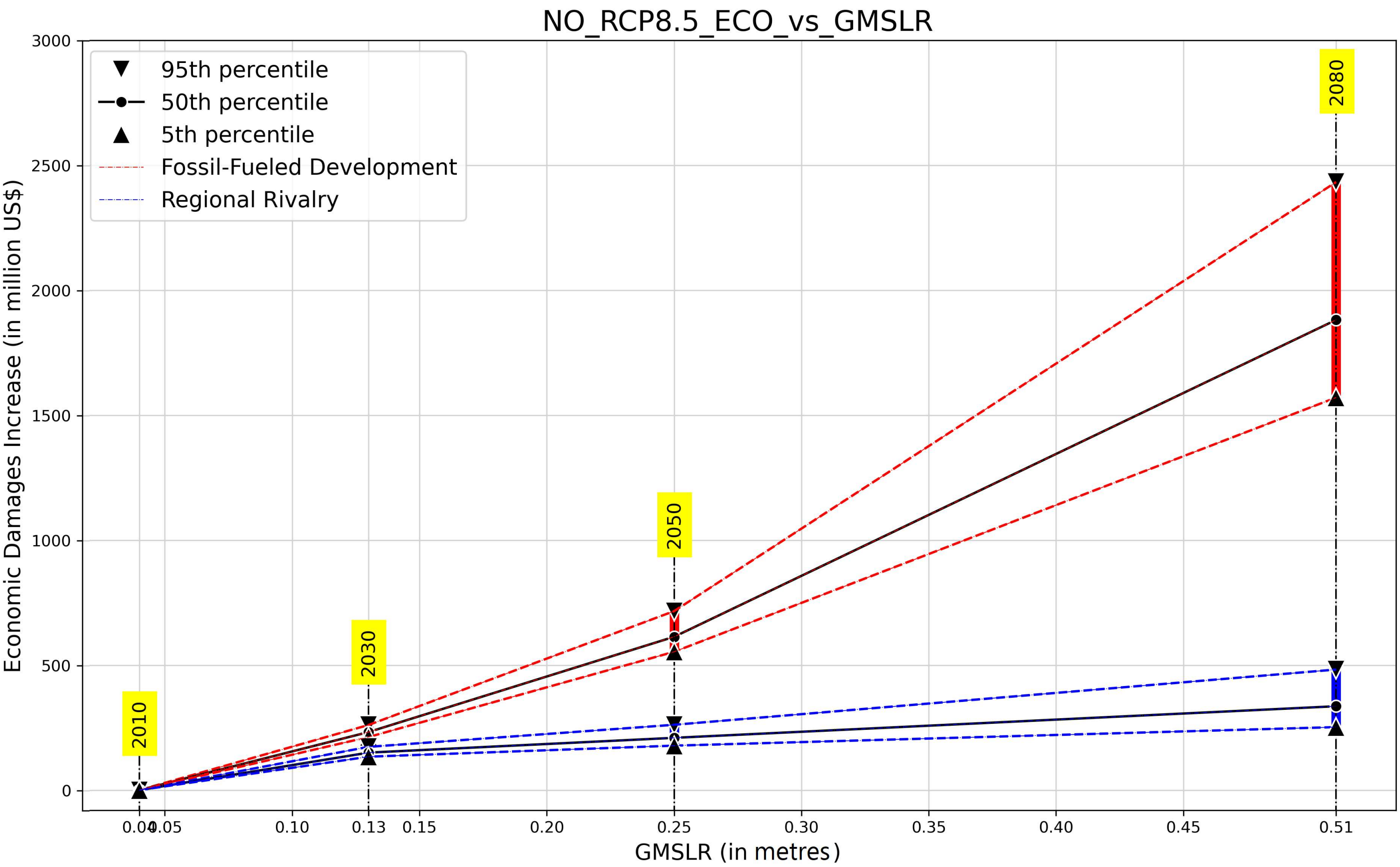



Figure C.58: Graph of NO_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.54: Overview of NO_ECO_RCP8.5_vs_GMSLR values.

| Norway - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 133.7 | 150.0 | 173.1 | 212.4 | 232.3 | 260.6 |
| **2050** | 177.9 | 209.2 | 261.4 | 553.4 | 613.4 | 716.1 |
| **2080** | 252.1 | 335.6 | 482.4 | 1,570.7 | 1,881.5 | 2,432.9 |

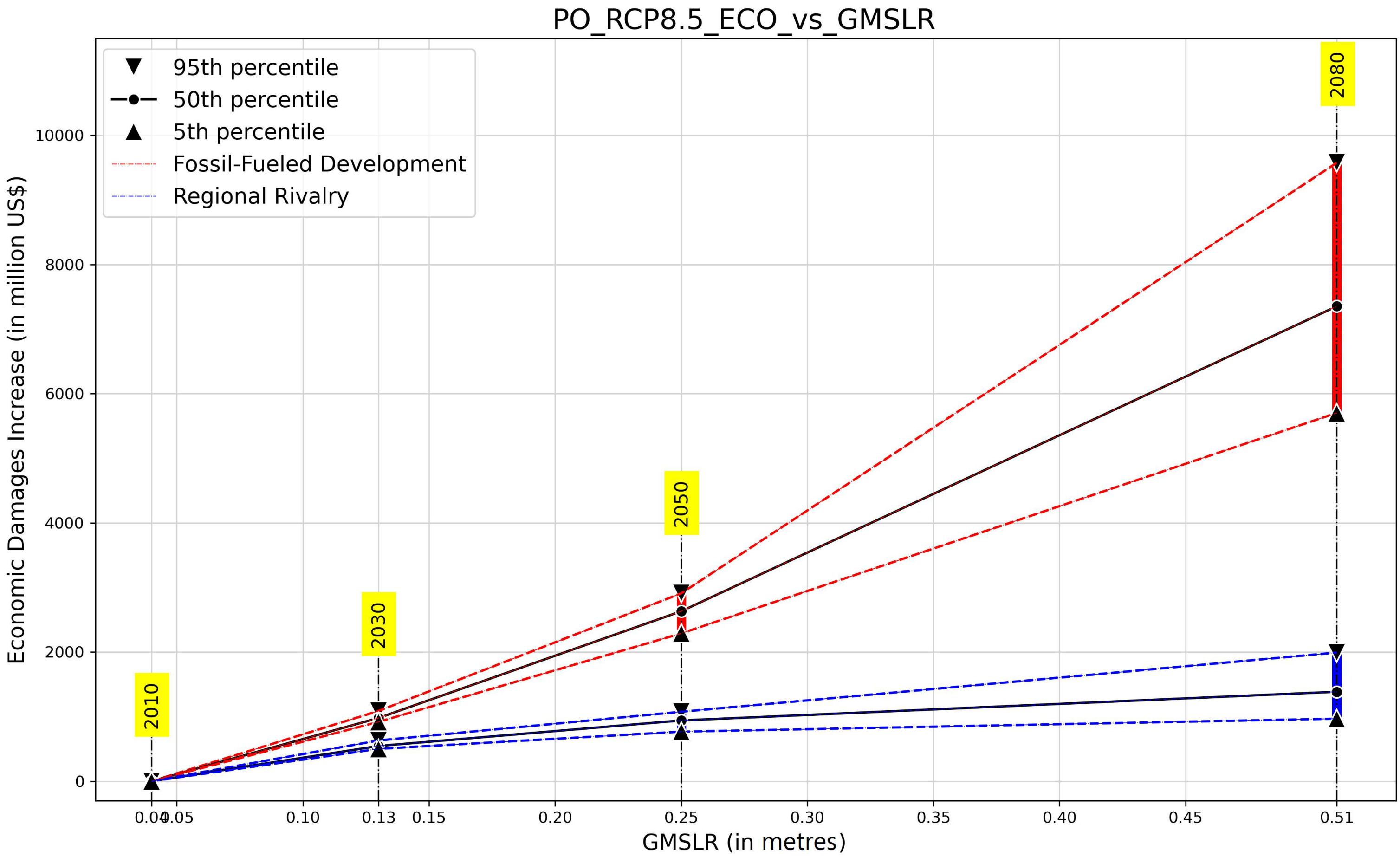



Figure C.59: Graph of PO_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.55: Overview of PO_ECO_RCP8.5_vs_GMSLR values.

| Poland - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| 2030 | 500.5 | 544.9 | 630.3 | 917.9 | 978.5 | 1,087.4 |
| 2050 | 766.2 | 940.1 | 1,074.6 | 2,287.5 | 2,630.4 | 2,908.1 |
| 2080 | 967.3 | 1,384.4 | 1,991.2 | 5,701.9 | 7,353.6 | 9,575.3 |

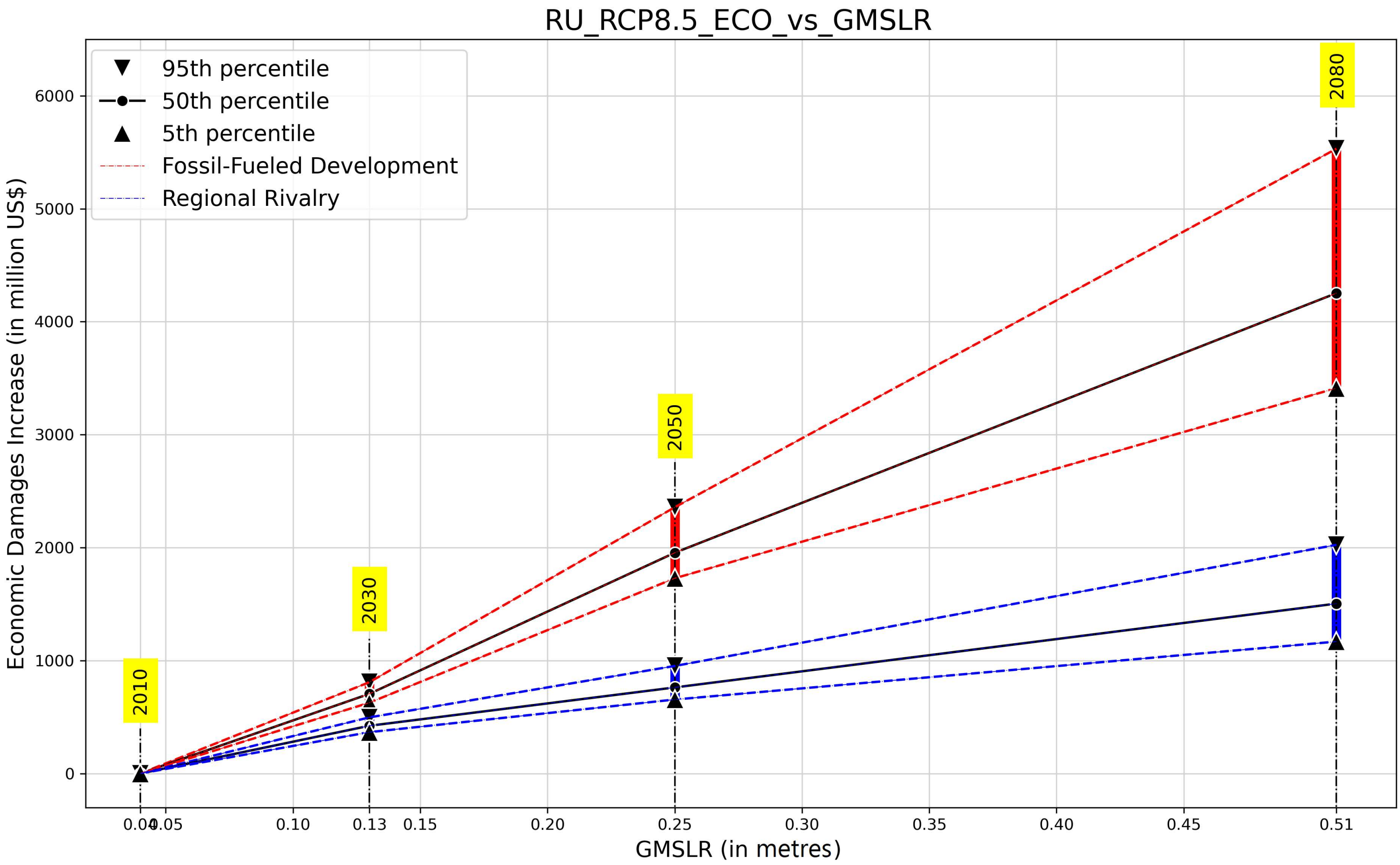



Figure C.60: Graph of RU_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.56: Overview of RU_ECO_RCP8.5_vs_GMSLR values.

| Russia - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | P05 | P50 | P95 | P05 | P50 | P95 |
| **2030** | 366.0 | 422.5 | 496.9 | 626.7 | 705.2 | 808.4 |
| **2050** | 654.9 | 761.9 | 952.1 | 1,728.4 | 1,954.4 | 2,357.2 |
| **2080** | 1,167.9 | 1,504.1 | 2,024.5 | 3,412.4 | 4,252.9 | 5,531.4 |

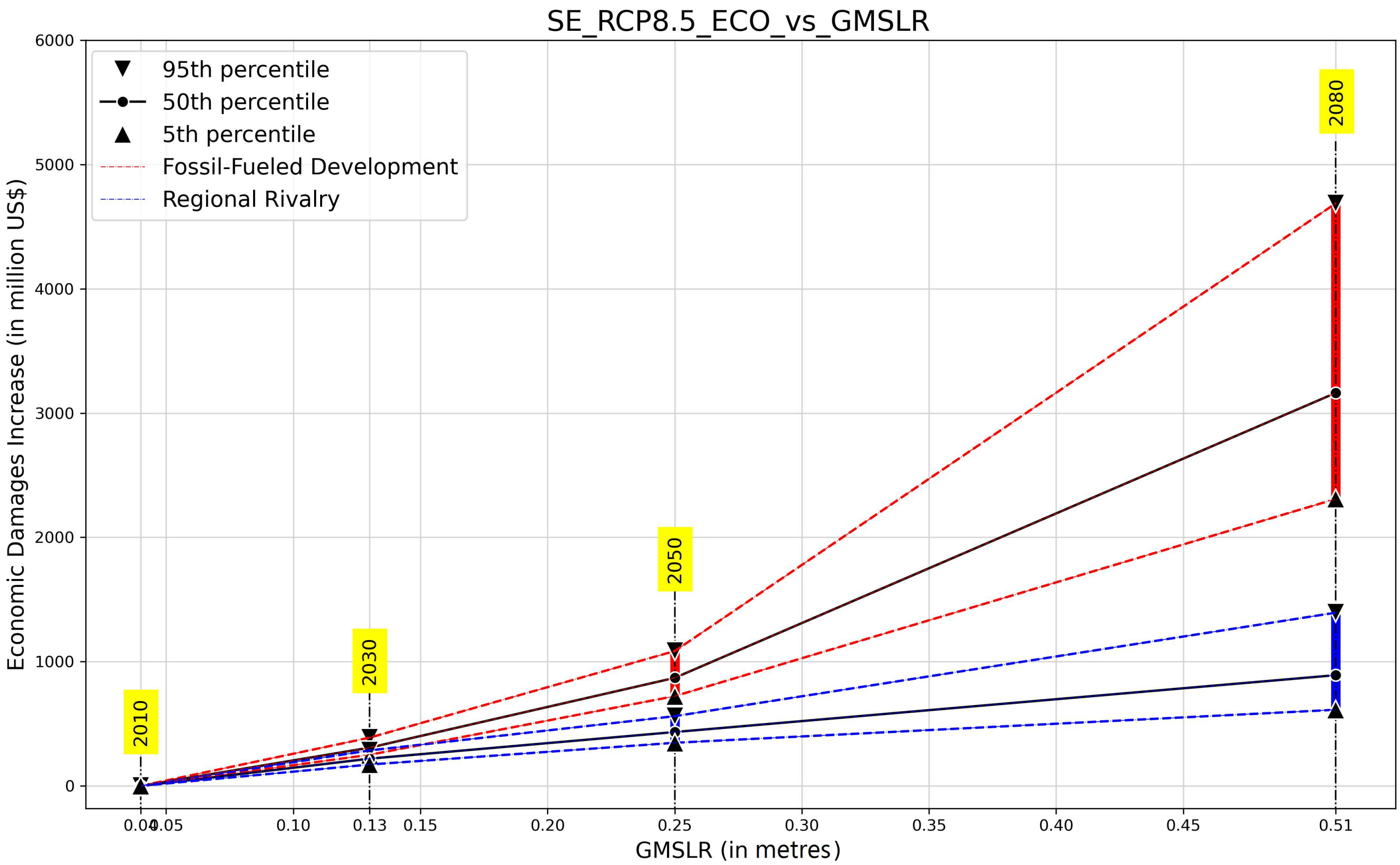



Figure C.61: Graph of SE_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.57: Overview of SE_ECO_RCP8.5_vs_GMSLR values.

| Sweden - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 171.9 | 219.1 | 285.3 | 250.2 | 307.6 | 388.0 |
| **2050** | 346.9 | 433.4 | 560.9 | 722.0 | 869.2 | 1,084.8 |
| **2080** | 612.5 | 891.1 | 1,393.9 | 2,309.0 | 3,162.6 | 4,687.9 |

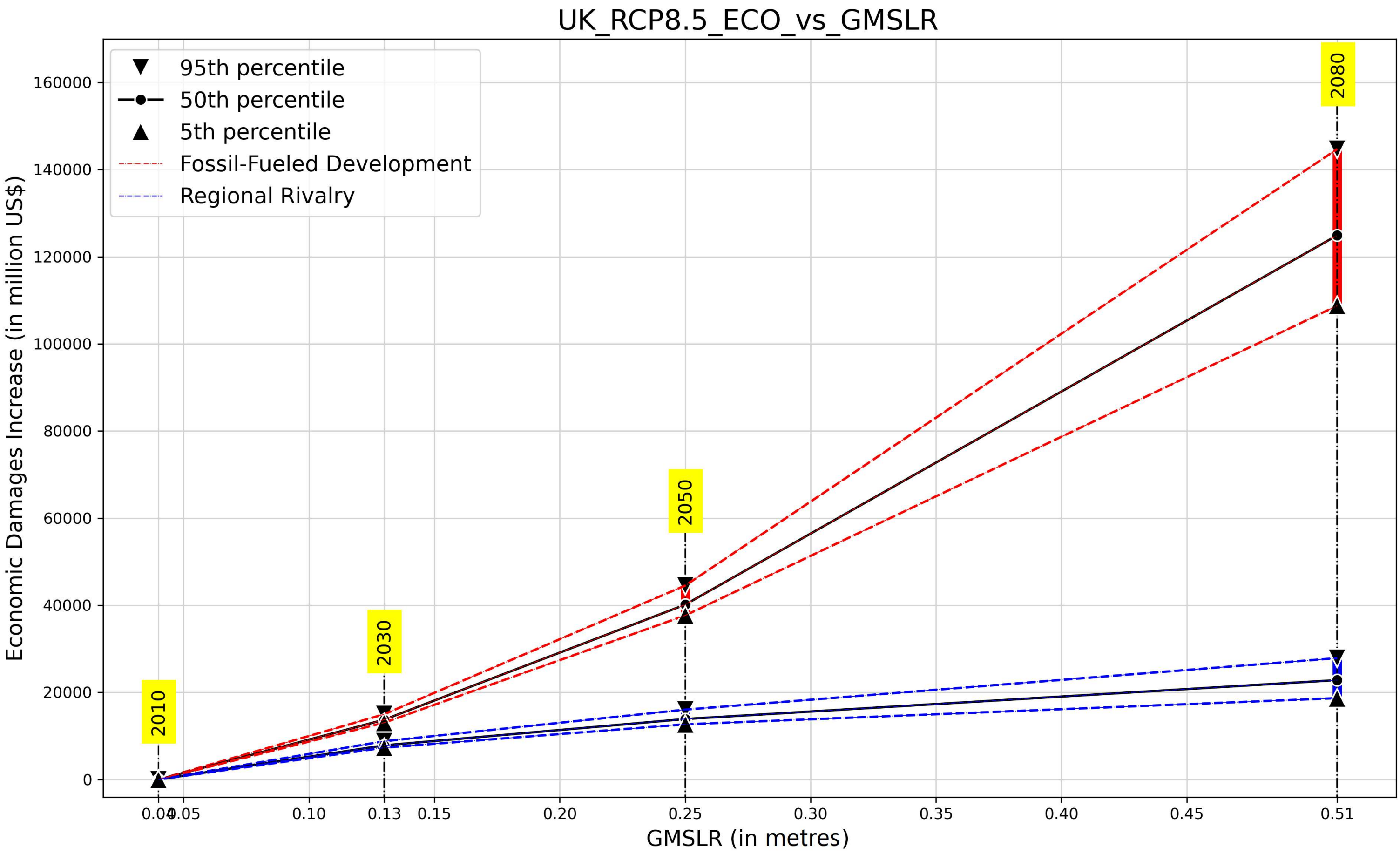



Figure C.62: Graph of UK_RCP8.5_RP1000_ECO_vs_GMSLR.

