Flooding and erosion of coastal roads - exposure, mitigation and climate change impact

Adell, Anna

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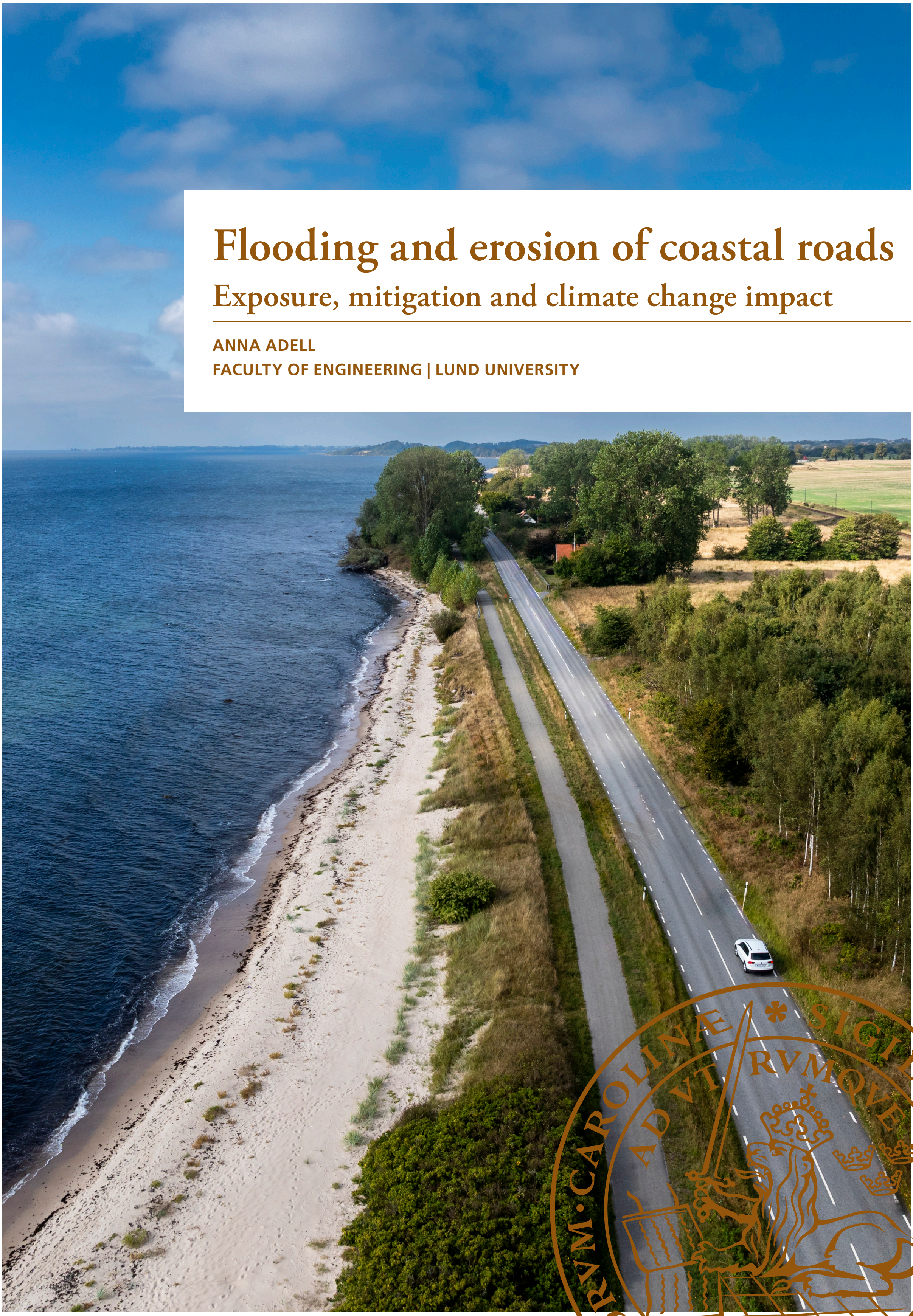

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Anna Adell

DOCTORAL DISSERTATION

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Abstract:

The coastal zone is a dynamic region where the sea meets land, making it highly influenced by environmental conditions such as storm surges, extreme weather events, and coastal erosion. Coastal areas are also characterized by high population densities, significant urban development, and important socio-economic functions such as transportation, trade, tourism and recreation. Consequently, they are particularly vulnerable to natural hazards and coastal processes, with risks such as flooding and erosion expected to increase due to climate change-driven global sea level rise.

This thesis focuses specifically on coastal roads, which are critical infrastructures typically situated at the frontline of exposure to flooding and erosion. Given their long design life, it is essential to assess how exposure will evolve under rising sea levels. A robust risk assessment requires high-quality data to estimate the probability of impacts and evaluate them against anticipated consequences. For coastal processes, such assessments rely on detailed data concerning wave dynamics and water level variations, which drive morphological changes. In this research, a detailed hindcast time series of decadal wave climate data for the southern Baltic Sea has been generated, validated, and analysed to enhance the understanding of variability in hydrodynamic forcing.

The aim of this thesis is to develop a methodology for assessing the exposure of coastal roads to the impacts of flooding, wave impact, and erosion. The proposed framework integrates numerical modelling, field observations, and case studies to evaluate exposure under both current climate conditions and future scenarios, accounting for sea level rise and long-term coastal development. Its application is demonstrated through a case study assessing the exposure of the main road along Sweden's southern coast. Results indicate that present-day exposure to flooding and erosion is limited to a few hotspots during extreme events. In future scenarios, the exposure will increase, and coastal erosion will pose the greatest threat to the road, highlighting the need for future coastal protection strategies.

To explore potential adaptation measures, a second case study was conducted along the east coast of Denmark. The study evaluated a hybrid coastal protection solution, combining rock revetments with small-scale beach nourishment, as a solution to mitigate the impact of coastal processes on the road. The morphological evolution of the nourishment was analysed under varying hydrodynamic conditions to better understand and optimize its design. Collectively, the findings of this thesis contribute to improved methodologies for risk assessment, enhanced datasets for wave climate analysis, and insights into the design of effective coastal protection measures to support infrastructure planning and resilience.

Key words: Wave hindcast, coastal protection, beach nouirhsment, infrastructure, Baltic Sea

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PhD thesis - Anna Adell

Flooding and erosion of coastal roads

Exposure, mitigation and climate change impact

This PhD thesis has been submitted to the PhD School of Science,

Faculty of Science, University of Copenhagen.

Do not complain about sand in your bed at the end of the day
It probably means it was a day well spent

Table of Contents

Abstract

The coastal zone is a dynamic region where the sea meets land, making it highly influenced by environmental conditions such as storm surges, extreme weather events, and coastal erosion. Coastal areas are also characterized by high population densities, significant urban development, and important socio-economic functions such as transportation, trade, tourism and recreation. Consequently, they are particularly vulnerable to natural hazards and coastal processes, with risks such as flooding and erosion expected to increase due to climate change-driven global sea level rise.

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Populärvetenskaplig sammanfattning

En stor andel av världens befolkning bor i kustområden. Kustområden är viktiga socioekonomiska områden, som alltid har varit betydelsefulla för mänsklig aktivitet och samhällsutvecklingen, genom att möjliggöra handel, fiske, rekreation och turism med mera. Alla dessa områden är beroende av transportnätverk som är avgörande för att binda samman samhällen och möjliggöra transport av människor och varor. Vägar i kustområden är ofta särskilt utsatta eftersom de byggs i låglänta områden. Det medför att de samtidigt är sårbara för påverkan från naturliga processer som erosion och översvämning. Detta kan innebära påverkan på trafiken under extrema stormar eller kostsamma reparationer till följd av stormskador på vägar.

I takt med att havet stiger, till följd av globala klimatförändringar, förväntas utbredningen av påverkan från kustprocesser på samhällen och infrastruktur öka. Samtidigt förväntas den globala befolkningen öka, särskilt i redan tätbefolkade kustområden. Detta medför ytterligare krav på infrastrukturen och potentiell belastning för kustzonen. Samhället står inför stora utmaningar och det behövs bättre kunskap och mer detaljerade data för att kunna begränsa riskerna för påverkan av kustprocesser och samtidigt se till att bevara de unika naturliga värdena i kustområden.