Table C.58: Overview of UK_ECO_RCP8.5_vs_GMSLR values.

| The United Kingdom - Economic Damages (million US$) - RCP8.5 - RP1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Regional Rivalry | | | Fossil-Fueled Development | | |
| | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| **2030** | 7,307.3 | 7,832.9 | 8,787.8 | 13,045.1 | 13,731.3 | 14,979.8 |
| **2050** | 12,665.0 | 13,883.5 | 16,042.7 | 37,654.7 | 40,136.0 | 44,515.7 |
| **2080** | 18,681.8 | 22,818.5 | 27,873.2 | 108,762.9 | 124,921.3 | 144,723.1 |

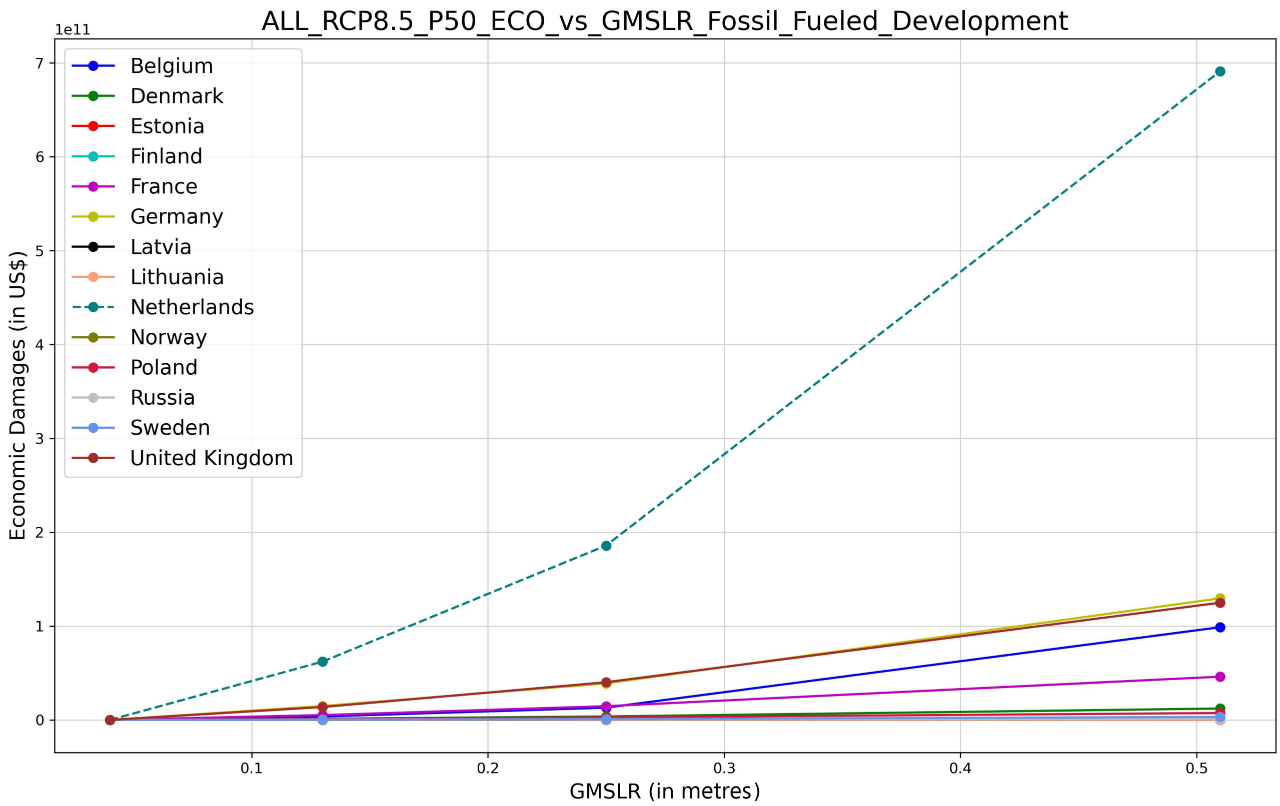



Figure C.63: Graph of ALL_RCP8.5_RP1000_ECO_vs_GMSLR.

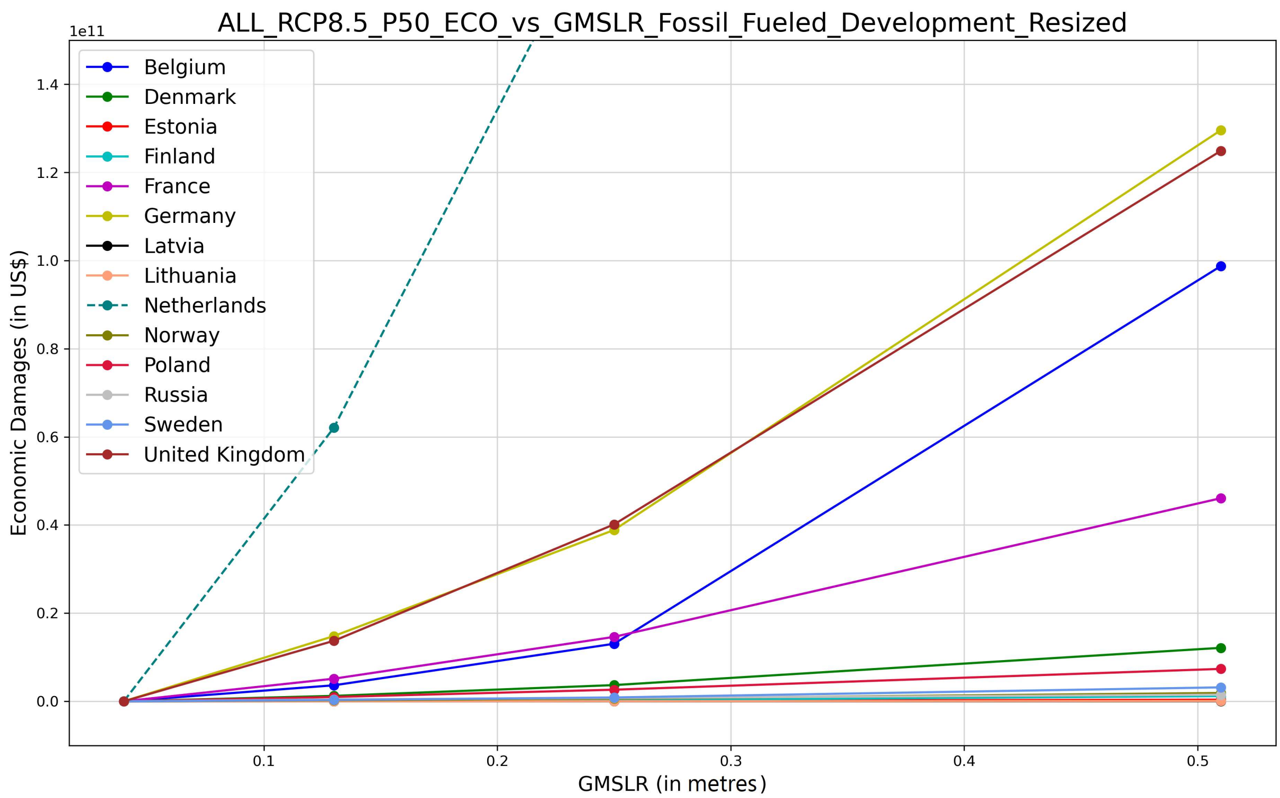



Figure C.64: Graph of ALL_RCP8.5_RP1000_ECO_vs_GMSLR_Resized.

# D

# Appendix D

## D.1. Inundation Maps and Coast Reinforcements (QGIS)

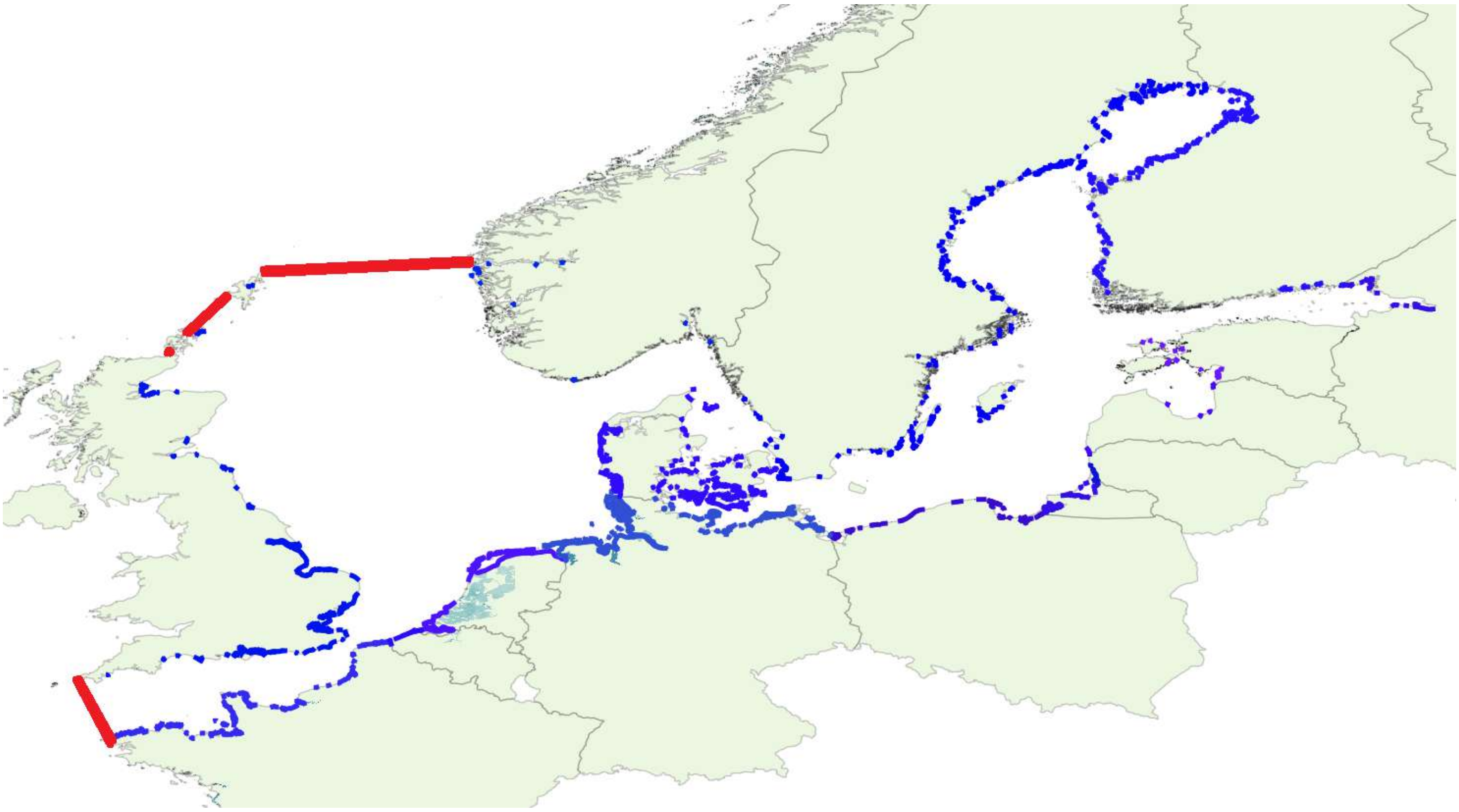
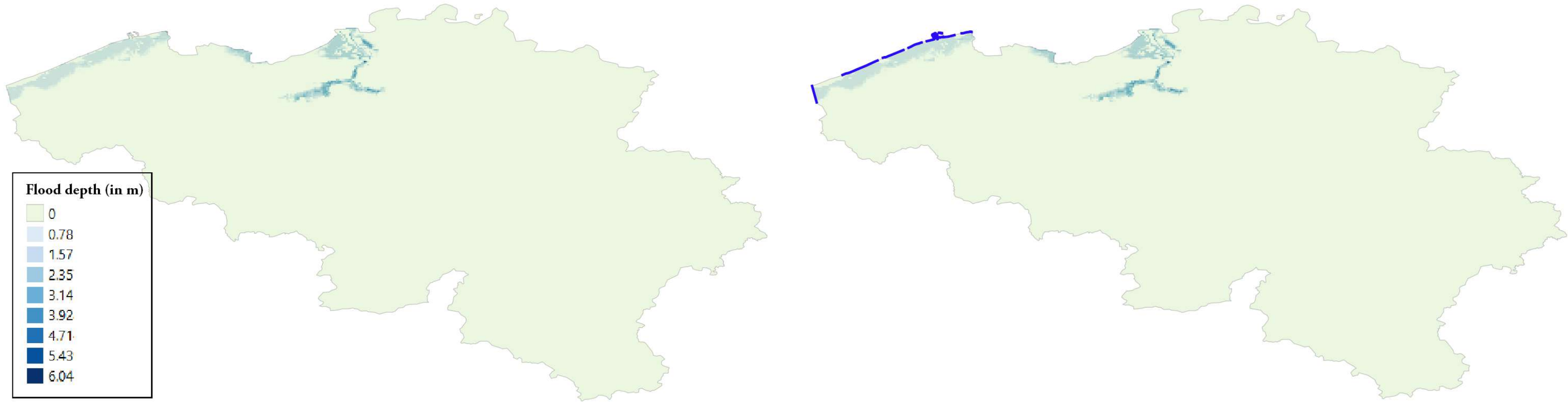


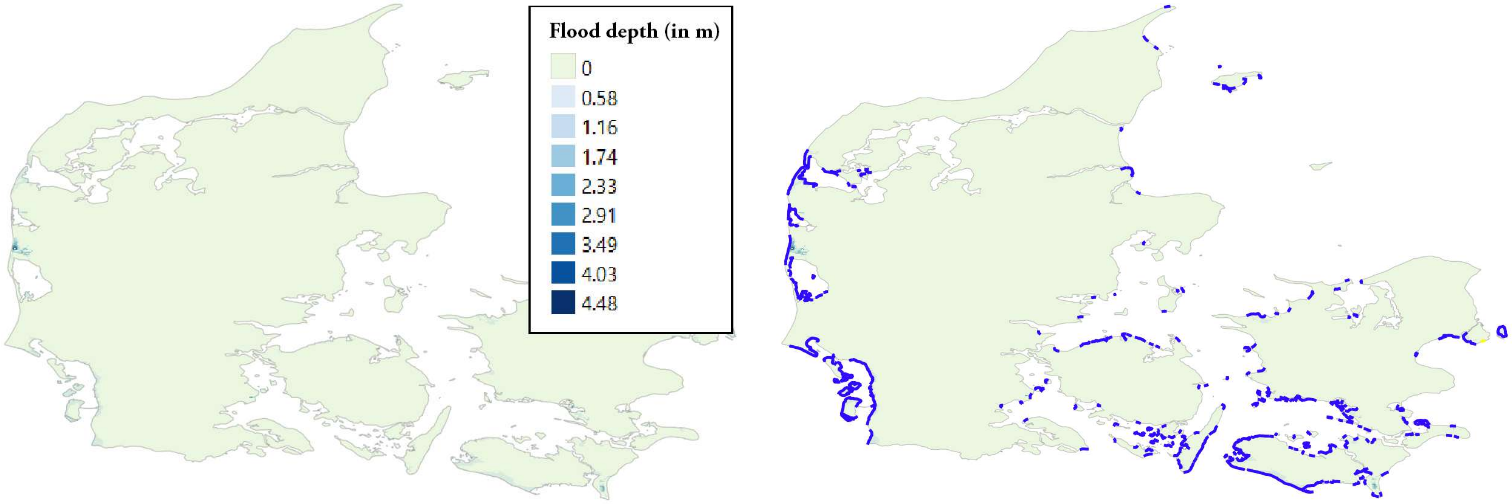
Figure D.1: The coast reinforcement map of the affected area by the N.E.E.D.




(a) Inundation Map

(b) Indicated Coast Reinforcement

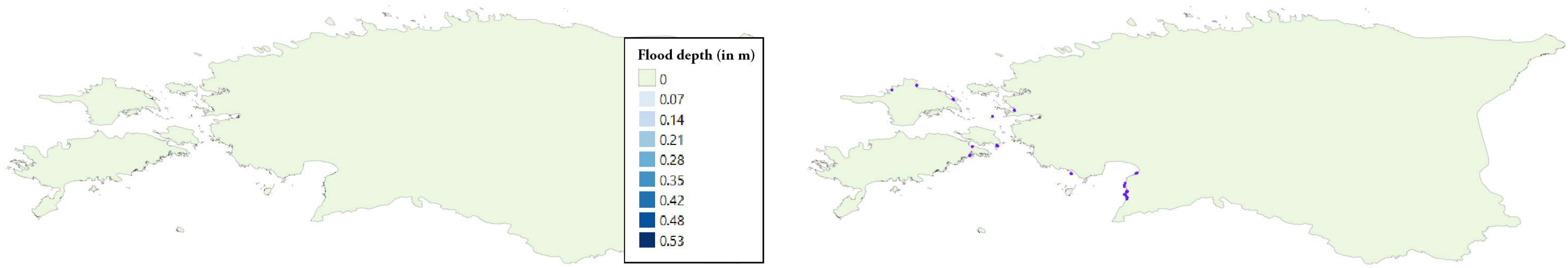
Figure D.2: Inundation and coastal reinforcement map of Belgium for RCP8.5 in 2080 for the 50th percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

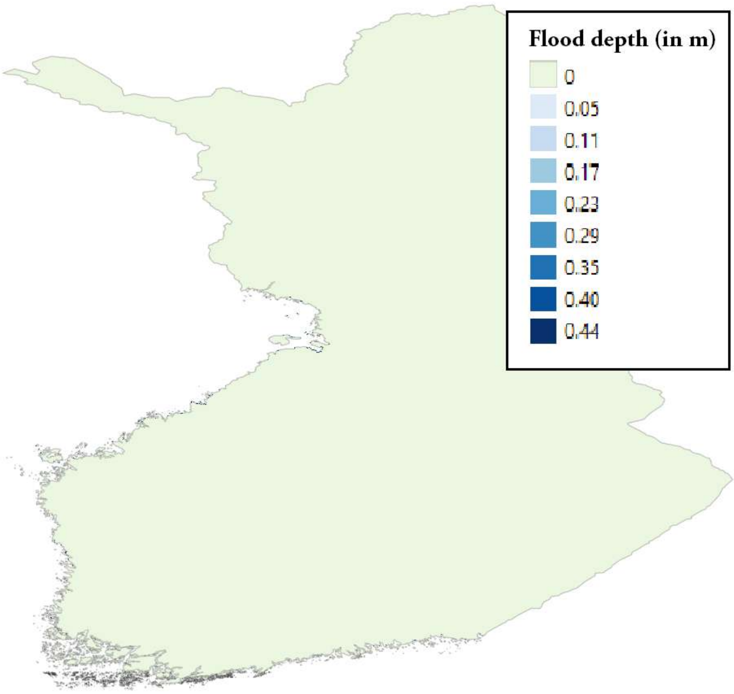
Figure D.3: Inundation and coastal reinforcement map of Denmark for RCP8.5 in 2080 for the 50th percentile.



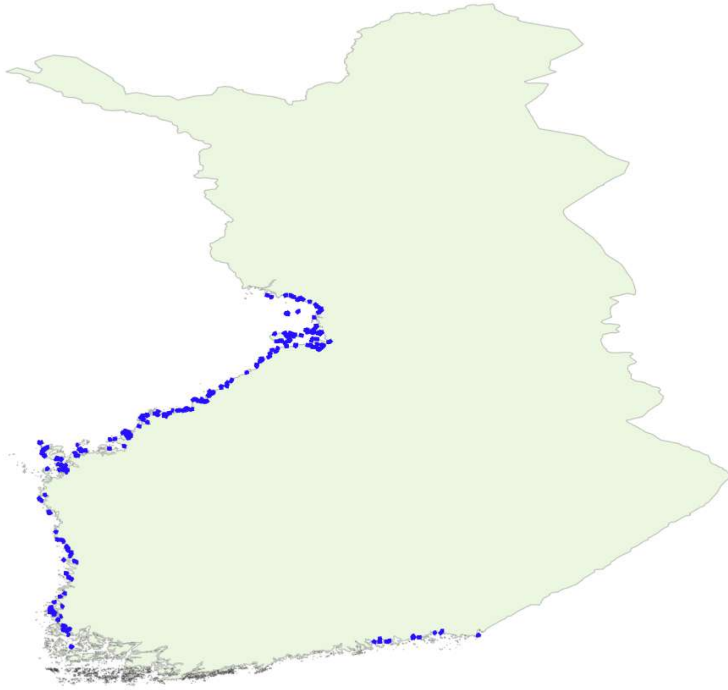

(a) Inundation Map

(b) Indicated Coast Reinforcement

Figure D.4: Inundation and coastal reinforcement map of Estonia for RCP8.5 in 2080 for the 50th percentile.