Resultaten av denna avhandling bidrar till samhället genom att presentera underlag som är till grund för att bistå riskbedömning av kustnära vägar och järnvägar som kan påverkas negativt av kustprocesser (erosion och översvämning) både i dagens klimat och i framtiden. Med hjälp av numerisk modellering, datainsamling i fält och fallstudier i Östersjöregionen har metoder utvecklats för att identifiera vilka sårbara vägsträckor som riskerar att drabbas av kustöversvämningar och erosion. Resultatet visar att utbredningen av vägsträckor som kan påverkas av kustprocesser förväntas öka i framtiden i takt med klimatförändringar och stigande havsnivåer, särskilt förväntas risken för erosion som drabbar vägar att öka.

Det kommer därför att krävas åtgärder för att skydda och anpassa transportinfrastrukturen i ett föränderligt klimat, så att samhället kan fortsätta att förlita sig på dess funktion och service. Denna avhandling presenterar exempel på strategier för hur infrastrukturen kan skyddas genom att etablera kustskydd. En ny typ av lösning som kombinerar traditionella hårda skydd och strandfodring har utvärderats för dess effektivitet att minska vågpåverkan på vägen och samtidigt erbjuda alternativa funktioner. Visionen är att transportsystemet ska vara robust och tillförlitligt idag och i framtiden och att negativ påverkan från kustprocesser ska kunna begränsas utan att innebära negativ påverkan på kustzonen och dess funktion och värden.

Sammenfatning

En stor del af verdens befolkning bor i kystområder. Kystområder er vigtige socioøkonomiske regioner, som altid har været centrale for menneskelig aktivitet og samfundsudvikling ved at muliggøre handel, fiskeri, rekreation, turisme og meget mere. Alle disse områder er afhængige af transportnetværk, som er afgørende for at forbinde samfund og muliggøre transport af mennesker og varer. Veje i kystområder er ofte særligt udsatte, fordi de bygges i lavtliggende områder. Dette gør dem samtidig sårbare over for påvirkninger fra naturlige processer som erosion og oversvømmelser. Det kan føre til trafikproblemer under ekstreme storme eller omkostningsfulde reparationer som følge af stormskader på vejene.

Efterhånden som havniveauet stiger på grund af globale klimaforandringer, forventes påvirkningen fra kystprocesser på samfund og infrastruktur at blive mere udbredt. Samtidig forventes den globale befolkning at stige, især i kystområder og i allerede tætbefolkede områder. Dette medfører yderligere krav til infrastrukturen og en potentiel belastning af kystzonen. Samfundet står over for store udfordringer, og der er behov for bedre viden og mere detaljerede data for at kunne reducere risikoen for påvirkninger fra kystprocesser og samtidig bevare de unikke naturlige værdier i kystområderne.

Resultaterne af denne afhandling bidrager til samfundet ved at præsentere datagrundlag, der kan støtte risikovurderingen af kystnære veje og jernbaner, som kan blive negativt påvirket af kystprocesser (erosion og oversvømmelse), både i dagens klima og i fremtiden. Ved hjælp af numerisk modellering, dataindsamling i felten og casestudier i Østersøregionen er der udviklet metoder til at identificere, hvilke sårbare vejstrækninger der risikerer at blive påvirket af kystoversvømmelser og erosion. Resultaterne viser, at omfanget af vejstrækninger, der kan blive påvirket af kystprocesser, forventes at stige i fremtiden i takt med klimaforandringer og stigende havniveauer. Især forventes risikoen for erosion, der påvirker veje, at stige.

Der vil derfor være behov for tiltag for at beskytte og tilpasse transportinfrastrukturen i et foranderligt klima, så samfundet fortsat kan stole på dens funktion og service. Denne afhandling præsenterer eksempler på strategier til at beskytte infrastrukturen ved at etablere kystbeskyttelse. En ny type løsning, der kombinerer traditionelle hårde beskyttelser og strandfodring, er blevet evalueret for dens effektivitet i at reducere bølgepåvirkningen på vejen og samtidig tilbyde alternative funktioner. Visionen er, at transportsystemet skal være robust og pålideligt i dag og i fremtiden, og at negativ påvirkning fra kystprocesser skal kunne begrænses uden at skade kystzonens funktion og værdier.