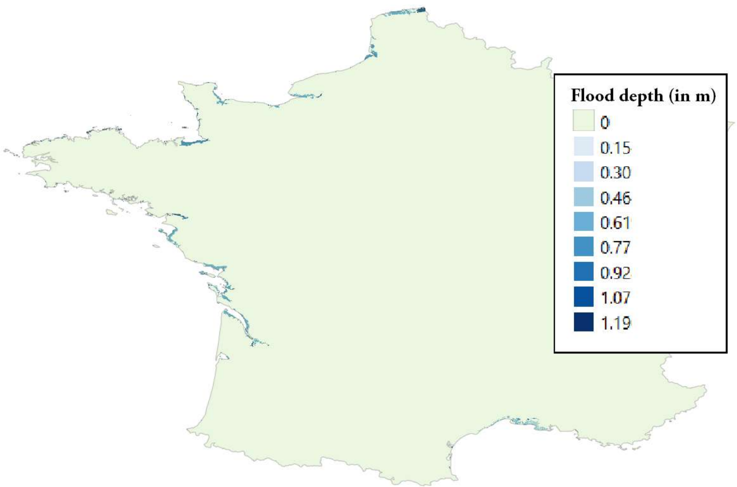



(a) Inundation Map

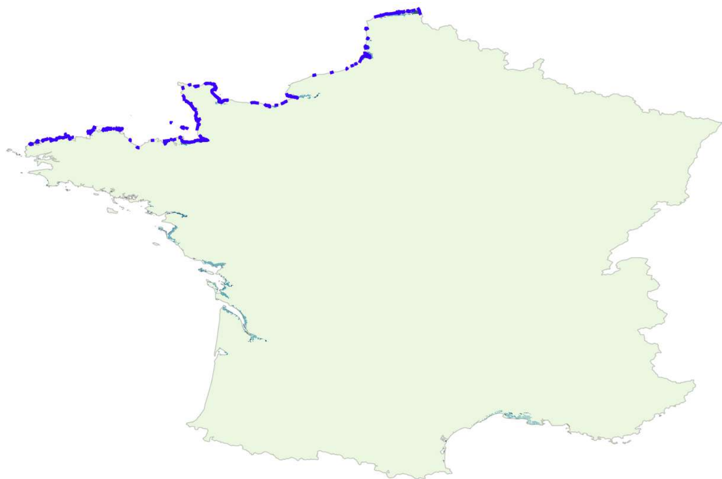


(b) Indicated Coast Reinforcement

Figure D.5: Inundation and coastal reinforcement map of Finland for RCP8.5 in 2080 for the 50th percentile.

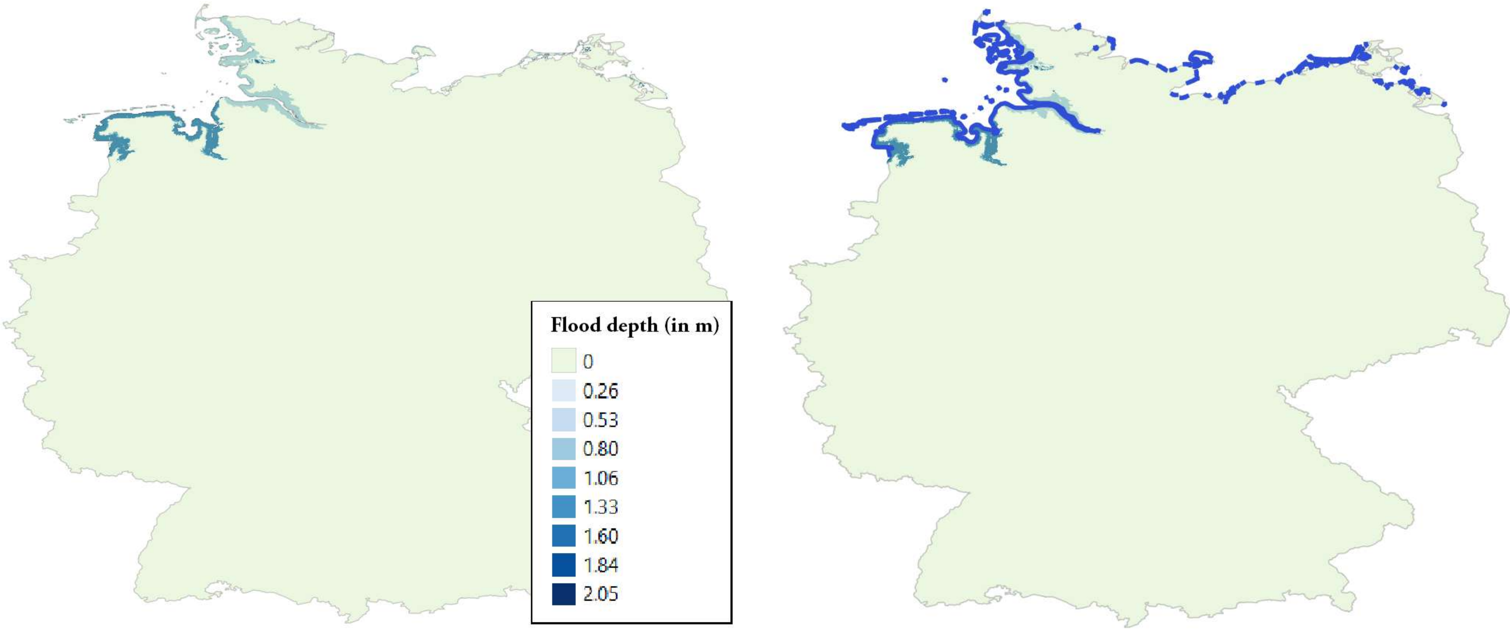



(a) Inundation Map



(b) Indicated Coast Reinforcement

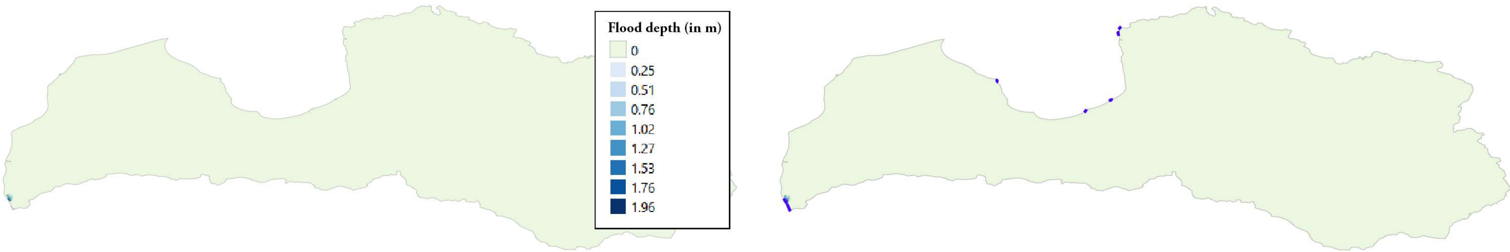
Figure D.6: Inundation and coastal reinforcement map of France for RCP8.5 in 2080 for the 50th percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

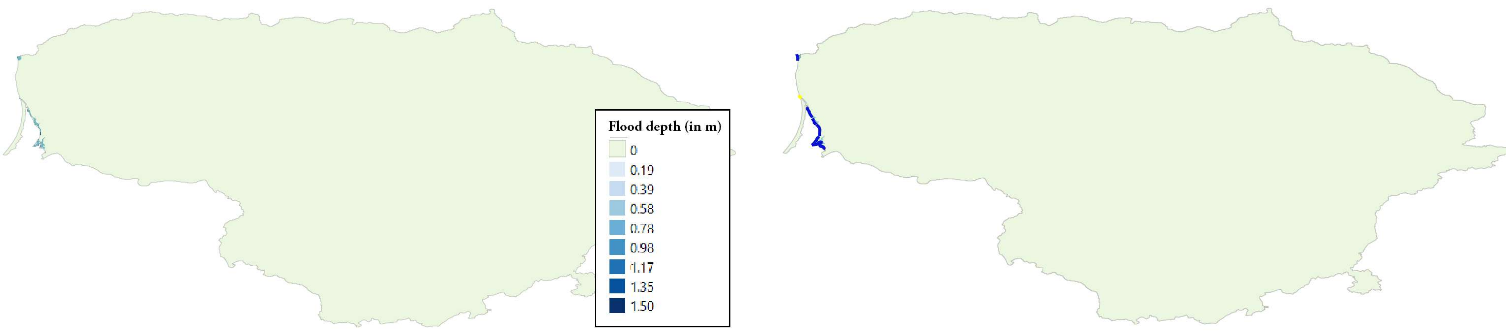
Figure D.7: Inundation and coastal reinforcement map of Germany for RCP8.5 in 2080 for the 50th percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

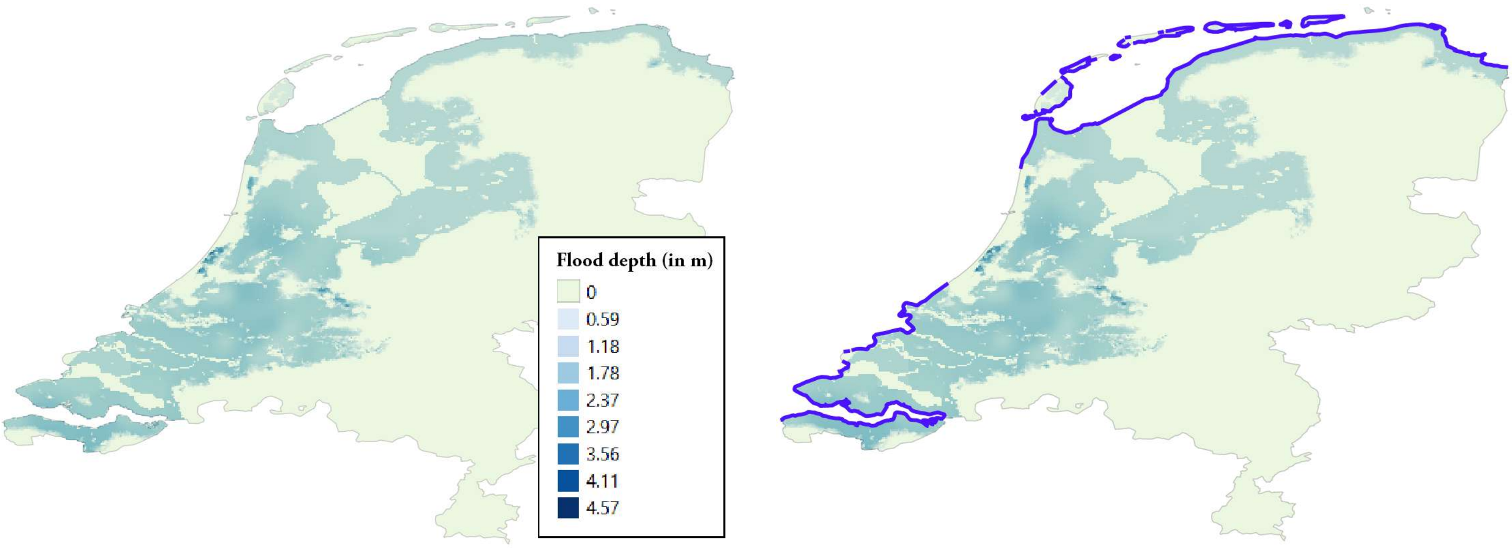
Figure D.8: Inundation and coastal reinforcement map of Latvia for RCP8.5 in 2080 for the 50th percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

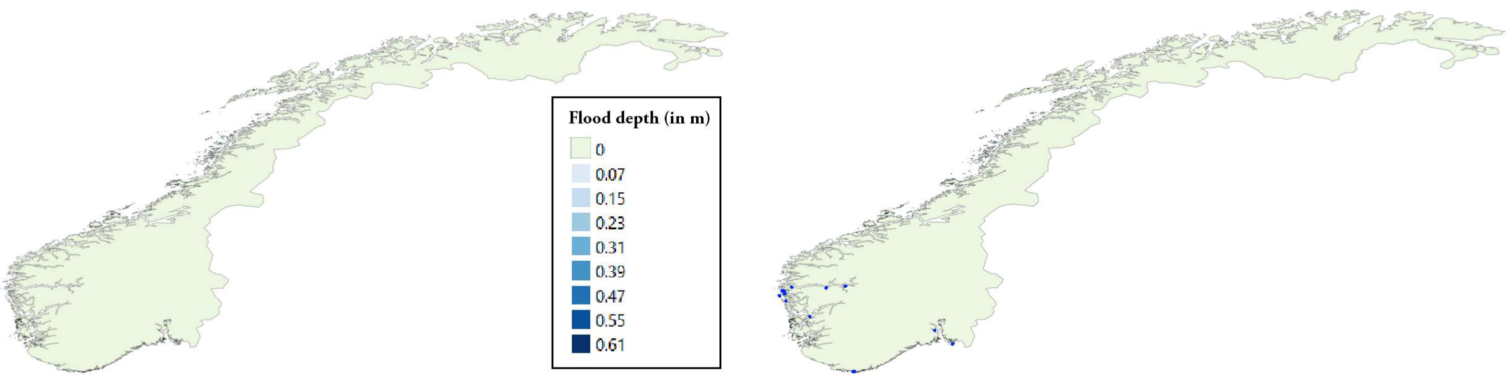
Figure D.9: Inundation and coastal reinforcement map of Lithuania for RCP8.5 in 2080 for the 50th percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

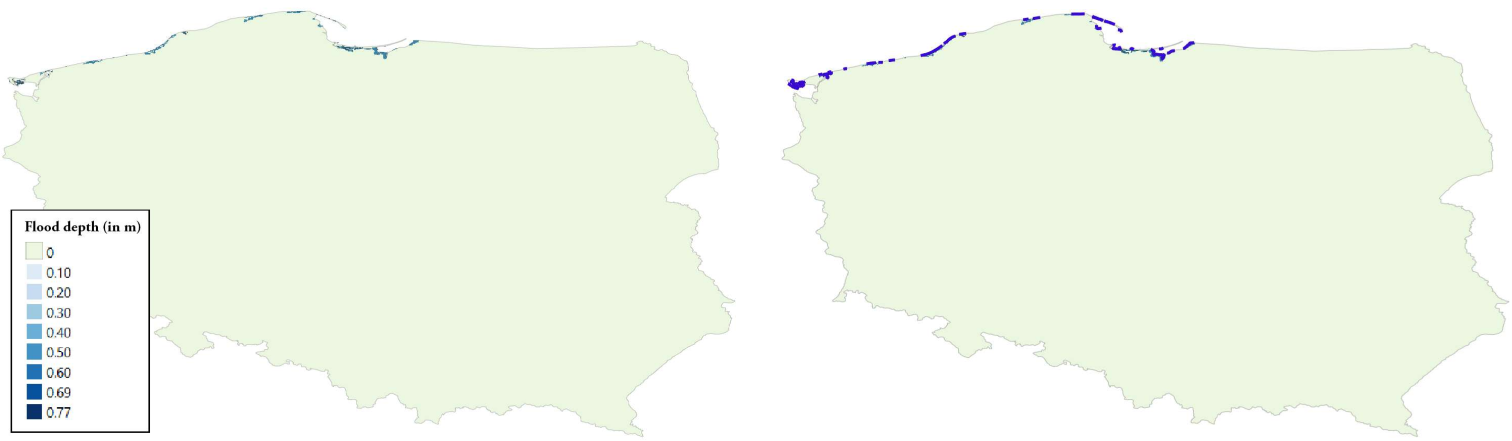
Figure D.10: Inundation and coastal reinforcement map of the Netherlands for RCP8.5 in 2080 for the 50$^{th}$ percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

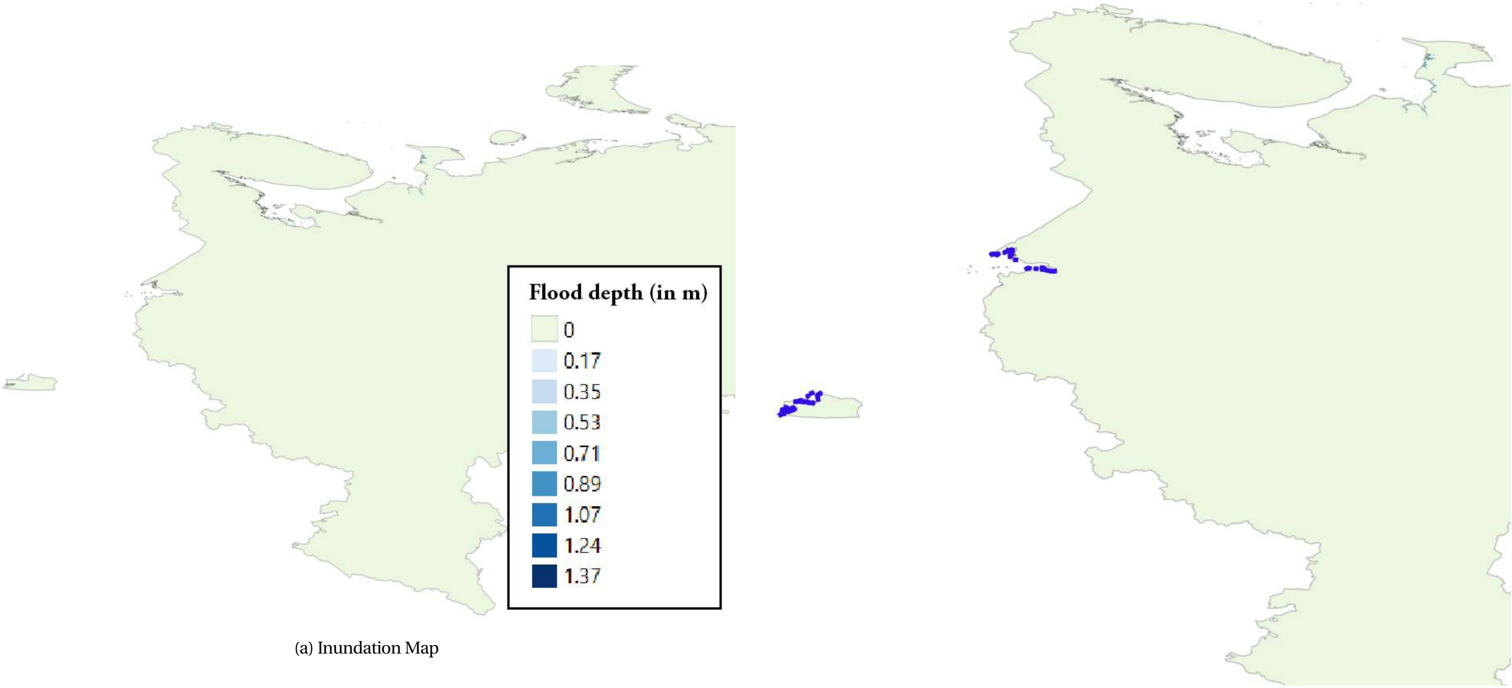
Figure D.11: Inundation and coastal reinforcement map of Norway for RCP8.5 in 2080 for the 50$^{th}$ percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

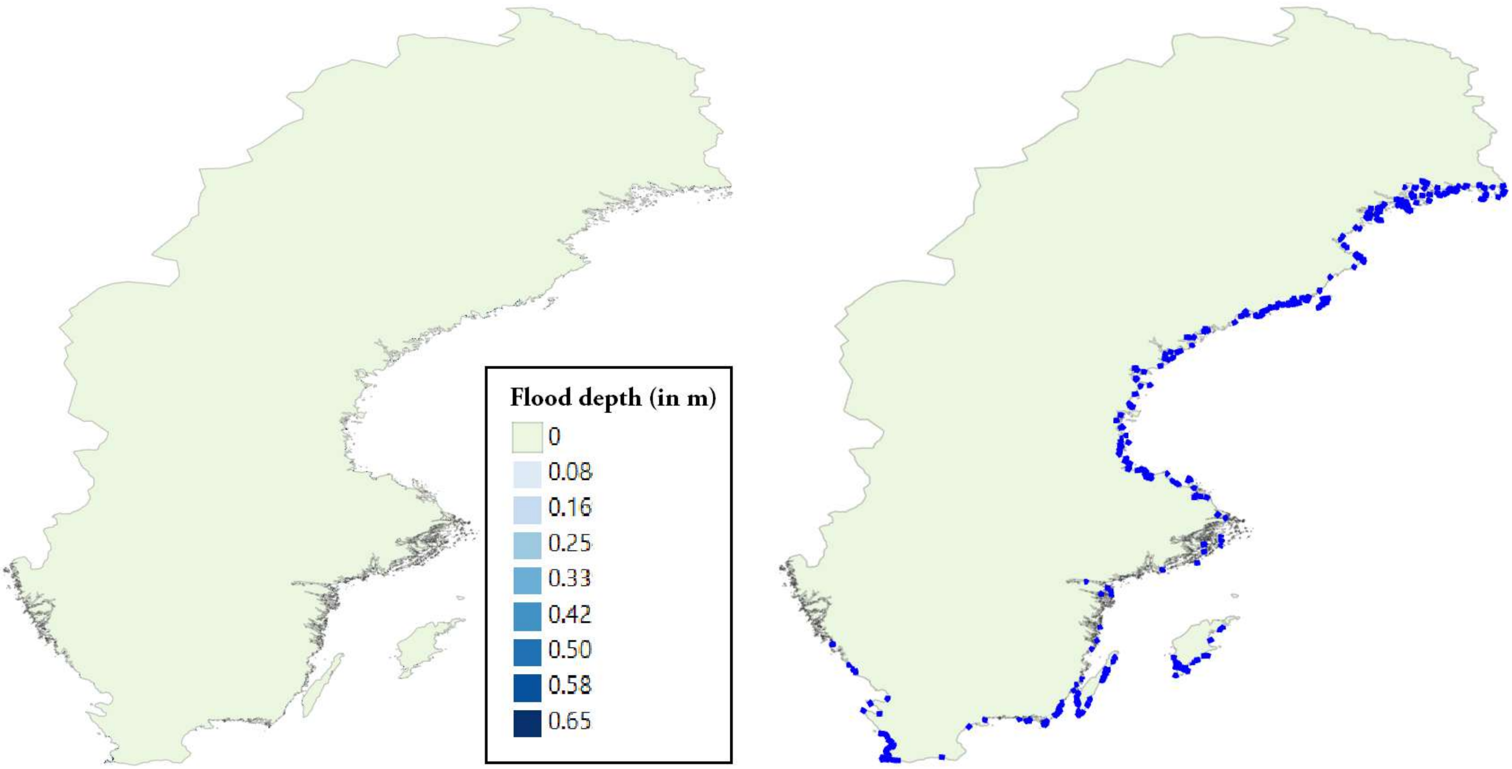
Figure D.12: Inundation and coastal reinforcement map of Poland for RCP8.5 in 2080 for the 50$^{th}$ percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

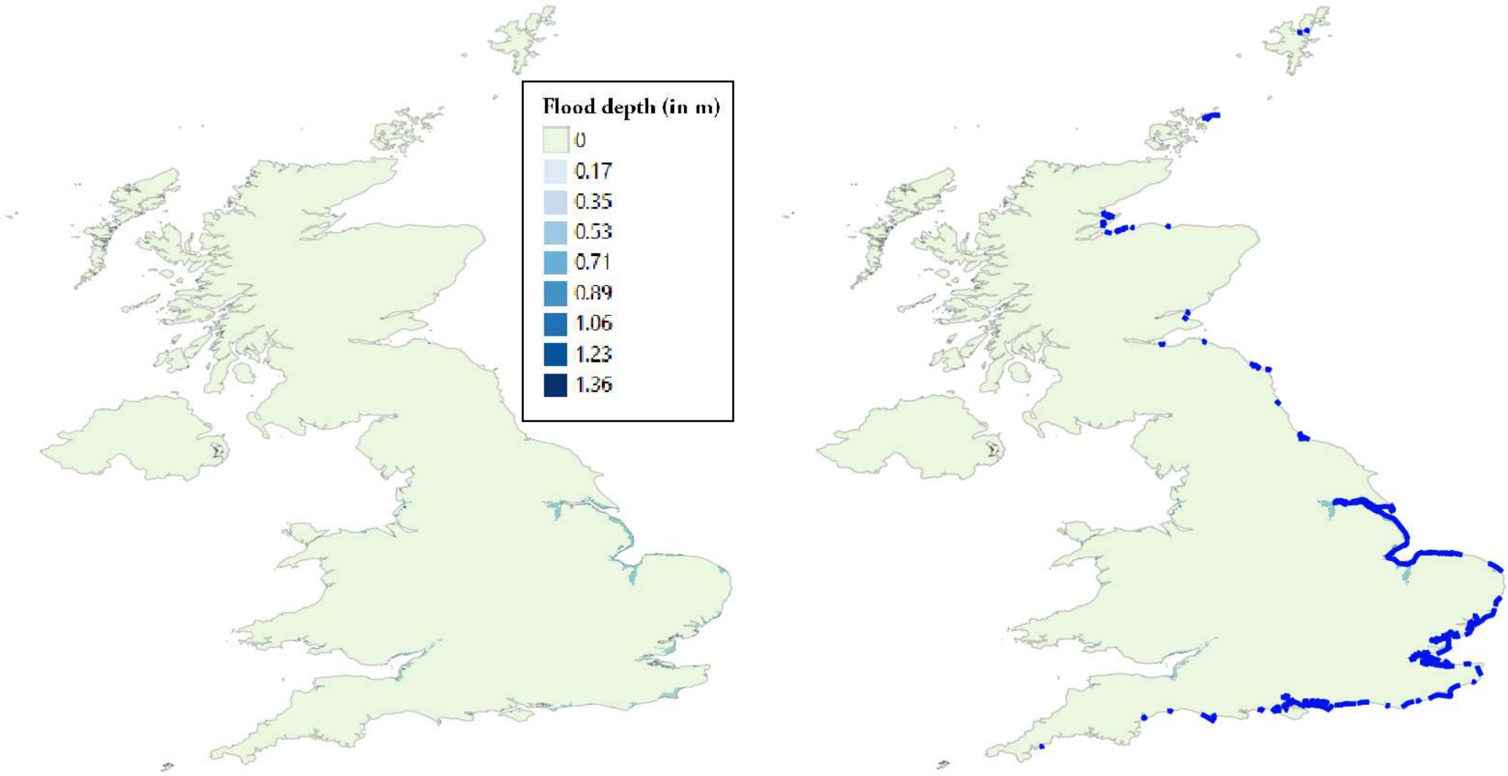
Figure D.13: Inundation and coastal reinforcement map of Russia for RCP8.5 in 2080 for the 50$^{th}$ percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

Figure D.14: Inundation and coastal reinforcement map of Sweden for RCP8.5 in 2080 for the 50$^{th}$ percentile.




(a) Inundation Map

(b) Indicated Coast Reinforcement

Figure D.15: Inundation and coastal reinforcement map of the United Kingdom for RCP8.5 in 2080 for the 50th percentile.

# E

# Appendix E

## E.1. NEED Bathymetry Information

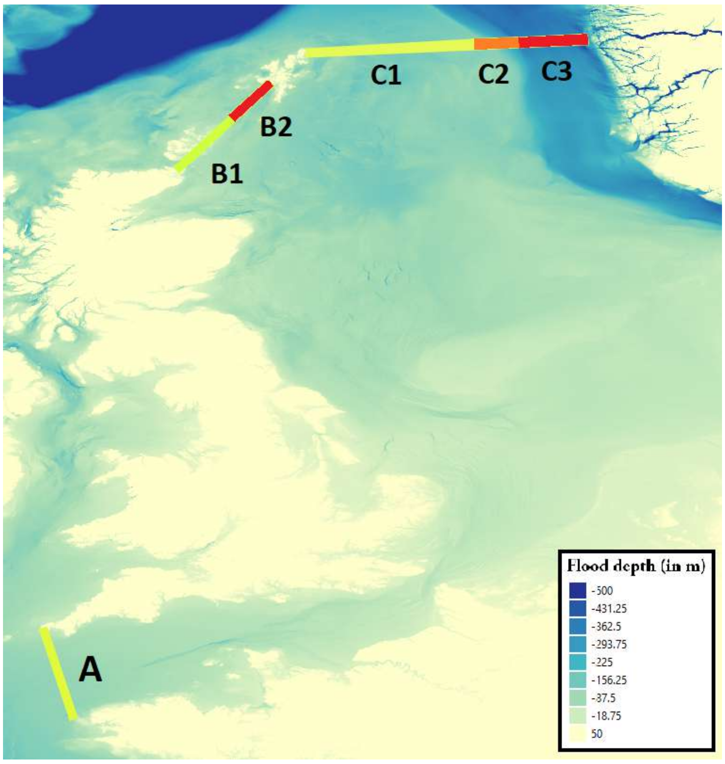



Figure E.1: Bathymetry map with the NEED structure divided in sections.

Table E.1: Overview of the lengths and depths of the NEED based on the bathymetry map from GEBCO.

| Section | Part | Length (km) | Depth Interval (m) | Depth Average (m) |
|---|---|---|---|---|
| **A** | Total | **150** | 60 - 120 | 90 |
| **B1** | Shallow | 75 | 30 - 90 | 60 |
| **B2** | Deep | 70 | 90 - 110 | 100 |
| **C1** | Shallow | 180 | 90 - 140 | 130 |
| **C2** | Transition | 50 | 140 - 350 | 240 |
| **C3** | Deep | 70 | 340 - 390 | 350 |

## E.2. NEED Calculation - Bottom Width

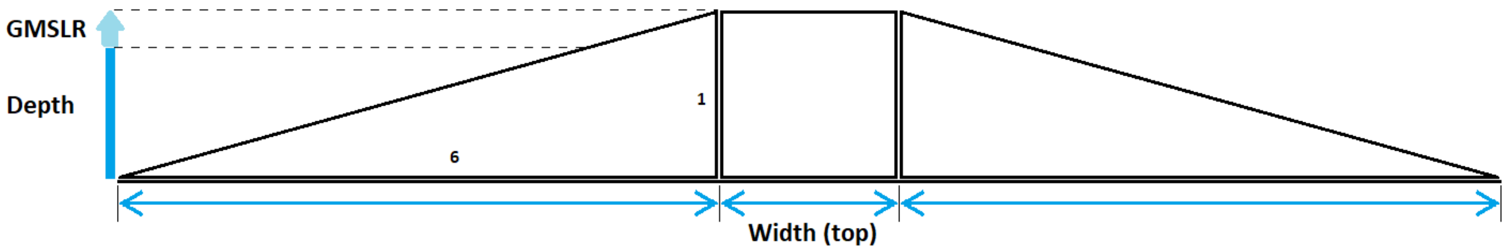



Figure E.2: Cross section of NEED which in blue indicates the calculated total bottom width of structure.

$$Bottom\ Width = Width\,(top) + Slope \cdot (Depth + GMSLR) \cdot 2 \tag{E.1}$$

Table E.2: Overview of the bottom widths (in m) per section as function of GMSLR for NEED with slope 1:6.

| | Bottom Width per Section (1:6) | | | | | |
|---|---|---|---|---|---|---|
| GMSLR | A | B1 | B2 | C1 | C2 | C3 |
| 0 | 1,105 | 745 | 1,225 | 1,585 | 2,905 | 4,225 |
| 1 | 1,117 | 757 | 1,237 | 1,597 | 2,917 | 4,237 |
| 2 | 1,129 | 769 | 1,249 | 1,609 | 2,929 | 4,249 |
| 3 | 1,141 | 781 | 1,261 | 1,621 | 2,941 | 4,261 |
| 4 | 1,153 | 793 | 1,273 | 1,633 | 2,953 | 4,273 |
| 5 | 1,165 | 805 | 1,285 | 1,645 | 2,965 | 4,285 |
| 6 | 1,177 | 817 | 1,297 | 1,657 | 2,977 | 4,297 |
| 7 | 1,189 | 829 | 1,309 | 1,669 | 2,989 | 4,309 |
| 8 | 1,201 | 841 | 1,321 | 1,681 | 3,001 | 4,321 |
| 9 | 1,213 | 853 | 1,333 | 1,693 | 3,013 | 4,333 |
| 10 | 1,225 | 865 | 1,345 | 1,705 | 3,025 | 4,345 |

Table E.3: Overview of the bottom widths (in m) per section as function of GMSLR for NEED with slope 1:4 and 1:5.

| | Bottom Width per Section (1:4) | | | | | | Bottom Width per Section (1:5) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GMSLR | A | B1 | B2 | C1 | C2 | C3 | A | B1 | B2 | C1 | C2 | C3 |
| 0 | 745 | 505 | 825 | 1,065 | 1,945 | 2,825 | 925 | 625 | 1,025 | 1,325 | 2,425 | 3,525 |
| 1 | 753 | 513 | 833 | 1,073 | 1,953 | 2,833 | 935 | 635 | 1,035 | 1,335 | 2,435 | 3,535 |
| 2 | 761 | 521 | 841 | 1,081 | 1,961 | 2,841 | 945 | 645 | 1,045 | 1,345 | 2,445 | 3,545 |
| 3 | 769 | 529 | 849 | 1,089 | 1,969 | 2,849 | 955 | 655 | 1,055 | 1,355 | 2,455 | 3,555 |
| 4 | 777 | 537 | 857 | 1,097 | 1,977 | 2,857 | 965 | 665 | 1,065 | 1,365 | 2,465 | 3,565 |
| 5 | 785 | 545 | 865 | 1,105 | 1,985 | 2,865 | 975 | 675 | 1,075 | 1,375 | 2,475 | 3,575 |
| 6 | 793 | 553 | 873 | 1,113 | 1,993 | 2,873 | 985 | 685 | 1,085 | 1,385 | 2,485 | 3,585 |
| 7 | 801 | 561 | 881 | 1,121 | 2,001 | 2,881 | 995 | 695 | 1,095 | 1,395 | 2,495 | 3,595 |
| 8 | 809 | 569 | 889 | 1,129 | 2,009 | 2,889 | 1,005 | 705 | 1,105 | 1,405 | 2,505 | 3,605 |
| 9 | 817 | 577 | 897 | 1,137 | 2,017 | 2,897 | 1,015 | 715 | 1,115 | 1,415 | 2,515 | 3,615 |
| 10 | 825 | 585 | 905 | 1,145 | 2,025 | 2,905 | 1,025 | 725 | 1,125 | 1,425 | 2,525 | 3,625 |

## E.3. NEED Calculation - Length Sloped Side

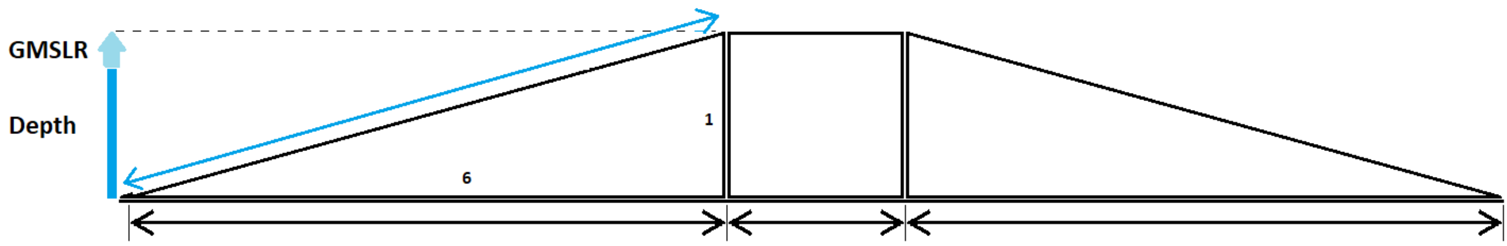



Figure E.3: Cross section of NEED which in blue indicates the calculated length of one sloped side of structure.

$$Length\ One\ Sloped\ Side = \sqrt{(Depth + GMSLR)^2 + (Depth \cdot Slope)^2} \tag{E.2}$$

Table E.4: Overview of the length on one sloped side (in m) per section as function of GMSLR for NEED with slope 1:6.

| | Length Sloped Side (one side) (1:6) | | | | | |
|---|---|---|---|---|---|---|
| **GMSLR** | **A** | **B1** | **B2** | **C1** | **C2** | **C3** |
| 0 | 547.45 | 364.97 | 608.28 | 790.76 | 1,459.86 | 2,128.97 |
| 1 | 547.61 | 365.13 | 608.44 | 790.92 | 1,460.03 | 2,129.13 |
| 2 | 547.78 | 365.30 | 608.61 | 791.09 | 1,460.19 | 2,129.30 |
| 3 | 547.95 | 365.47 | 608.78 | 791.26 | 1,460.36 | 2,129.46 |
| 4 | 548.12 | 365.64 | 608.95 | 791.43 | 1,460.53 | 2,129.63 |
| 5 | 548.29 | 365.82 | 609.12 | 791.60 | 1,460.69 | 2,129.79 |
| 6 | 548.47 | 366.00 | 609.29 | 791.77 | 1,460.86 | 2,129.96 |
| 7 | 548.64 | 366.18 | 609.47 | 791.94 | 1,461.03 | 2,130.13 |
| 8 | 548.82 | 366.37 | 609.64 | 792.11 | 1,461.20 | 2,130.30 |
| 9 | 549.00 | 366.55 | 609.82 | 792.29 | 1,461.37 | 2,130.46 |
| 10 | 549.18 | 366.74 | 610.00 | 792.46 | 1,461.54 | 2,130.63 |

Table E.5: Overview of the length on one sloped side (in m) per section as function of GMSLR for NEED with slope 1:4 and 1:5.

| | Length Sloped Side (one side) (1:4) | | | | | | Length Sloped Side (one side) (1:5) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GMSLR** | **A** | **B1** | **B2** | **C1** | **C2** | **C3** | **A** | **B1** | **B2** | **C1** | **C2** | **C3** |
| 0 | 371.08 | 247.39 | 412.31 | 536.00 | 989.55 | 1,443.09 | 458.91 | 305.94 | 509.90 | 662.87 | 1,223.76 | 1,784.66 |
| 1 | 371.32 | 247.63 | 412.55 | 536.25 | 989.79 | 1,443.33 | 459.11 | 306.14 | 510.10 | 663.07 | 1,223.96 | 1,784.85 |
| 2 | 371.57 | 247.88 | 412.80 | 536.49 | 990.03 | 1,443.57 | 459.31 | 306.34 | 510.30 | 663.27 | 1,224.16 | 1,785.05 |
| 3 | 371.82 | 248.13 | 413.05 | 536.74 | 990.28 | 1,443.82 | 459.51 | 306.54 | 510.50 | 663.47 | 1,224.36 | 1,785.25 |
| 4 | 372.07 | 248.39 | 413.30 | 536.99 | 990.52 | 1,444.06 | 459.71 | 306.75 | 510.70 | 663.67 | 1,224.56 | 1,785.45 |
| 5 | 372.32 | 248.65 | 413.55 | 537.24 | 990.77 | 1,444.31 | 459.92 | 306.96 | 510.91 | 663.87 | 1,224.76 | 1,785.64 |
| 6 | 372.58 | 248.91 | 413.81 | 537.49 | 991.02 | 1,444.55 | 460.13 | 307.17 | 511.11 | 664.08 | 1,224.96 | 1,785.84 |
| 7 | 372.84 | 249.18 | 414.06 | 537.74 | 991.27 | 1,444.80 | 460.34 | 307.39 | 511.32 | 664.28 | 1,225.16 | 1,786.04 |
| 8 | 373.10 | 249.45 | 414.32 | 538.00 | 991.52 | 1,445.05 | 460.55 | 307.61 | 511.53 | 664.49 | 1,225.36 | 1,786.24 |
| 9 | 373.36 | 249.72 | 414.59 | 538.26 | 991.77 | 1,445.30 | 460.76 | 307.83 | 511.74 | 664.70 | 1,225.56 | 1,786.44 |
| 10 | 373.63 | 250.00 | 414.85 | 538.52 | 992.02 | 1,445.54 | 460.98 | 308.06 | 511.96 | 664.91 | 1,225.77 | 1,786.64 |

## E.4. NEED Calculation - Surface Area Sloped Side

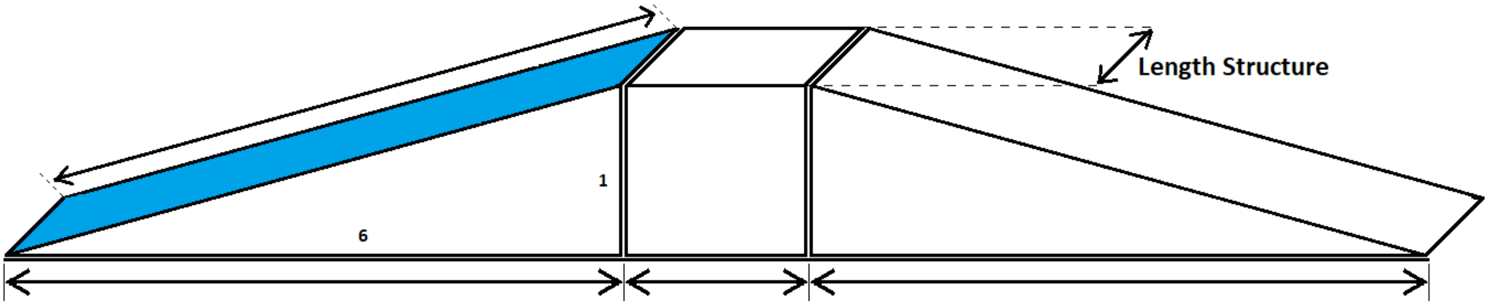



Figure E.4: Cross section of NEED which in blue indicates the calculated surface area of one sloped side of structure.

$$Surface\ Area\ Sloped\ Side = Length\ One\ Sloped\ Side \cdot Length\ Structure \tag{E.3}$$

Table E.6: Overview of the surface area of one sloped side (in $m^2$) per section as function of GMSLR for NEED with slope 1:6.

| GMSLR | Surface Area Sloped Side (one side) (1:6) | | | | | | NEED Total |
|---|---|---|---|---|---|---|---|
| | A | B1 | B2 | C1 | C2 | C3 | |
| 0 | 82,117,294 | 27,372,431 | 42,579,338 | 142,336,643 | 72,993,150 | 149,027,682 | 1,032,853,078 |
| 1 | 82,142,087 | 27,384,861 | 42,590,902 | 142,366,346 | 73,001,387 | 149,039,206 | 1,033,049,577 |
| 2 | 82,167,147 | 27,397,491 | 42,602,577 | 142,396,270 | 73,009,657 | 149,050,762 | 1,033,247,806 |
| 3 | 82,192,472 | 27,410,320 | 42,614,365 | 142,426,415 | 73,017,960 | 149,062,350 | 1,033,447,763 |
| 4 | 82,218,064 | 27,423,348 | 42,626,264 | 142,456,781 | 73,026,297 | 149,073,970 | 1,033,649,445 |
| 5 | 82,243,921 | 27,436,575 | 42,638,275 | 142,487,368 | 73,034,666 | 149,085,621 | 1,033,852,852 |
| 6 | 82,270,043 | 27,450,000 | 42,650,397 | 142,518,176 | 73,043,069 | 149,097,305 | 1,034,057,982 |
| 7 | 82,296,431 | 27,463,624 | 42,662,631 | 142,549,204 | 73,051,506 | 149,109,021 | 1,034,264,833 |
| 8 | 82,323,083 | 27,477,445 | 42,674,976 | 142,580,453 | 73,059,975 | 149,120,769 | 1,034,473,403 |
| 9 | 82,350,000 | 27,491,465 | 42,687,433 | 142,611,922 | 73,068,478 | 149,132,548 | 1,034,683,692 |
| 10 | 82,377,181 | 27,505,681 | 42,700,000 | 142,643,612 | 73,077,014 | 149,144,360 | 1,034,895,696 |