Acknowledgements

There are many people I share this journey and my accomplishments with, without them this process and thesis would not have been possible.

First and foremost, I would like to thank my dedicated team of supervisors, Dr. Caroline Hallin, Prof. Aart Kroon, Dr. Björn Almström, and Prof. Magnus Larson. I am grateful for the opportunities you have given me. Thanks for supporting and believing in me, and for your trust, encouragement and inspiration. Thank you for introducing me to your networks and for sharing your passion and knowledge of coastal engineering and geosciences.

I have had the privilege to be part of research groups both in Lund and Copenhagen, I am very grateful for the opportunity and experience of doing a double degree. I would like to thank all colleagues at TVRL, especially the fellow PhD students and early career scientists; Fainaz, Behshid, Ellinor, Martin, August, Anna, Kristofer, Alireza, Dauren and Clemens. It has been a joy to share this journey with you all. Thank you for nice discussions, positive encouragement and many lovely fika breaks. Thanks to Oskar Ranefjärd for being a dedicated PhD representative, a supportive friend and for helping me navigate the PhD process.

Thanks to colleagues at IGN and the research group for always being welcoming and creating an inspiring work environment. Thanks to the PhD students and postdocs in the research group; Flora, Rasmus, Mads, Drude, and Jonas for your help and kindness. Thanks to Paul Christiansen for immense help, organisation and support in the field. Your ease, positivity and expertise made every trip to Faxe Ladeplads very enjoyable. To the Writing club, our sessions were something I always looked forward to and it made the writing more fun, thank you for the support in the final year of my PhD studies. Thanks to Gregor and Meriel for friendship and inspiration over the years, I always enjoyed sharing reflections on the PhD process and life in academia with you.

I would also specifically like to thank Emmy Sukchaiwan and Glenn Strypsteen, who became a valuable part of the coastal group at TVRL halfway through my PhD journey. Thank you for your positive attitude and support through encouragement, discussions, fieldwork, coffee breaks and fun times.

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Thanks to Joachim Hein at LUNARC, Lund University, for your help and patience when teaching me about parallel processing and HPC-cluster operations.

Thanks to the project reference group; Sebastian Bokhari Irminger, Bradley Goodfellow, Per Sørensen, Emanuel Schmidt, Mona Skoog, Sofie Schöld, Gunnel Göransson and Charlotte Sparrenbom for your time and commitment, and for showing interest in my work. Thank you for sharing your insights and helping the progression through valuable discussions and support.

Throughout my PhD I have had the pleasure to be part of teaching activities at both TVRL and IGN. Something I sometimes found challenging but equally rewarding, developing and inspiring. I would like to thank the students that I have had the joy to meet in courses and through supervision in master thesis projects.

Finally, I would like to thank my family and friends who have supported me and have always been there for me. You have believed in me, and I share this achievement with you, whether it be listening to me go on about work or being there when I needed to occupy my mind with something else. I am forever grateful to have you in my life. To my parents, Eva and Mattias, thank you for your endless love and care, and for everything you do for me and my siblings.

Lastly, thanks to my partner Kalle, I could not have done this without you. Thank you for your unwavering support, love and patience. I love you and I am lucky to share my life with you.

Preface

This thesis summarizes the work I have conducted as a double degree doctoral student at the Division of Water Resources Engineering, Lund University, and at the Department of Geosciences and Natural Resource Management, University of Copenhagen. The project was funded by Trafikverket (Swedish Transport Administration). The thesis is a compilation of appended papers, and the preceding synthesis provides a framework for the collective research presented in the papers.

I am grateful to have been part of the two different and diverse research groups in Lund and Copenhagen. It has broadened my perspective to work interdisciplinary between coastal engineering, coastal geomorphology, and geosciences. At times, moving between the two institutions was challenging, but mostly, it is something that truly has inspired me in my work. This perspective and experience, I believe, is reflected in my thesis and has influenced how I design, conduct, and communicate my research.