Table E.7: Overview of the surface area of one sloped side (in $10^6$ $m^2$) per section as function of GMSLR for NEED with slope 1:4 and 1:5.

| GMSLR | Surface Area Sloped Side (one side) (1:4) | | | | | | | Surface Area Sloped Side (one side) (1:5) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B1 | B2 | C1 | C2 | C3 | NEED Total | A | B1 | B2 | C1 | C2 | C3 | NEED Total |
| 0 | 55.66 | 18.55 | 28.86 | 96.48 | 49.48 | 101.02 | 700.10 | 68.84 | 22.95 | 35.69 | 119.32 | 61.19 | 124.93 | 865.81 |
| 1 | 55.70 | 18.57 | 28.88 | 96.52 | 49.49 | 101.03 | 700.39 | 68.87 | 22.96 | 35.71 | 119.35 | 61.20 | 124.94 | 866.05 |
| 2 | 55.74 | 18.59 | 28.90 | 96.57 | 49.50 | 101.05 | 700.69 | 68.90 | 22.98 | 35.72 | 119.39 | 61.21 | 124.95 | 866.28 |
| 3 | 55.77 | 18.61 | 28.91 | 96.61 | 49.51 | 101.07 | 700.98 | 68.93 | 22.99 | 35.73 | 119.42 | 61.22 | 124.97 | 866.52 |
| 4 | 55.81 | 18.63 | 28.93 | 96.66 | 49.53 | 101.08 | 701.28 | 68.96 | 23.01 | 35.75 | 119.46 | 61.23 | 124.98 | 866.76 |
| 5 | 55.85 | 18.65 | 28.95 | 96.70 | 49.54 | 101.10 | 701.58 | 68.99 | 23.02 | 35.76 | 119.50 | 61.24 | 125.00 | 867.01 |
| 6 | 55.89 | 18.67 | 28.97 | 96.75 | 49.55 | 101.12 | 701.88 | 69.02 | 23.04 | 35.78 | 119.53 | 61.25 | 125.01 | 867.25 |
| 7 | 55.93 | 18.69 | 28.98 | 96.79 | 49.56 | 101.14 | 702.18 | 69.05 | 23.05 | 35.79 | 119.57 | 61.26 | 125.02 | 867.50 |
| 8 | 55.97 | 18.71 | 29.00 | 96.84 | 49.58 | 101.15 | 702.49 | 69.08 | 23.07 | 35.81 | 119.61 | 61.27 | 125.04 | 867.75 |
| 9 | 56.00 | 18.73 | 29.02 | 96.89 | 49.59 | 101.17 | 702.80 | 69.11 | 23.09 | 35.82 | 119.65 | 61.28 | 125.05 | 868.00 |
| 10 | 56.04 | 18.75 | 29.04 | 96.93 | 49.60 | 101.19 | 703.11 | 69.15 | 23.10 | 35.84 | 119.68 | 61.29 | 125.07 | 868.25 |

## E.5. NEED CALCULATION - CROSS-SECTIONAL AREA (ONE SLOPED SIDE)

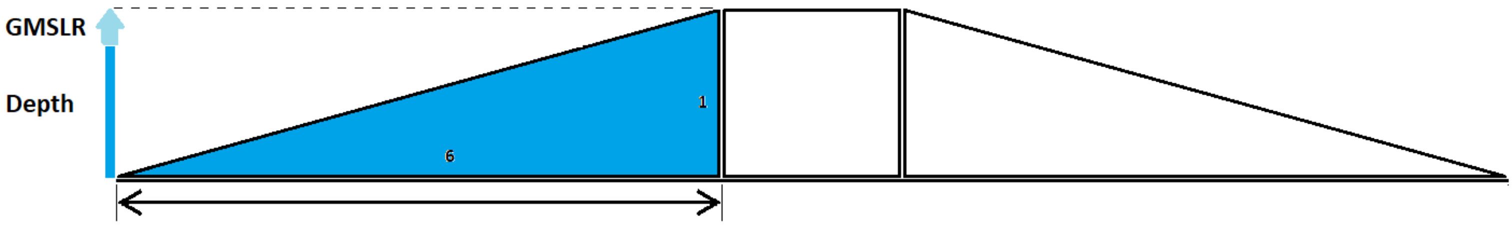



Figure E.5: Cross section of NEED which in blue indicates the calculated cross-sectional area of one sloped side.

$$CS.A\ One\ Sloped\ Side = \frac{(Depth + GMSLR) \cdot ((Depth + GMSLR) \cdot Slope)}{2} \tag{E.4}$$

Table E.8: Overview of the cross-sectional area of one sloped side (in $m^2$) per section as function of GMSLR for NEED with slope 1:6.

| | Cross-Sectional Area Sloped Side (one side) (1:6) | | | | | |
|---|---|---|---|---|---|---|
| **GMSLR** | **A** | **B1** | **B2** | **C1** | **C2** | **C3** |
| 0 | 24,300 | 10,800 | 30,000 | 50,700 | 172,800 | 367,500 |
| 1 | 24,843 | 11,163 | 30,603 | 51,483 | 174,243 | 369,603 |
| 2 | 25,392 | 11,532 | 31,212 | 52,272 | 175,692 | 371,712 |
| 3 | 25,947 | 11,907 | 31,827 | 53,067 | 177,147 | 373,827 |
| 4 | 26,508 | 12,288 | 32,448 | 53,868 | 178,608 | 375,948 |
| 5 | 27,075 | 12,675 | 33,075 | 54,675 | 180,075 | 378,075 |
| 6 | 27,648 | 13,068 | 33,708 | 55,488 | 181,548 | 380,208 |
| 7 | 28,227 | 13,467 | 34,347 | 56,307 | 183,027 | 382,347 |
| 8 | 28,812 | 13,872 | 34,992 | 57,132 | 184,512 | 384,492 |
| 9 | 29,403 | 14,283 | 35,643 | 57,963 | 186,003 | 386,643 |
| 10 | 30,000 | 14,700 | 36,300 | 58,800 | 187,500 | 388,800 |

Table E.9: Overview of the cross-sectional area of one sloped side (in $m^2$) per section as function of GMSLR for NEED with slope 1:4 and 1:5.

| | Cross-Sectional Area Sloped Side (one side) (1:4) | | | | | | Cross-Sectional Area Sloped Side (one side) (1:5) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GMSLR** | **A** | **B1** | **B2** | **C1** | **C2** | **C3** | **A** | **B1** | **B2** | **C1** | **C2** | **C3** |
| 0 | 16,200 | 7,200 | 20,000 | 33,800 | 115,200 | 245,000 | 20,250 | 9,000 | 25,000 | 42,250 | 144,000 | 306,250 |
| 1 | 16,562 | 7,442 | 20,402 | 34,322 | 116,162 | 246,402 | 20,703 | 9,303 | 25,503 | 42,903 | 145,203 | 308,003 |
| 2 | 16,928 | 7,688 | 20,808 | 34,848 | 117,128 | 247,808 | 21,160 | 9,610 | 26,010 | 43,560 | 146,410 | 309,760 |
| 3 | 17,298 | 7,938 | 21,218 | 35,378 | 118,098 | 249,218 | 21,623 | 9,923 | 26,523 | 44,223 | 147,623 | 311,523 |
| 4 | 17,672 | 8,192 | 21,632 | 35,912 | 119,072 | 250,632 | 22,090 | 10,240 | 27,040 | 44,890 | 148,840 | 313,290 |
| 5 | 18,050 | 8,450 | 22,050 | 36,450 | 120,050 | 252,050 | 22,563 | 10,563 | 27,563 | 45,563 | 150,063 | 315,063 |
| 6 | 18,432 | 8,712 | 22,472 | 36,992 | 121,032 | 253,472 | 23,040 | 10,890 | 28,090 | 46,240 | 151,290 | 316,840 |
| 7 | 18,818 | 8,978 | 22,898 | 37,538 | 122,018 | 254,898 | 23,523 | 11,223 | 28,623 | 46,923 | 152,523 | 318,623 |
| 8 | 19,208 | 9,248 | 23,328 | 38,088 | 123,008 | 256,328 | 24,010 | 11,560 | 29,160 | 47,610 | 153,760 | 320,410 |
| 9 | 19,602 | 9,522 | 23,762 | 38,642 | 124,002 | 257,762 | 24,503 | 11,903 | 29,703 | 48,303 | 155,003 | 322,203 |
| 10 | 20,000 | 9,800 | 24,200 | 39,200 | 125,000 | 259,200 | 25,000 | 12,250 | 30,250 | 49,000 | 156,250 | 324,000 |

## E.6. NEED Calculation - Cross-Sectional Area (middle)

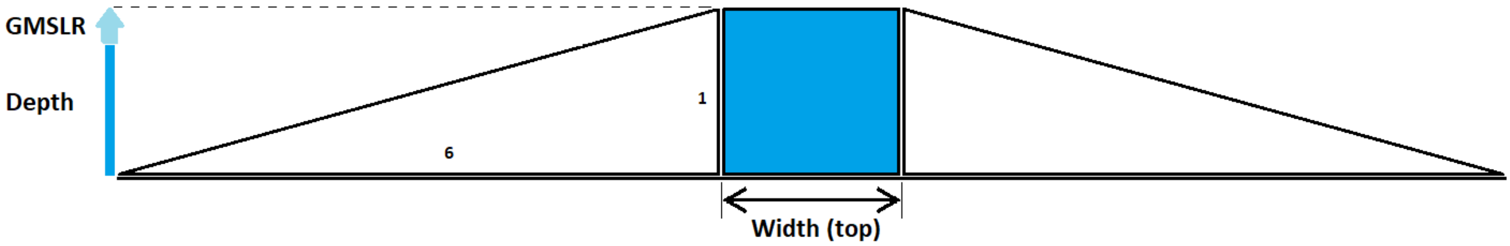



Figure E.6: Cross section of NEED which in blue indicates the calculated cross-sectional area of middle part.

$$CS.A\ Middle = (Depth + GMSLR) \cdot Width\,(top) \tag{E.5}$$

Table E.10: Overview of the cross-sectional area of middle part (in $m^2$) per section as function of GMSLR for NEED with slope 1:6.

| | Cross-Sectional Area Middle Part | | | | | |
|---|---|---|---|---|---|---|
| **GMSLR** | **A** | **B1** | **B2** | **C1** | **C2** | **C3** |
| 0 | 2,250 | 1,500 | 2,500 | 3,250 | 6,000 | 8,750 |
| 1 | 2,275 | 1,525 | 2,525 | 3,275 | 6,025 | 8,775 |
| 2 | 2,300 | 1,550 | 2,550 | 3,300 | 6,050 | 8,800 |
| 3 | 2,325 | 1,575 | 2,575 | 3,325 | 6,075 | 8,825 |
| 4 | 2,350 | 1,600 | 2,600 | 3,350 | 6,100 | 8,850 |
| 5 | 2,375 | 1,625 | 2,625 | 3,375 | 6,125 | 8,875 |
| 6 | 2,400 | 1,650 | 2,650 | 3,400 | 6,150 | 8,900 |
| 7 | 2,425 | 1,675 | 2,675 | 3,425 | 6,175 | 8,925 |
| 8 | 2,450 | 1,700 | 2,700 | 3,450 | 6,200 | 8,950 |
| 9 | 2,475 | 1,725 | 2,725 | 3,475 | 6,225 | 8,975 |
| 10 | 2,500 | 1,750 | 2,750 | 3,500 | 6,250 | 9,000 |

The cross-sectional area of the middle part is not dependent on the slope. Thus, the values stated in Table E.10 are also for the NEED structures with a slope 1:4 and 1:5.

## E.7. NEED Calculation - Cross-Sectional Area (whole)

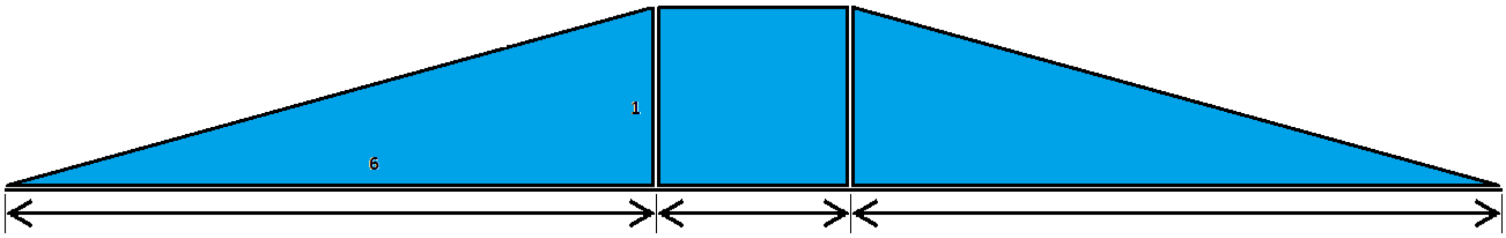



Figure E.7: Cross section of NEED which in blue indicates the calculated cross-sectional area of whole structure.

$$Cross\text{−}Sectional\ Area\ (CS.A)\ Section = CS.A\ One\ Sloped\ Side + CS.A\ Middle + CS.A\ One\ Sloped\ Side \tag{E.6}$$

Table E.11: Overview of the entire cross-sectional area (in $m^2$) per section as function of GMSLR for NEED with slope 1:6.

| | Cross-Sectional Area (whole) (1:6) | | | | | | |
|---|---|---|---|---|---|---|---|
| GMSLR | A | B1 | B2 | C1 | C2 | C3 | NEED Total |
| 0 | 50,850 | 23,100 | 62,500 | 104,650 | 351,600 | 743,750 | 1,336,450 |
| 1 | 51,961 | 23,851 | 63,731 | 106,241 | 354,511 | 747,981 | 1,348,276 |
| 2 | 53,084 | 24,614 | 64,974 | 107,844 | 357,434 | 752,224 | 1,360,174 |
| 3 | 54,219 | 25,389 | 66,229 | 109,459 | 360,369 | 756,479 | 1,372,144 |
| 4 | 55,366 | 26,176 | 67,496 | 111,086 | 363,316 | 760,746 | 1,384,186 |
| 5 | 56,525 | 26,975 | 68,775 | 112,725 | 366,275 | 765,025 | 1,396,300 |
| 6 | 57,696 | 27,786 | 70,066 | 114,376 | 369,246 | 769,316 | 1,408,486 |
| 7 | 58,879 | 28,609 | 71,369 | 116,039 | 372,229 | 773,619 | 1,420,744 |
| 8 | 60,074 | 29,444 | 72,684 | 117,714 | 375,224 | 777,934 | 1,433,074 |
| 9 | 61,281 | 30,291 | 74,011 | 119,401 | 378,231 | 782,261 | 1,445,476 |
| 10 | 62,500 | 31,150 | 75,350 | 121,100 | 381,250 | 786,600 | 1,457,950 |

Table E.12: Overview of the entire cross-sectional area (in $10^3$ $m^2$) per section as function of GMSLR for NEED with slope 1:4 and 1:5.

| | Cross-Sectional Area (whole) (1:4) | | | | | | | Cross-Sectional Area (whole) (1:5) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GMSLR | A | B1 | B2 | C1 | C2 | C3 | NEED Total | A | B1 | B2 | C1 | C2 | C3 | NEED Total |
| 0 | 34.65 | 15.90 | 42.50 | 70.85 | 236.40 | 498.75 | 899.05 | 42.75 | 19.50 | 52.50 | 87.75 | 294.00 | 621.25 | 1,117.75 |
| 1 | 35.40 | 16.41 | 43.33 | 71.92 | 238.35 | 501.58 | 906.98 | 43.68 | 20.13 | 53.53 | 89.08 | 296.43 | 624.78 | 1,127.63 |
| 2 | 36.16 | 16.93 | 44.17 | 73.00 | 240.31 | 504.42 | 914.97 | 44.62 | 20.77 | 54.57 | 90.42 | 298.87 | 628.32 | 1,137.57 |
| 3 | 36.92 | 17.45 | 45.01 | 74.08 | 242.27 | 507.26 | 923.00 | 45.57 | 21.42 | 55.62 | 91.77 | 301.32 | 631.87 | 1,147.57 |
| 4 | 37.69 | 17.98 | 45.86 | 75.17 | 244.24 | 510.11 | 931.07 | 46.53 | 22.08 | 56.68 | 93.13 | 303.78 | 635.43 | 1,157.63 |
| 5 | 38.48 | 18.53 | 46.73 | 76.28 | 246.23 | 512.98 | 939.20 | 47.50 | 22.75 | 57.75 | 94.50 | 306.25 | 639.00 | 1,167.75 |
| 6 | 39.26 | 19.07 | 47.59 | 77.38 | 248.21 | 515.84 | 947.37 | 48.48 | 23.43 | 58.83 | 95.88 | 308.73 | 642.58 | 1,177.93 |
| 7 | 40.06 | 19.63 | 48.47 | 78.50 | 250.21 | 518.72 | 955.60 | 49.47 | 24.12 | 59.92 | 97.27 | 311.22 | 646.17 | 1,188.17 |
| 8 | 40.87 | 20.20 | 49.36 | 79.63 | 252.22 | 521.61 | 963.87 | 50.47 | 24.82 | 61.02 | 98.67 | 313.72 | 649.77 | 1,198.47 |
| 9 | 41.68 | 20.77 | 50.25 | 80.76 | 254.23 | 524.50 | 972.18 | 51.48 | 25.53 | 62.13 | 100.08 | 316.23 | 653.38 | 1,208.83 |
| 10 | 42.50 | 21.35 | 51.15 | 81.90 | 256.25 | 527.40 | 980.55 | 52.50 | 26.25 | 63.25 | 101.50 | 318.75 | 657.00 | 1,219.25 |

## E.8. NEED Calculation - Volume (whole)

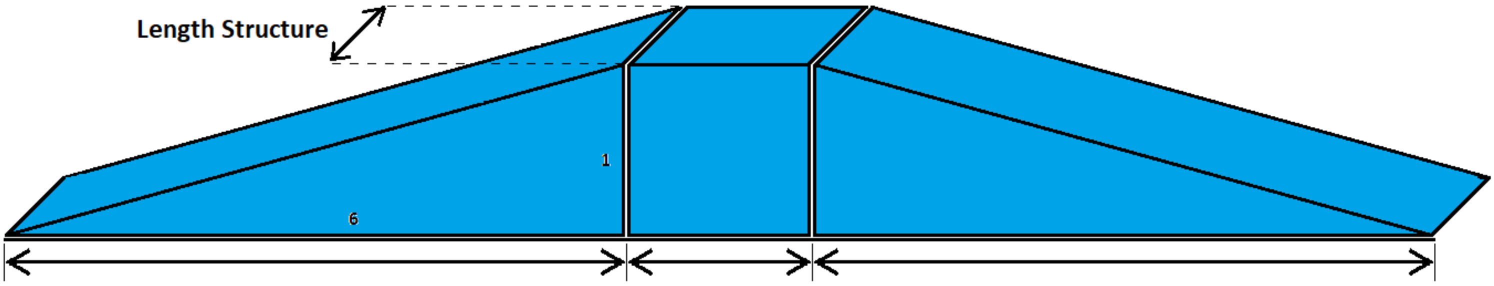



Figure E.8: Cross section of NEED which in blue indicates the calculated volume of whole structure.

$$Volume\ Section = CS.A\ Section \cdot Length\ Structure \tag{E.7}$$

Table E.13: Overview of the entire volume (in $m^3$) per section as function of GMSLR for NEED with slope 1:6.

| | Volume (whole) | | | | | | |
|---|---|---|---|---|---|---|---|
| GMSLR | A | B1 | B2 | C1 | C2 | C3 | NEED Total |
| 0 | 7,627,500,000 | 1,732,500,000 | 4,375,000,000 | 18,837,000,000 | 17,580,000,000 | 52,062,500,000 | 102,214,500,000 |
| 1 | 7,794,150,000 | 1,788,825,000 | 4,461,170,000 | 19,123,380,000 | 17,725,550,000 | 52,358,670,000 | 103,251,745,000 |
| 2 | 7,962,600,000 | 1,846,050,000 | 4,548,180,000 | 19,411,920,000 | 17,871,700,000 | 52,655,680,000 | 104,296,130,000 |
| 3 | 8,132,850,000 | 1,904,175,000 | 4,636,030,000 | 19,702,620,000 | 18,018,450,000 | 52,953,530,000 | 105,347,655,000 |
| 4 | 8,304,900,000 | 1,963,200,000 | 4,724,720,000 | 19,995,480,000 | 18,165,800,000 | 53,252,220,000 | 106,406,320,000 |
| 5 | 8,478,750,000 | 2,023,125,000 | 4,814,250,000 | 20,290,500,000 | 18,313,750,000 | 53,551,750,000 | 107,472,125,000 |
| 6 | 8,654,400,000 | 2,083,950,000 | 4,904,620,000 | 20,587,680,000 | 18,462,300,000 | 53,852,120,000 | 108,545,070,000 |
| 7 | 8,831,850,000 | 2,145,675,000 | 4,995,830,000 | 20,887,020,000 | 18,611,450,000 | 54,153,330,000 | 109,625,155,000 |
| 8 | 9,011,100,000 | 2,208,300,000 | 5,087,880,000 | 21,188,520,000 | 18,761,200,000 | 54,455,380,000 | 110,712,380,000 |
| 9 | 9,192,150,000 | 2,271,825,000 | 5,180,770,000 | 21,492,180,000 | 18,911,550,000 | 54,758,270,000 | 111,806,745,000 |
| 10 | 9,375,000,000 | 2,336,250,000 | 5,274,500,000 | 21,798,000,000 | 19,062,500,000 | 55,062,000,000 | 112,908,250,000 |

Table E.14: Overview of the entire volume (in $10^9$ $m^3$) per section as function of GMSLR for NEED with slope 1:4 and 1:5.

| | Volume (whole) (1:4) | | | | | | | Volume (whole) (1:5) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GMSLR | A | B1 | B2 | C1 | C2 | C3 | NEED Total | A | B1 | B2 | C1 | C2 | C3 | NEED Total |
| 0 | 5.20 | 1.19 | 2.98 | 12.75 | 11.82 | 34.91 | 68.85 | 6.41 | 1.46 | 3.68 | 15.80 | 14.70 | 43.49 | 85.53 |
| 1 | 5.31 | 1.23 | 3.03 | 12.95 | 11.92 | 35.11 | 69.55 | 6.55 | 1.51 | 3.75 | 16.03 | 14.82 | 43.73 | 86.40 |
| 2 | 5.42 | 1.27 | 3.09 | 13.14 | 12.02 | 35.31 | 70.25 | 6.69 | 1.56 | 3.82 | 16.28 | 14.94 | 43.98 | 87.27 |
| 3 | 5.54 | 1.31 | 3.15 | 13.33 | 12.11 | 35.51 | 70.95 | 6.84 | 1.61 | 3.89 | 16.52 | 15.07 | 44.23 | 88.15 |
| 4 | 5.65 | 1.35 | 3.21 | 13.53 | 12.21 | 35.71 | 71.66 | 6.98 | 1.66 | 3.97 | 16.76 | 15.19 | 44.48 | 89.04 |
| 5 | 5.77 | 1.39 | 3.27 | 13.73 | 12.31 | 35.91 | 72.38 | 7.13 | 1.71 | 4.04 | 17.01 | 15.31 | 44.73 | 89.93 |
| 6 | 5.89 | 1.43 | 3.33 | 13.93 | 12.41 | 36.11 | 73.10 | 7.27 | 1.76 | 4.12 | 17.26 | 15.44 | 44.98 | 90.82 |
| 7 | 6.01 | 1.47 | 3.39 | 14.13 | 12.51 | 36.31 | 73.83 | 7.42 | 1.81 | 4.19 | 17.51 | 15.56 | 45.23 | 91.73 |
| 8 | 6.13 | 1.51 | 3.45 | 14.33 | 12.61 | 36.51 | 74.56 | 7.57 | 1.86 | 4.27 | 17.76 | 15.69 | 45.48 | 92.63 |
| 9 | 6.25 | 1.56 | 3.52 | 14.54 | 12.71 | 36.71 | 75.29 | 7.72 | 1.91 | 4.35 | 18.01 | 15.81 | 45.74 | 93.55 |
| 10 | 6.38 | 1.60 | 3.58 | 14.74 | 12.81 | 36.92 | 76.03 | 7.88 | 1.97 | 4.43 | 18.27 | 15.94 | 45.99 | 94.47 |

# F

# APPENDIX F

## F.1. REQUIRED DIKE RAISING VS GMSLR

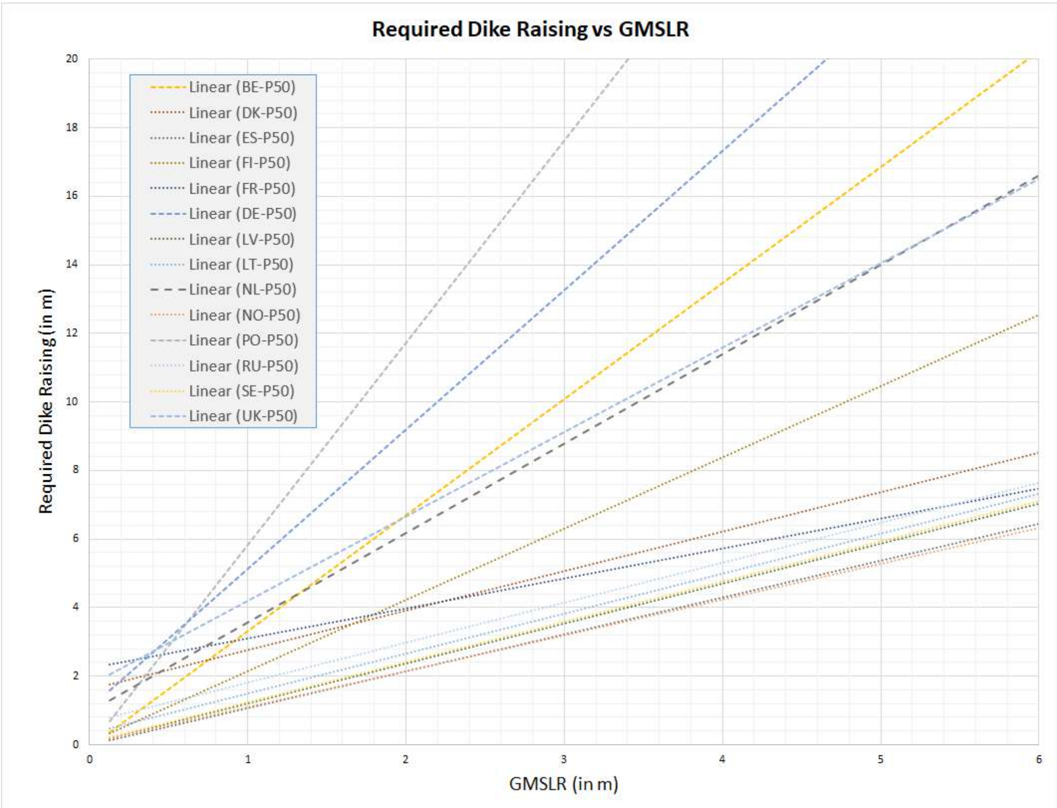



Figure F.1: Graph of required dike raising (in metres) as a function of GMSLR for all countries using the maximum inundation approach.

## F.2. Cost Distribution Tables per Category

Table F.1: Cost contribution (in million €) of all the countries for the construction of the NEED based on the coastline reinforcement length.

| Country | NEED (slope 1:4) | | | NEED (slope 1:5) | | | NEED (slope 1:6) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Costs P05 | Costs P50 | Costs P95 | Costs P05 | Costs P50 | Costs P95 | Costs P05 | Costs P50 | Costs P95 |
| Belgium | 6,243 | 7,443 | 8,548 | 7,636 | 9,172 | 10,517 | 9,124 | 10,997 | 12,630 |
| Denmark | 115,114 | 137,251 | 157,618 | 140,793 | 169,129 | 193,923 | 168,244 | 202,778 | 232,885 |
| Estonia | 3,235 | 3,857 | 4,429 | 3,956 | 4,753 | 5,449 | 4,728 | 5,698 | 6,544 |
| Finland | 36,062 | 42,997 | 49,378 | 44,107 | 52,984 | 60,751 | 52,707 | 63,525 | 72,957 |
| France | 55,032 | 65,615 | 75,351 | 67,308 | 80,854 | 92,707 | 80,431 | 96,941 | 111,333 |
| Germany | 195,852 | 233,516 | 268,167 | 239,542 | 287,752 | 329,936 | 286,246 | 345,001 | 396,224 |
| Latvia | 2,020 | 2,408 | 2,766 | 2,470 | 2,968 | 3,403 | 2,952 | 3,558 | 4,086 |
| Lithuania | 8,609 | 10,265 | 11,788 | 10,530 | 12,649 | 14,503 | 12,583 | 15,165 | 17,417 |
| the Netherlands | 38,256 | 45,613 | 52,381 | 46,790 | 56,207 | 64,447 | 55,913 | 67,389 | 77,395 |
| Norway | 3,400 | 4,054 | 4,655 | 4,158 | 4,995 | 5,727 | 4,969 | 5,989 | 6,878 |
| Poland | 21,179 | 25,252 | 28,999 | 25,904 | 31,117 | 35,679 | 30,954 | 37,308 | 42,847 |
| Russia | 22,725 | 27,095 | 31,116 | 27,795 | 33,389 | 38,283 | 33,214 | 40,031 | 45,975 |
| Sweden | 42,669 | 50,874 | 58,424 | 52,187 | 62,690 | 71,881 | 62,362 | 75,163 | 86,322 |
| the United Kingdom | 99,604 | 118,759 | 136,381 | 121,823 | 146,341 | 167,794 | 145,575 | 175,456 | 201,506 |
| **Total** | 650,000 | 775,000 | 890,000 | 795,000 | 955,000 | 1,095,000 | 950,000 | 1,145,000 | 1,315,000 |

Table F.2: Cost contribution (in million €) of all the countries for the construction of the NEED based on the inundated area.

| Country | NEED (slope 1:4) | | | NEED (slope 1:5) | | | NEED (slope 1:6) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Costs P05 | Costs P50 | Costs P95 | Costs P05 | Costs P50 | Costs P95 | Costs P05 | Costs P50 | Costs P95 |
| Belgium | 20,312 | 24,218 | 27,812 | 24,843 | 29,843 | 34,218 | 29,687 | 35,781 | 41,093 |
| Denmark | 111 | 132 | 152 | 136 | 163 | 187 | 162 | 195 | 224 |
| Estonia | 195 | 233 | 267 | 239 | 287 | 329 | 285 | 344 | 395 |
| Finland | 3,917 | 4,670 | 5,363 | 4,791 | 5,755 | 6,598 | 5,725 | 6,900 | 7,924 |
| France | 62,154 | 74,107 | 85,103 | 76,019 | 91,319 | 104,706 | 90,841 | 109,487 | 125,742 |
| Germany | 166,295 | 198,275 | 227,696 | 203,392 | 244,326 | 280,143 | 243,046 | 292,935 | 336,428 |
| Latvia | 897 | 1,070 | 1,229 | 1,098 | 1,319 | 1,512 | 1,312 | 1,581 | 1,816 |
| Lithuania | 1,777 | 2,119 | 2,433 | 2,173 | 2,611 | 2,993 | 2,597 | 3,130 | 3,595 |
| the Netherlands | 255,736 | 304,916 | 350,162 | 312,785 | 375,735 | 430,817 | 373,768 | 450,489 | 517,374 |
| Norway | 3,910 | 4,662 | 5,354 | 4,782 | 5,745 | 6,587 | 5,715 | 6,888 | 7,911 |
| Poland | 18,174 | 21,669 | 24,884 | 22,228 | 26,701 | 30,616 | 26,561 | 32,014 | 36,767 |
| Russia | 89,618 | 106,852 | 122,707 | 109,609 | 131,669 | 150,971 | 130,980 | 157,865 | 181,304 |
| Sweden | 2,541 | 3,030 | 3,480 | 3,108 | 3,734 | 4,281 | 3,714 | 4,476 | 5,141 |
| the United Kingdom | 24,363 | 29,048 | 33,359 | 29,798 | 35,795 | 41,042 | 35,608 | 42,916 | 49,288 |
| **Total** | 650,000 | 775,000 | 890,000 | 795,000 | 955,000 | 1,095,000 | 950,000 | 1,145,000 | 1,315,000 |

Table F.3: Cost contribution (in million €) of all the countries for the construction of the NEED based on the economic damages.

| | NEED (slope 1:4) | | | NEED (slope 1:5) | | | NEED (slope 1:6) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Country** | **Costs P05** | **Costs P50** | **Costs P95** | **Costs P05** | **Costs P50** | **Costs P95** | **Costs P05** | **Costs P50** | **Costs P95** |
| Belgium | 57,269 | 68,283 | 78,415 | 70,045 | 84,142 | 96,477 | 83,701 | 100,882 | 115,860 |
| Denmark | 7,034 | 8,387 | 9,632 | 8,604 | 10,335 | 11,850 | 10,281 | 12,391 | 14,231 |
| Estonia | 210 | 251 | 288 | 257 | 309 | 354 | 307 | 370 | 425 |
| Finland | 686 | 818 | 939 | 839 | 1,008 | 1,156 | 1,003 | 1,209 | 1,388 |
| France | 26,723 | 31,862 | 36,590 | 32,684 | 39,262 | 45,018 | 39,057 | 47,074 | 54,063 |
| Germany | 75,146 | 89,597 | 102,892 | 91,909 | 110,407 | 126,592 | 109,829 | 132,372 | 152,026 |
| Latvia | 23 | 27 | 31 | 28 | 33 | 38 | 33 | 40 | 46 |
| Lithuania | 80 | 95 | 109 | 98 | 117 | 134 | 117 | 141 | 161 |
| the Netherlands | 400,750 | 477,817 | 548,719 | 490,148 | 588,794 | 675,109 | 585,711 | 705,936 | 810,747 |
| Norway | 1,091 | 1,301 | 1,494 | 1,334 | 1,603 | 1,838 | 1,594 | 1,922 | 2,207 |
| Poland | 4,263 | 5,083 | 5,838 | 5,214 | 6,264 | 7,182 | 6,231 | 7,510 | 8,625 |
| Russia | 2,466 | 2,940 | 3,376 | 3,016 | 3,623 | 4,154 | 3,604 | 4,343 | 4,988 |
| Sweden | 1,834 | 2,186 | 2,511 | 2,243 | 2,694 | 3,089 | 2,680 | 3,230 | 3,709 |
| the United Kingdom | 72,426 | 86,354 | 99,168 | 88,582 | 106,410 | 122,010 | 105,853 | 127,581 | 146,523 |
| **Total** | 650,000 | 775,000 | 890,000 | 795,000 | 955,000 | 1,095,000 | 950,000 | 1,145,000 | 1,315,000 |

Table F.4: Cost contribution (in million €) of all the countries for the construction of the NEED based on the population affected.

| | NEED (slope 1:4) | | | NEED (slope 1:5) | | | NEED (slope 1:6) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Country** | **Costs P05** | **Costs P50** | **Costs P95** | **Costs P05** | **Costs P50** | **Costs P95** | **Costs P05** | **Costs P50** | **Costs P95** |
| Belgium | 35,966 | 42,882 | 49,245 | 43,989 | 52,842 | 60,588 | 52,565 | 63,355 | 72,761 |
| Denmark | 4,983 | 5,942 | 6,824 | 6,095 | 7,322 | 8,395 | 7,284 | 8,779 | 10,082 |
| Estonia | 30 | 36 | 41 | 36 | 44 | 50 | 44 | 52 | 60 |
| Finland | 897 | 1,070 | 1,229 | 1,098 | 1,318 | 1,512 | 1,312 | 1,581 | 1,816 |
| France | 48,845 | 58,239 | 66,881 | 59,742 | 71,765 | 82,286 | 71,389 | 86,043 | 98,818 |
| Germany | 28,662 | 34,173 | 39,244 | 35,055 | 42,111 | 48,284 | 41,890 | 50,489 | 57,985 |
| Latvia | 41 | 49 | 56 | 50 | 60 | 69 | 59 | 72 | 82 |
| Lithuania | 16 | 19 | 22 | 20 | 24 | 27 | 24 | 29 | 33 |
| the Netherlands | 426,430 | 508,436 | 583,882 | 521,557 | 626,525 | 718,371 | 623,244 | 751,174 | 862,702 |
| Norway | 2,740 | 3,267 | 3,752 | 3,351 | 4,026 | 4,616 | 4,005 | 4,827 | 5,543 |
| Poland | 1,585 | 1,890 | 2,170 | 1,939 | 2,329 | 2,670 | 2,317 | 2,792 | 3,207 |
| Russia | 305 | 364 | 418 | 374 | 449 | 514 | 446 | 538 | 618 |
| Sweden | 2,414 | 2,878 | 3,305 | 2,952 | 3,546 | 4,066 | 3,528 | 4,252 | 4,883 |
| the United Kingdom | 97,085 | 115,755 | 132,932 | 118,742 | 142,640 | 163,551 | 141,893 | 171,019 | 196,410 |
| **Total** | 650,000 | 775,000 | 890,000 | 795,000 | 955,000 | 1,095,000 | 950,000 | 1,145,000 | 1,315,000 |

Table F.5: Regional protection costs (in million €) of all the countries projected for the three NEED structure designs.

| Country | NEED (slope 1:4) | | | NEED (slope 1:5) | | | NEED (slope 1:6) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Costs P05 | Costs P50 | Costs P95 | Costs P05 | Costs P50 | Costs P95 | Costs P05 | Costs P50 | Costs P95 |
| Belgium | 7,305 | 7,335 | 8,086 | 9,187 | 9,293 | 10,299 | 11,090 | 11,274 | 12,537 |
| Denmark | 88,082 | 119,920 | 159,818 | 104,556 | 146,879 | 195,836 | 121,215 | 174,141 | 232,258 |
| Estonia | 375 | 642 | 899 | 475 | 812 | 1,136 | 576 | 984 | 1,376 |
| Finland | 9,425 | 28,678 | 49,761 | 11,669 | 36,217 | 63,071 | 13,939 | 43,841 | 76,531 |
| France | 22,039 | 26,571 | 33,193 | 24,856 | 30,577 | 38,944 | 27,705 | 34,627 | 44,759 |
| Germany | 247,799 | 289,072 | 314,574 | 303,143 | 359,958 | 392,068 | 359,108 | 431,640 | 470,433 |
| Latvia | 230 | 330 | 485 | 291 | 416 | 612 | 352 | 503 | 740 |
| Lithuania | 1,215 | 1,691 | 2,420 | 1,504 | 2,104 | 3,024 | 1,797 | 2,521 | 3,635 |
| Netherlands, the | 74,794 | 80,121 | 83,999 | 93,731 | 100,394 | 104,852 | 112,881 | 120,894 | 125,939 |
| Norway | 1,342 | 2,066 | 3,158 | 1,690 | 2,604 | 3,984 | 2,042 | 3,149 | 4,820 |
| Poland | 8,935 | 13,886 | 14,704 | 11,023 | 17,733 | 18,614 | 13,134 | 21,622 | 22,568 |
| Russia | 58,155 | 93,328 | 149,302 | 73,515 | 117,791 | 188,479 | 89,047 | 142,529 | 228,096 |
| Sweden | 14,723 | 20,943 | 30,527 | 18,585 | 26,414 | 38,504 | 22,490 | 31,947 | 46,571 |
| United Kingdom, the | 33,920 | 97,457 | 112,526 | 37,738 | 118,846 | 137,852 | 41,600 | 140,475 | 163,462 |

## F.3. Cost Distribution Tables per NEED Design

Table F.6: Cost contribution (in million €) of all the countries for the construction of the NEED with slope of 1 over 4.

| Country | Coastline Length | | | Inundated Area | | | Population Exposed | | | Economic Damages | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P05 | P50 | P95 | P05 | P50 | P95 | P05 | P50 | P95 | P05 | P50 | P95 |
| BE | 6,243 | 7,443 | 8,548 | 20,312 | 24,218 | 27,812 | 35,966 | 42,882 | 49,245 | 57,269 | 68,283 | 78,415 |
| DK | 115,114 | 137,251 | 157,618 | 111 | 132 | 152 | 4,983 | 5,942 | 6,824 | 7,034 | 8,387 | 9,632 |
| ES | 3,235 | 3,857 | 4,429 | 195 | 233 | 267 | 30 | 36 | 41 | 210 | 251 | 288 |
| FI | 36,062 | 42,997 | 49,378 | 3,917 | 4,670 | 5,363 | 897 | 1,070 | 1,229 | 686 | 818 | 939 |
| FR | 55,032 | 65,615 | 75,351 | 62,154 | 74,107 | 85,103 | 48,845 | 58,239 | 66,881 | 26,723 | 31,862 | 36,590 |
| DE | 195,852 | 233,516 | 268,167 | 166,295 | 198,275 | 227,696 | 28,662 | 34,173 | 39,244 | 75,146 | 89,597 | 102,892 |
| LV | 2,020 | 2,408 | 2,766 | 897 | 1,070 | 1,229 | 41 | 49 | 56 | 23 | 27 | 31 |
| LT | 8,609 | 10,265 | 11,788 | 1,777 | 2,119 | 2,433 | 16 | 19 | 22 | 80 | 95 | 109 |
| NL | 38,256 | 45,613 | 52,381 | 255,736 | 304,916 | 350,162 | 426,430 | 508,436 | 583,882 | 400,750 | 477,817 | 548,719 |
| NO | 3,400 | 4,054 | 4,655 | 3,910 | 4,662 | 5,354 | 2,740 | 3,267 | 3,752 | 1,091 | 1,301 | 1,494 |
| PO | 21,179 | 25,252 | 28,999 | 18,174 | 21,669 | 24,884 | 1,585 | 1,890 | 2,170 | 4,263 | 5,083 | 5,838 |
| RU | 22,725 | 27,095 | 31,116 | 89,618 | 106,852 | 122,707 | 305 | 364 | 418 | 2,466 | 2,940 | 3,376 |
| SE | 42,669 | 50,874 | 58,424 | 2,541 | 3,030 | 3,480 | 2,414 | 2,878 | 3,305 | 1,834 | 2,186 | 2,511 |
| UK | 99,604 | 118,759 | 136,381 | 24,363 | 29,048 | 33,359 | 97,085 | 115,755 | 132,932 | 72,426 | 86,354 | 99,168 |