I started my PhD studies in the middle of the Covid-19 pandemic with lockdowns and a lot of working from home, which made it challenging to get into my new role and the loneliness that can come with a position in academia was aggravated. When international travel and mobility were possible again, I made the most of it and attended numerous conferences, research schools, and research visits, finding great inspiration among fellow researchers and PhD students in the coastal community. I am very grateful for having the opportunity to experience and be a part of these scientific events which have had a positive influence on my PhD journey and my own personal development. It provided me with valuable perspectives on the broader scope that my research can contribute to.

A defining moment of my PhD journey was when the extreme storm surge Babet happened in October 2023. It was a severe event with significant societal impact, material damage, and damage to natural coastal areas. The storm event also demonstrated that this research is needed and relevant for the coastal communities in the southern Baltic Sea, and it strengthened my motivation to pursue and continue this research. Babet got to dictate the fate of finalising my PhD, it was an unforeseeable opportunity to learn more about the coastal systems I had been studying thus far and how they develop and respond to such extreme conditions.

List of appended papers

Paper I

Adell, A., Almström, B., Kroon, A., Larson, M., Bertacchi-Uvo, C. and Hallin, C. (2023) Spatial and temporal wave climate variability along the south coast of Sweden 1959-2021. *Regional Studies in Marine Science.* 63, 103011. https://doi.org/10.1016/j.rsma.2023.103011

Paper II

Bokhari Irminger, S., **Adell, A.,** Karlsson, M., Schöld, S. and Magnusson, Å. Impact and response of storm Babet in a Swedish perspective. *Die Küste.* (Under revision)

Paper III

Hallin, C., **Adell, A.,** Almström, B., Kroon, A., and Larson, M. RoadRAT – a new framework to assess the probability of flooding, wave runup, and erosion impacting coastal roads. (Manuscript submitted to *Coastal Engineering*)

Paper IV

Adell, A., Kroon, A., Almström, B., Larson, M. and Hallin, C. (2024) Observed beach nourishment development in a shallow embayment. *Geomorphology.* 462, 109324. https://doi.org/10.1016/j.geomorph.2024.109324

Paper V

Adell A., Van Wiechen, P., Luetzenburg, G., Almström, B., Kroon, A. and Hallin, C. Performance of hybrid coastal protection in extreme storm conditions. (Manuscript submitted to *Coastal Engineering*)

Author’s contribution to the papers

Paper I

The author formulated the scope and conceptualisation of the study. The author was responsible for the investigation, formal analysis, collected and processed the nearshore wave data and conducted the wave modelling. The author wrote the manuscript.

Paper II

The author contributed to the conceptualisation of the study, was responsible for the wave modelling and wrote the corresponding sections of the manuscript and produced the visualisation of the results. The author contributed to discussions regarding framing analysis and discussion of results. The author assisted in review and editing of the introduction, study area description and discussion. The author provided comments on the final version of the written manuscript before submission.

Paper III

The author contributed to the literature review, the conceptualisation of the study, and discussion and analysis of results. Simulated the wave data used for the analysis and complementing visualisation for the paper. The author contributed to the writing of manuscript in the review and editing phase, particularly the introduction and discussion sections of the paper. The author provided comments on the final version of the written manuscript before submission.

Paper IV

The author was responsible for formulating the scope of the study and setting up the field campaign and collect and process the data. Investigation, methodology, visualisation and formal analysis. The author wrote the manuscript.

Paper V

The author was responsible for the conceptualisation of the study, conducted the numerical modelling, data processing and visualisation of results. Investigation, methodology, visualisation and formal analysis. The author wrote the manuscript.

Other publications and conferences

Adell, A., Nunes De Brito Junior, A., Almström, B., Goodfellow, B., Bokhari Irminger, S., Hallin, C. and Nyberg, J. (2021) Open-access portal with hindcast wave data for Skåne and Halland. *VATTEN - Journal of Water Management and Research.* 77 (2), 81-90

Adell A., Almström B., Kroon A., Larson M. and Hallin C. (2023) Multi-scale wave modelling; Field validation in Faxe Bay, Denmark. *Coastal Engineering Proceedings,* 37. ASCE publishing. https://doi.org/10.9753/icce.v37.waves.11

Adell, A., Kroon, A., Almström, B., Larson, M., and Hallin, C. (2023) Morphological development of a small-scale beach nourishment in a non-tidal area. *Coastal Sediments 2023.* 117-121. https://doi.org/10.1142/9789811275135_0011

Sukchaiwan, E., **Adell, A.**, Hallin, C. and Almström, B. (2024) Analysis of the wave conditions during the 1872 storm. *VATTEN – Journal of Water Management and Research.* 80 (3), 142-151.