Table F.7: Cost contribution (in million €) of all the countries for the construction of the NEED with slope of 1 over 5.

| | Coastline Length | | | Inundated Area | | | Population Exposed | | | Economic Damages | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country** | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| BE | 7,636 | 9,172 | 10,517 | 24,843 | 29,843 | 34,218 | 43,989 | 52,842 | 60,588 | 70,045 | 84,142 | 96,477 |
| DK | 140,793 | 169,129 | 193,923 | 136 | 163 | 187 | 6,095 | 7,322 | 8,395 | 8,604 | 10,335 | 11,850 |
| ES | 3,956 | 4,753 | 5,449 | 239 | 287 | 329 | 36 | 44 | 50 | 257 | 309 | 354 |
| FI | 44,107 | 52,984 | 60,751 | 4,791 | 5,755 | 6,598 | 1,098 | 1,318 | 1,512 | 839 | 1,008 | 1,156 |
| FR | 67,308 | 80,854 | 92,707 | 76,019 | 91,319 | 104,706 | 59,742 | 71,765 | 82,286 | 32,684 | 39,262 | 45,018 |
| DE | 239,542 | 287,752 | 329,936 | 203,392 | 244,326 | 280,143 | 35,055 | 42,111 | 48,284 | 91,909 | 110,407 | 126,592 |
| LV | 2,470 | 2,968 | 3,403 | 1,098 | 1,319 | 1,512 | 50 | 60 | 69 | 28 | 33 | 38 |
| LT | 10,530 | 12,649 | 14,503 | 2,173 | 2,611 | 2,993 | 20 | 24 | 27 | 98 | 117 | 134 |
| NL | 46,790 | 56,207 | 64,447 | 312,785 | 375,735 | 430,817 | 521,557 | 626,525 | 718,371 | 490,148 | 588,794 | 675,109 |
| NO | 4,158 | 4,995 | 5,727 | 4,782 | 5,745 | 6,587 | 3,351 | 4,026 | 4,616 | 1,334 | 1,603 | 1,838 |
| PO | 25,904 | 31,117 | 35,679 | 22,228 | 26,701 | 30,616 | 1,939 | 2,329 | 2,670 | 5,214 | 6,264 | 7,182 |
| RU | 27,795 | 33,389 | 38,283 | 109,609 | 131,669 | 150,971 | 374 | 449 | 514 | 3,016 | 3,623 | 4,154 |
| SE | 52,187 | 62,690 | 71,881 | 3,108 | 3,734 | 4,281 | 2,952 | 3,546 | 4,066 | 2,243 | 2,694 | 3,089 |
| UK | 121,823 | 146,341 | 167,794 | 29,798 | 35,795 | 41,042 | 118,742 | 142,640 | 163,551 | 88,582 | 106,410 | 122,010 |

Table F.8: Cost contribution (in million €) of all the countries for the construction of the NEED with slope 1:6.

| | Coastline Length | | | Inundated Area | | | Population Exposed | | | Economic Damages | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country** | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** | **P05** | **P50** | **P95** |
| BE | 9,124 | 10,997 | 12,630 | 29,687 | 35,781 | 41,093 | 29,687 | 35,781 | 41,093 | 83,701 | 100,882 | 115,860 |
| DK | 168,244 | 202,778 | 232,885 | 162 | 195 | 224 | 162 | 195 | 224 | 10,281 | 12,391 | 14,231 |
| ES | 4,728 | 5,698 | 6,544 | 285 | 344 | 395 | 285 | 344 | 395 | 307 | 370 | 425 |
| FI | 52,707 | 63,525 | 72,957 | 5,725 | 6,900 | 7,924 | 5,725 | 6,900 | 7,924 | 1,003 | 1,209 | 1,388 |
| FR | 80,431 | 96,941 | 111,333 | 90,841 | 109,487 | 125,742 | 90,841 | 109,487 | 125,742 | 39,057 | 47,074 | 54,063 |
| DE | 286,246 | 345,001 | 396,224 | 243,046 | 292,935 | 336,428 | 243,046 | 292,935 | 336,428 | 109,829 | 132,372 | 152,026 |
| LV | 2,952 | 3,558 | 4,086 | 1,312 | 1,581 | 1,816 | 1,312 | 1,581 | 1,816 | 33 | 40 | 46 |
| LT | 12,583 | 15,165 | 17,417 | 2,597 | 3,130 | 3,595 | 2,597 | 3,130 | 3,595 | 117 | 141 | 161 |
| NL | 55,913 | 67,389 | 77,395 | 373,768 | 450,489 | 517,374 | 373,768 | 450,489 | 517,374 | 585,711 | 705,936 | 810,747 |
| NO | 4,969 | 5,989 | 6,878 | 5,715 | 6,888 | 7,911 | 5,715 | 6,888 | 7,911 | 1,594 | 1,922 | 2,207 |
| PO | 30,954 | 37,308 | 42,847 | 26,561 | 32,014 | 36,767 | 26,561 | 32,014 | 36,767 | 6,231 | 7,510 | 8,625 |
| RU | 33,214 | 40,031 | 45,975 | 130,980 | 157,865 | 181,304 | 130,980 | 157,865 | 181,304 | 3,604 | 4,343 | 4,988 |
| SE | 62,362 | 75,163 | 86,322 | 3,714 | 4,476 | 5,141 | 3,714 | 4,476 | 5,141 | 2,680 | 3,230 | 3,709 |
| UK | 145,575 | 175,456 | 201,506 | 35,608 | 42,916 | 49,288 | 35,608 | 42,916 | 49,288 | 105,853 | 127,581 | 146,523 |

## F.4. Cost Distribution Figures

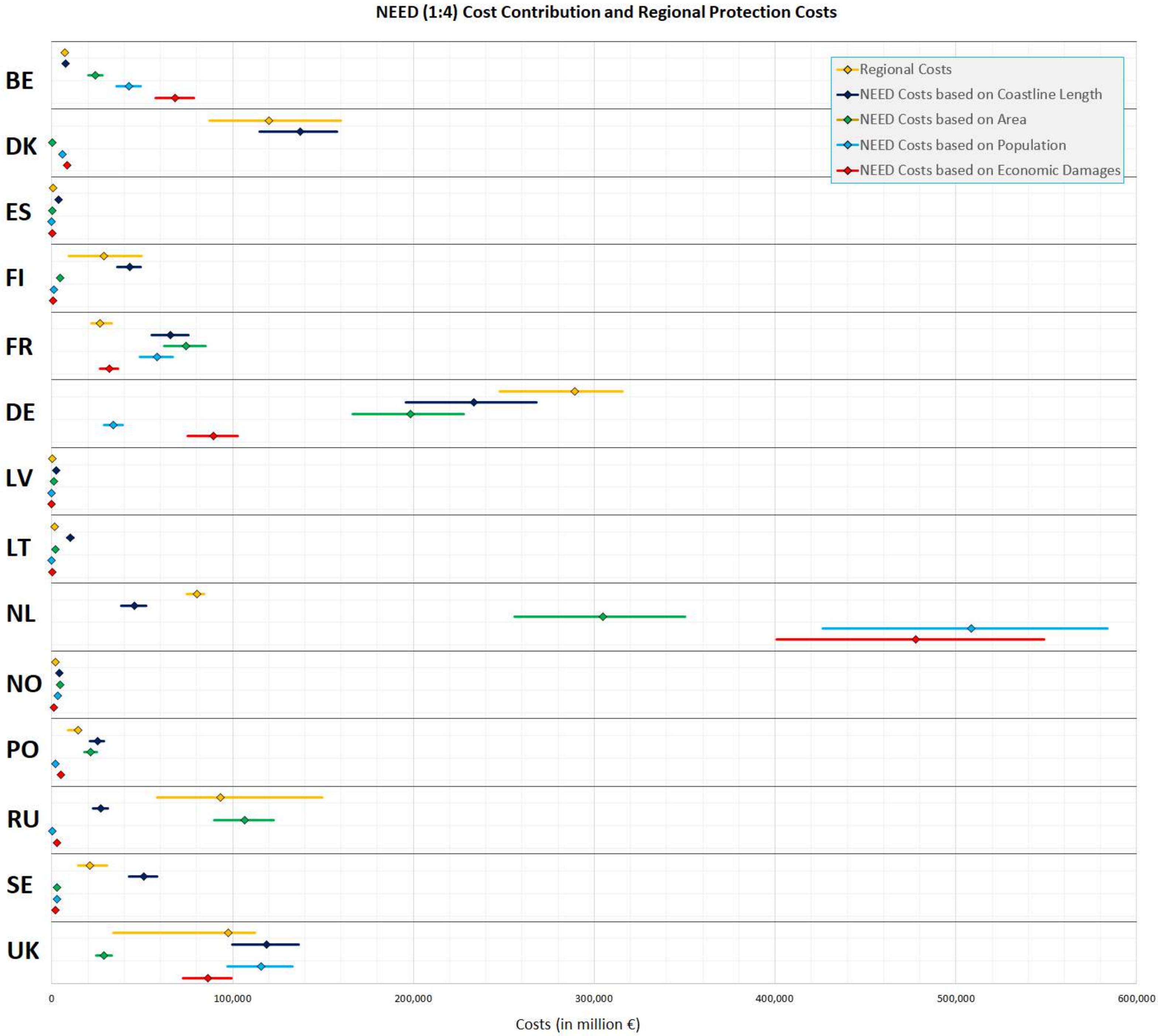



Figure F.2: Overview of the NEED (1:4) cost contribution ranges per country based on the four distributions and each country's regional costs.

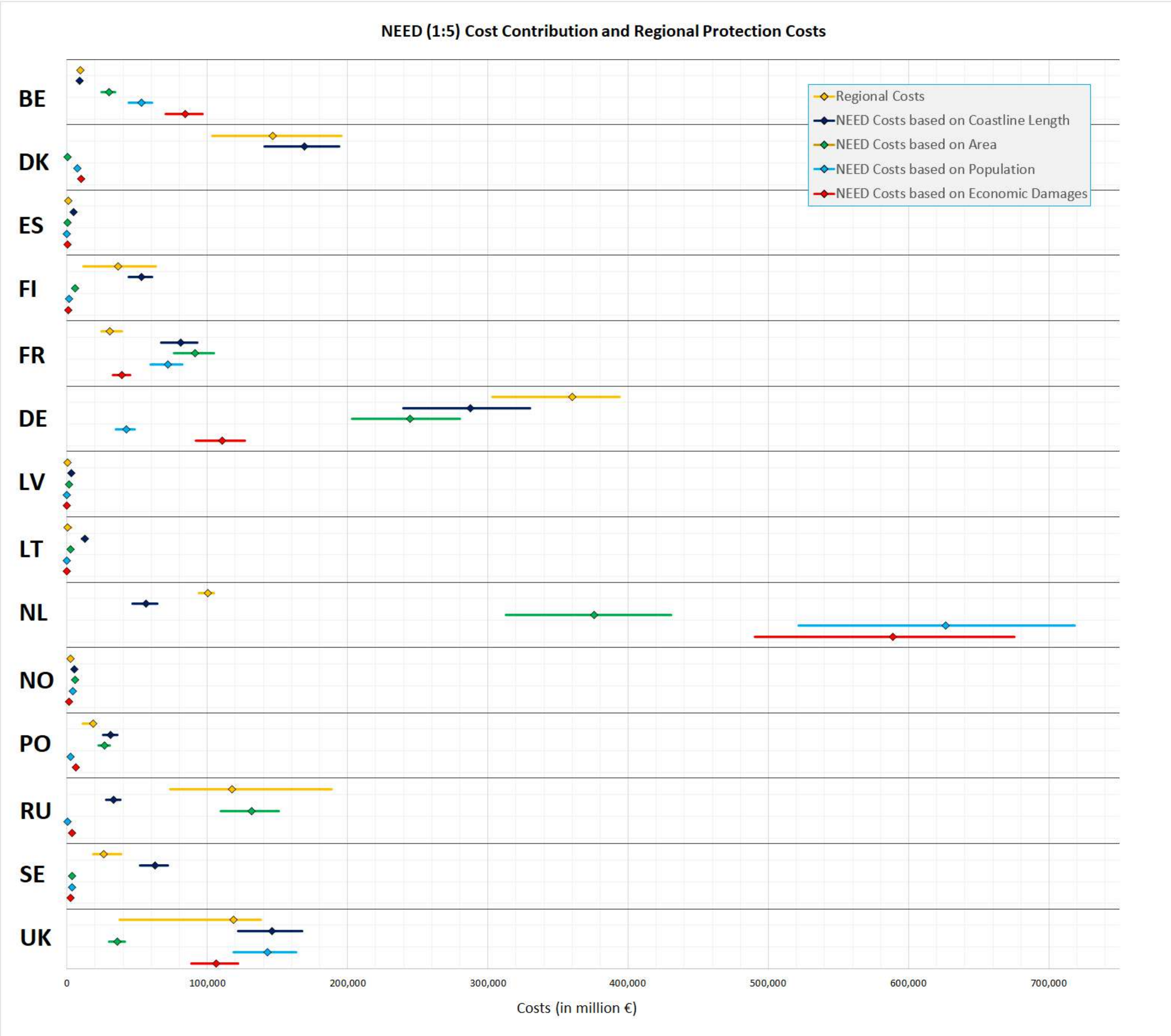



Figure F.3: Overview of the NEED (1:5) cost contribution ranges per country based on the four distributions and each country's regional costs.

# G
# Appendix F

## G.1. Sensitivity Analysis 1: Average Inundation Height

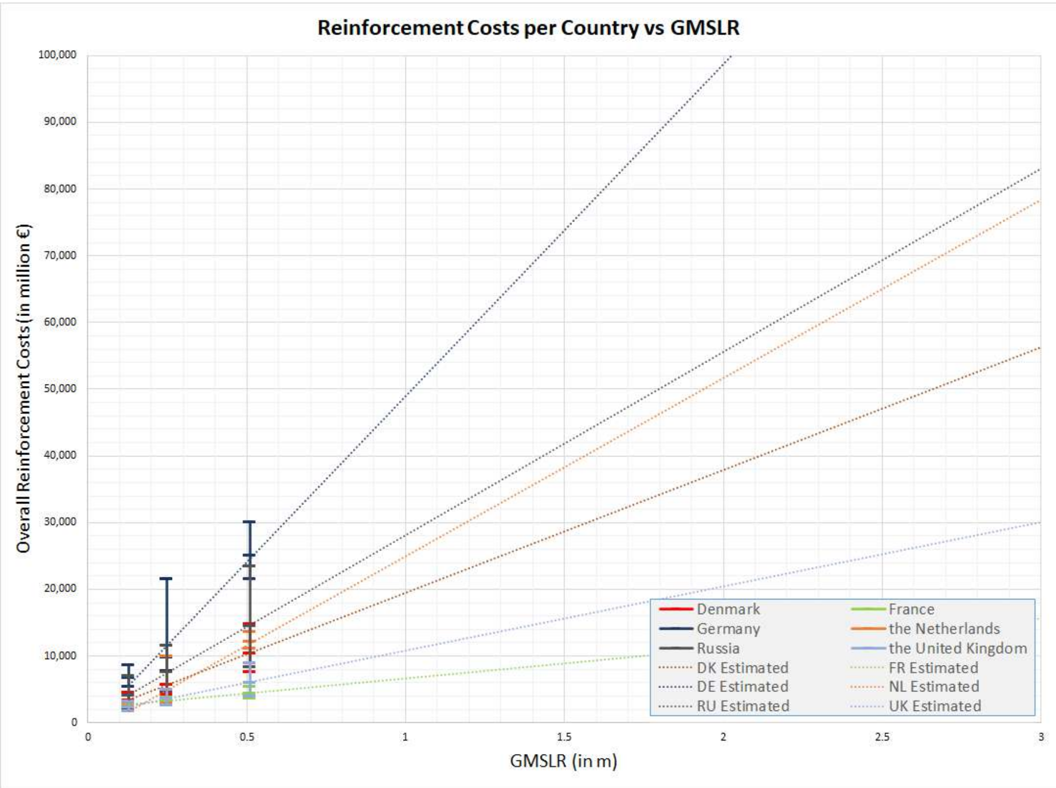



Figure G.1: Graph of total reinforcement costs for countries on the higher spectrum using average inundation height as reinforcement height.

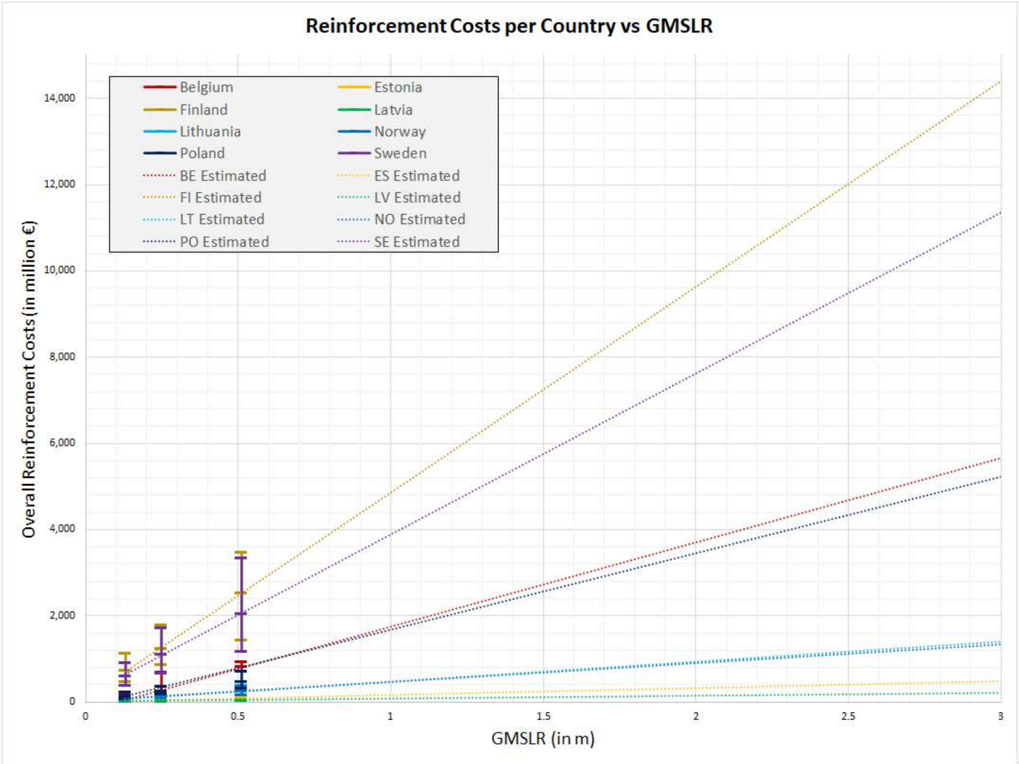



Figure G.2: Graph of total reinforcement costs for countries on the lower spectrum using average inundation height as reinforcement height.

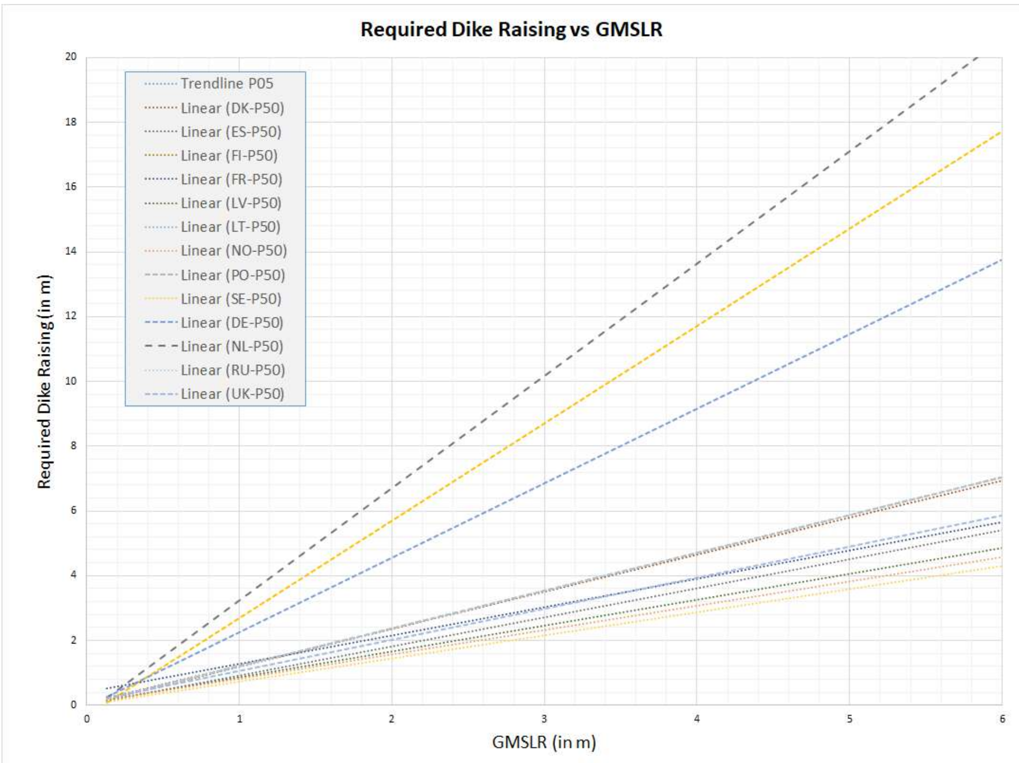



Figure G.3: Graph of required dike raising (in metres) as a function of GMSLR for all countries using the average inundation approach.