Conference abstracts

Adell A., Kroon A., Almström B. and Hallin C. (2024) Combination of extreme water levels and waves in a semi-enclosed sea: Reconstruction of the Baltic Sea storm surge (Babet). EGU General Assembly 2024, Vienna, Austria, 14–19 April 2024, EGU24-10476.

Adell, A., Luetzenburg, G., Kroon, A., Almström, B. and Hallin, C. (2024) Storm impact on beach nourishment morphology in a shallow bay. International Conference on Coastal Engineering, Rome, Italy, 8-14 September 2024.

Hallin, C., Almström, B. and **Adell A.** (2024) Road-RAT – Regional risk assessment tool for flooding, erosion and overtopping of coastal roads. International Conference on Coastal Engineering, Rome, Italy, 8-14 September 2024.

Fritzbøger Christensen, D., **Adell, A.** and Kroon, A. (2024) Coastal overwash – the impact of a 100-year storm flood event in south-eastern Denmark. International Conference on Coastal Engineering, Rome, Italy, 8-14 September 2024.

1 Introduction

Coastal areas worldwide are densely populated and host important societal and ecological functions. Sandy coastal systems are dynamic and develop in relation to the acting hydrodynamic forcing and sedimentologic boundary conditions. They are particularly vulnerable to environmental issues like coastal flooding and erosion, extreme weather events, and sea level rise (SLR). Risks associated with these impacts are expected to further increase in the future due to climate change (Nicholls & Cazenave, 2010; Oppenheimer et al., 2019). In addition, the development of these areas is impacted by human activities in the coastal zone, e.g., exploitation, urbanization, population increase, tourism, and anthropogenic influences on sediment budgets through dredging operations and the presence of hard structures. Both natural and human activities increase the pressure on coastal environments and can cause coastal squeeze and increased coastal erosion (Defeo et al., 2009; Vousdoukas et al., 2020). Eroding beaches and coastal systems means both loss of ecological functions (e.g., habitats and biodiversity) and risk for societal functions like critical infrastructure and anthropogenic use of coastal areas.

There is an abundance of critical infrastructure located in the coastal zone, like coastal roads. In some places, these are the first line of infrastructure and are therefore vulnerable to coastal flooding and erosion and could potentially suffer temporary or longer disruptions if damaged (Douglass & Webb, 2020). A recent study (Nawarat et al., 2024b) concluded that 1205 km of European transport networks are already exposed to annual flooding due to extreme sea levels today. This is expected to increase in the future with aggravated rates of SLR due to climate change, meaning that flooding will become more frequent and road networks that are not at risk of flooding today can become impacted in the future (Pal et al., 2023). For continued use of these services, the risks must be assessed and mitigated through sustainable coastal management.

In the coastal zone, it is not only an elevated sea surface level that can cause flooding. There is also the contribution of waves that can cause flooding through wave runup and overtopping. Most risk assessments at regional scales have only considered flooding caused by the static sea level, considering the effects of storm surges of specific return periods or SLR scenarios (Demirel et al., 2015; Neumann et al., 2021; Paulik et al.,

2020) but discarded the contribution of dynamic processes like waves and coastal erosion. This is because wave impact can be complex and largely vary under local conditions (e.g., slope, shoreline orientation, depth), but dynamic processes may further increase the vulnerability of coastal roads and future SLR impact (Anderson et al., 2018). Therefore, to present an accurate assessment of the contribution of waves to potential flooding, detailed high-resolution data, both spatial and temporal, is required (Asariotis et al., 2020). Another important aspect of wave impact in the coastal zone is the potential to drive morphological change that alters the local conditions. Waves drive littoral processes in the nearshore, and coastal erosion is a threat to coastal roads and other infrastructure in the coastal zone. Long-term coastal erosion results in landward retreat of the shoreline, increasing the vulnerability of roads to be subject to flooding. Additionally, storm erosion can undermine and damage road infrastructure.

Historically, coastal management strategies to mitigate problems with coastal erosion have been dominated by the implementation of hard structures. This may inhibit the natural dynamics of sandy systems and profile adjustment in response to the acting hydrodynamic forces. Due to the known shortcomings of using hard structures for coastal protection, there has been a shift towards working with nature through implementing nature-based solutions in recent decades (Smith et al., 2020; Temmerman et al., 2013). For example, beach nourishments are extensively applied in many places around the world (e.g., Hanson et al., 2002), and other soft solutions are becoming increasingly more applied. Sustainable coastal management relies on data and knowledge about the coastal system. Implementation of coastal protection or management strategies must be adapted to the local conditions and setting. These concern technical aspects like hydrodynamic conditions, but the feasibility of implementation can also concern legal or operational aspects, both of which can vary between different coastal settings.

1.1 Scope

The scope of this thesis is the southern Baltic Sea, specifically the coastal areas of southern Sweden and Zealand in Denmark. Because of the enclosed nature of the basin, the conditions vary compared to coasts along the open ocean. The coastlines in the southern part of the Baltic Sea mainly consist of soft Quaternary sediments. Their morphologies are dictated by permanent transgression. The post-glacial uplift in the region is limited and cannot counteract current rates of eustatic SLR. Consequently, the region is subsiding and is vulnerable to coastal flooding and erosion. The need for coastal management strategies is the most predominant in this part of the Baltic Sea (Harff et al., 2017).

The southern Baltic region holds critical infrastructure in its coastal zones, including roads and railways, which are essential to societal functioning. Because coastal infrastructure is especially sensitive to flooding and erosion, its resilience and continuity may be compromised by extreme weather or gradual environmental changes. Given the long-expected operational lifespan of transport infrastructure, assessing current and future risks is essential to ensure that these remain reliable over the coming decades. In addition, identifying the risk areas allows for planning and adapting the infrastructure to the changing climate conditions is needed.

1.2 Aim and objectives

The aim of this thesis is to present a methodology for risk analysis of coastal roads impacted by coastal flooding and erosion and investigate potential adaptation solutions to reduce negative impacts from coastal processes. To reach the aim, the work is designed to address four separate research objectives:

(i) Forcing: Provide high-resolution hindcast data of wave climate conditions for the southern Baltic Sea and analyse drivers for inter-annual variability and extreme events.

(ii) Response: Analyse morphological response at local to regional scales in relation to varying hydrodynamic input and showcase the consequences of an extreme storm surge (Babet) on the coastal zone and impacts on road infrastructure.

(iii) Exposure: Develop a regional screening tool to assess exposure of coastal roads to estimate the probability of coastal flooding and erosion in today's climate and under future SLR scenarios.

(iv) Mitigation: Showcase and evaluate the potential of small-scale beach nourishment as a measure to mitigate the impact of coastal processes on a road.

Figure 1.1 provides an overview of the work compiled in this thesis. It illustrates the scope and content that is addressed in the different papers and the corresponding research objectives. To meet the objectives, the analysis is structured to cover various temporal and spatial scales and the methods applied includes a combination of numerical modelling, field observations, and a case study.