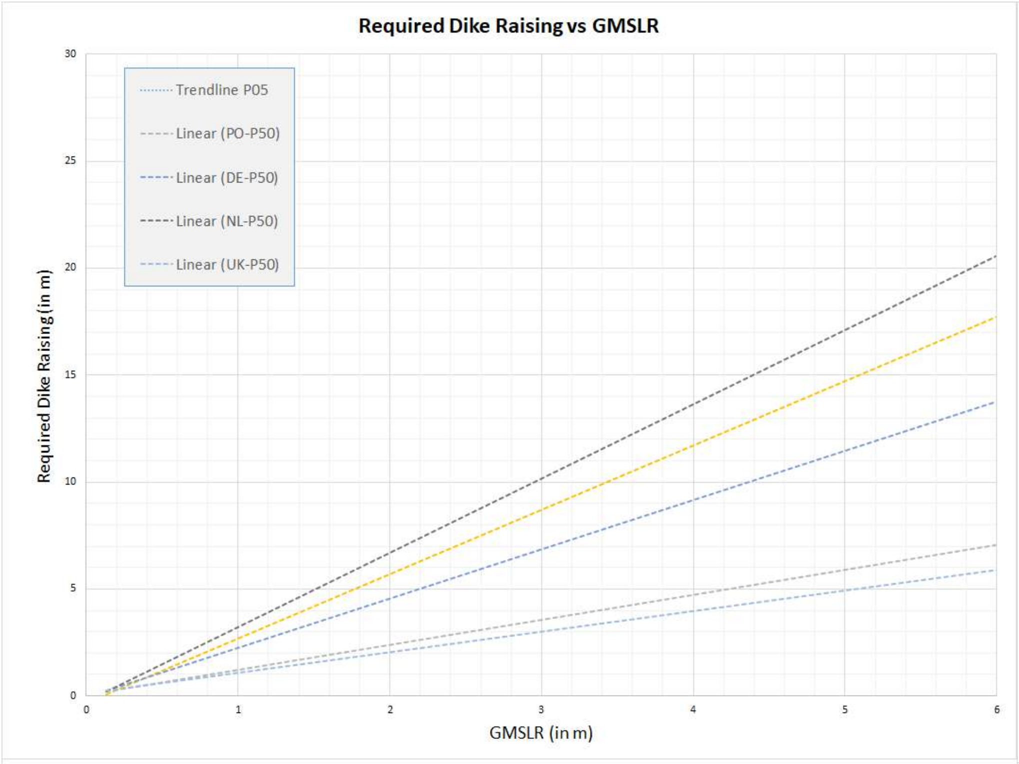



Figure G.4: Graph of required
dike raising (in metres) as a function of GMSLR for the 5 countries with the highest required dike raising using the average inundation approach.

## G.2. Sensitivity Analysis 2: Double GMSLR

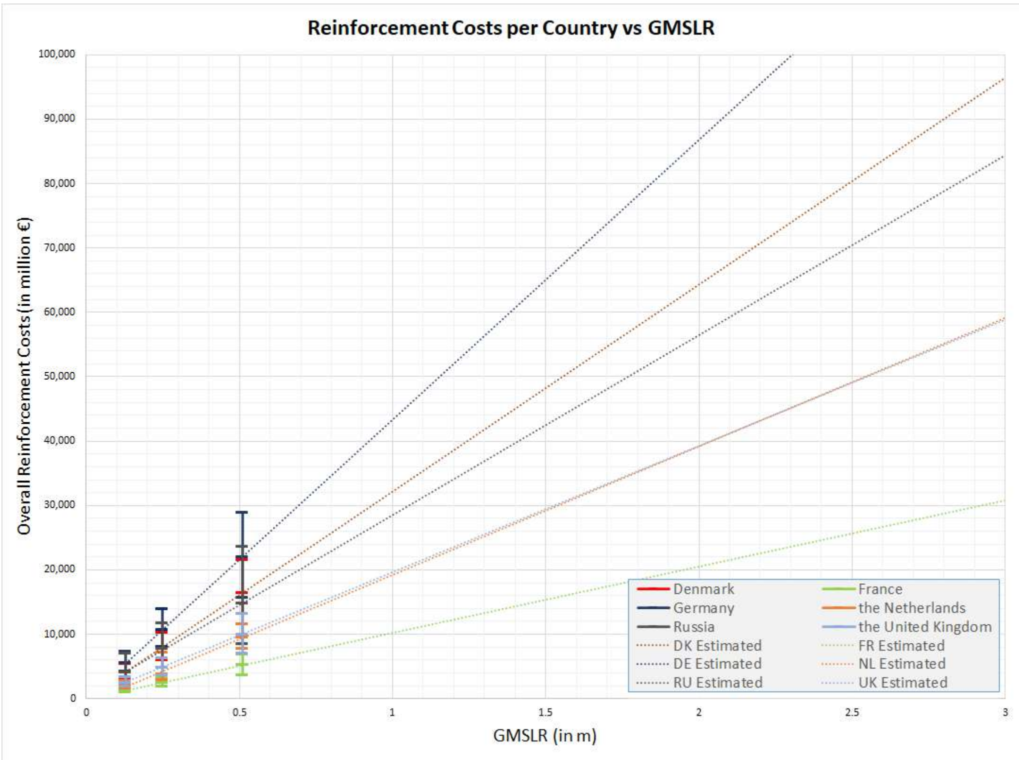



Figure G.5: Graph of total reinforcement costs for countries on the higher spectrum using 2x SLR as reinforcement height.

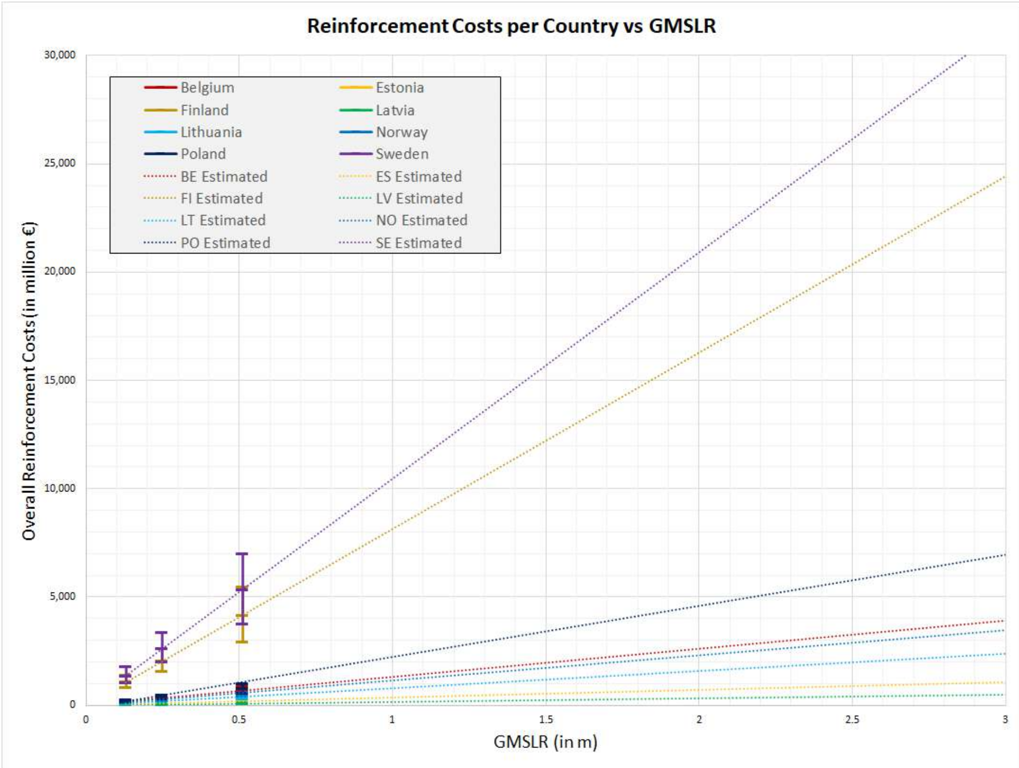



Figure G.6: Graph of total reinforcement costs for countries on the lower spectrum using 2x SLR as reinforcement height.

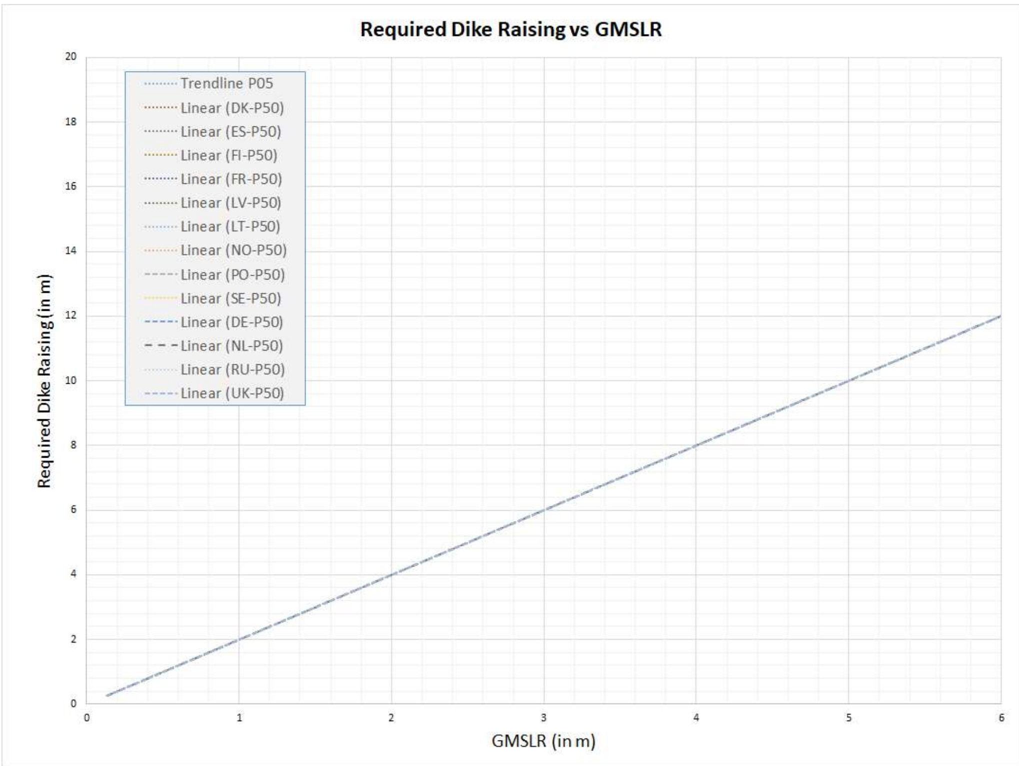



Figure G.7: Graph of required dike raising (in metres) as a function of GMSLR for all countries using the 2x SLR approach.

## G.3. Sensitivity Analysis 3: Reinforcement Pricing of Sea Dikes

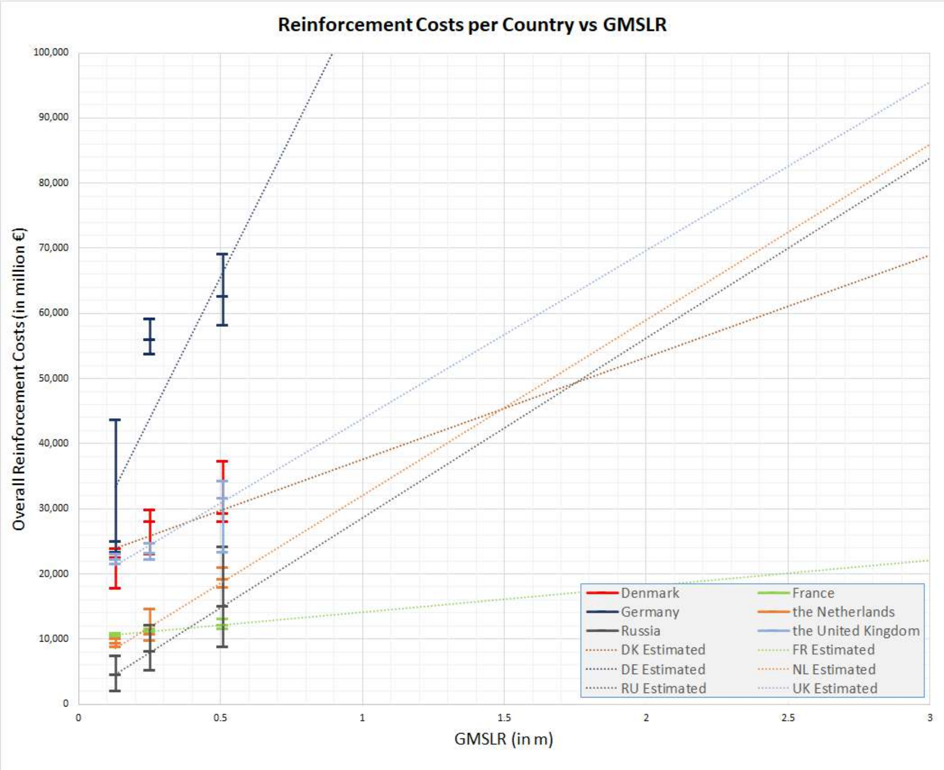



Figure G.8: Graph of total reinforcement costs for countries on the higher spectrum using the distinction between urban and rural areas.

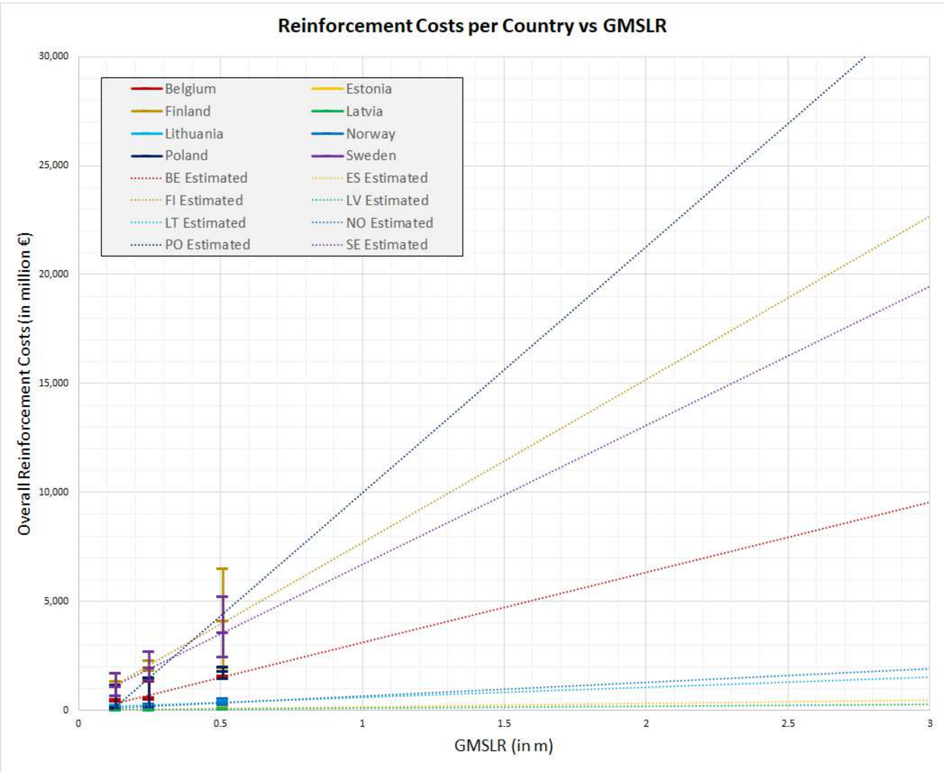



Figure G.9: Graph of total reinforcement costs for countries on the lower spectrum using the distinction between urban and rural areas.

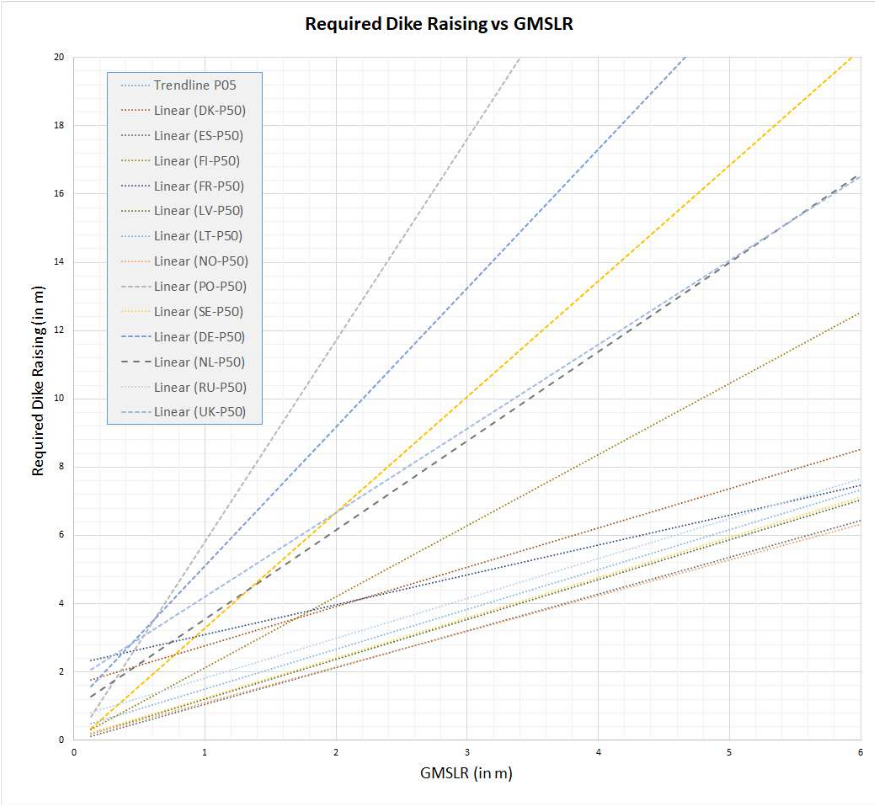



Figure G.10: Graph of required dike raising (in metres) as a function of GMSLR for all countries using the urban-rural approach.

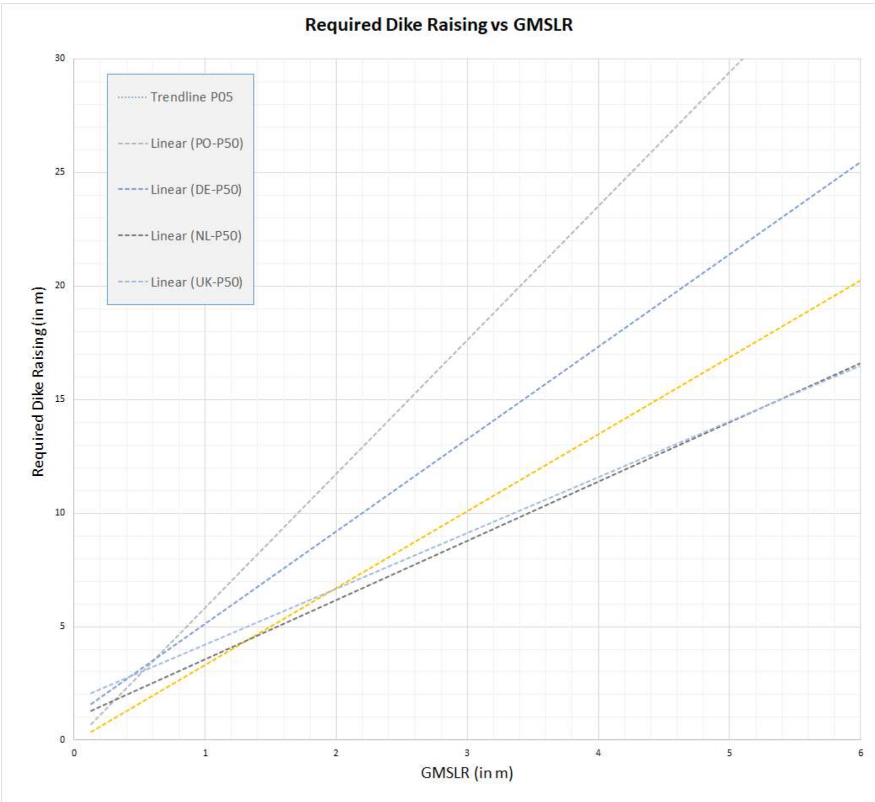



Figure G.11: Graph of required
dike raising (in metres) as a function of GMSLR for the 5 countries with the highest required dike raising using the urban-rural approach.