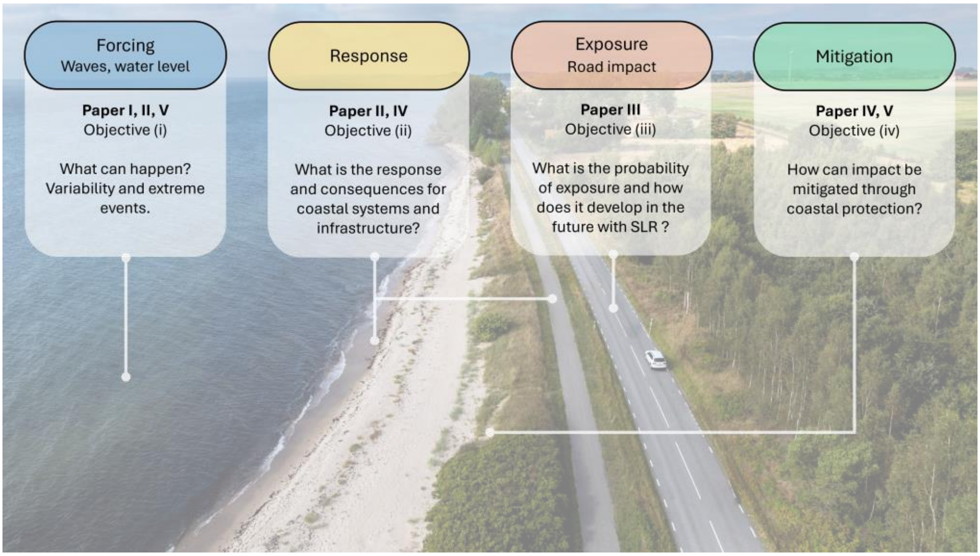


Figure 1.1: Overview of the thesis work presented to illustrate the objectives and rhetorical research questions addressed in the different appended research papers.

1.3 Limitations

For the context of the work presented in this thesis, the definition of exposure of roads to coastal hazards concerns the probability of flooding, wave impact, and erosion quantified as the extent of road stretch that is affected. No formal risk assessment of the consequence of the operation is considered. The presented framework only highlights where the exposed sections are, and then those result can be evaluated in relation to traffic data to assess the impacts on society or potential cascading effects following the impacts of coastal processes.

Regarding future development of coastal hazards related to climate change, this thesis considers climate change driven sea level rise (SLR). Impacts from other climate change effects like, e.g., drought, heatwaves, and increased precipitation are not considered as these are not specific to coastal roads but have the potential to impact any part of the transport network system. Projections concerning changes in storm intensity, frequency, and direction are not considered, although relevant for future development of coastal processes. However, aspects of future storm impact and wind direction for the Baltic Sea and the potential for impact of coastal process are discussed.

General risk mitigation strategies for coastal roads include maintenance, increase redundancy, protection, accommodation, and relocation (Douglass & Webb, 2020).

This thesis focuses on mitigation through coastal protection, particularly hybrid solutions combining hard and soft engineering approaches. Measures interfering directly with road infrastructure (e.g., altering elevation) are not considered. Other management options, either temporal (close the road and re-direct traffic during extreme events) or long-term (relocate the road), are not considered, although feasible adaptation strategies they are not considered as coastal engineering solutions.

1.4 Summary of appended papers

This thesis contextualizes and synthesises the research presented in the appended papers; the conceptual scales that are considered are illustrated in Figure 1.2.

Paper I presents the procedure for generating decadal hindcast wave climate data for the southern Baltic Sea, followed by an analysis of spatial and temporal wave climate variability. The model performance was calibrated and validated against existing public data records and nearshore wave buoy measurements obtained within this study. This study relates to objective (i).

Paper II presents a description of the extreme storm surge (Babet) that impacted the coastlines of the south Baltic Sea in October 2023. The paper discloses detailed assessment of both the impacts regarding acting processes and the resulting societal response in southern Sweden. The findings relate to objectives (i) and (ii).

Paper III presents a new screening framework designed to analyse exposure for coastal roads to flooding, wave runup and erosion. The analysis can be applied on regional scale and in the paper, it is applied to the south coast of Sweden. The probability of flooding and erosion are assessed in today's climate conditions and under all SSP SLR scenarios. The work relates to objective (iii).

Paper IV presents a case study investigating the morphological response of small-scale beach nourishment, over varying timescales. The study contributes to better understanding morphodynamics and implementation of nourishments of low energy sheltered coastal environments and thereby relates to objectives (ii) and (iv).

Paper V presents a modelling study to investigate beach nourishment design in combination with a rock revetment, creating a hybrid coastal protection solution. The protection is implemented to protect a coastal road against wave overtopping and the beach nourishment design is evaluated as the effectiveness in reducing overtopping discharge through wave dampening. The findings relate to objective (iv).

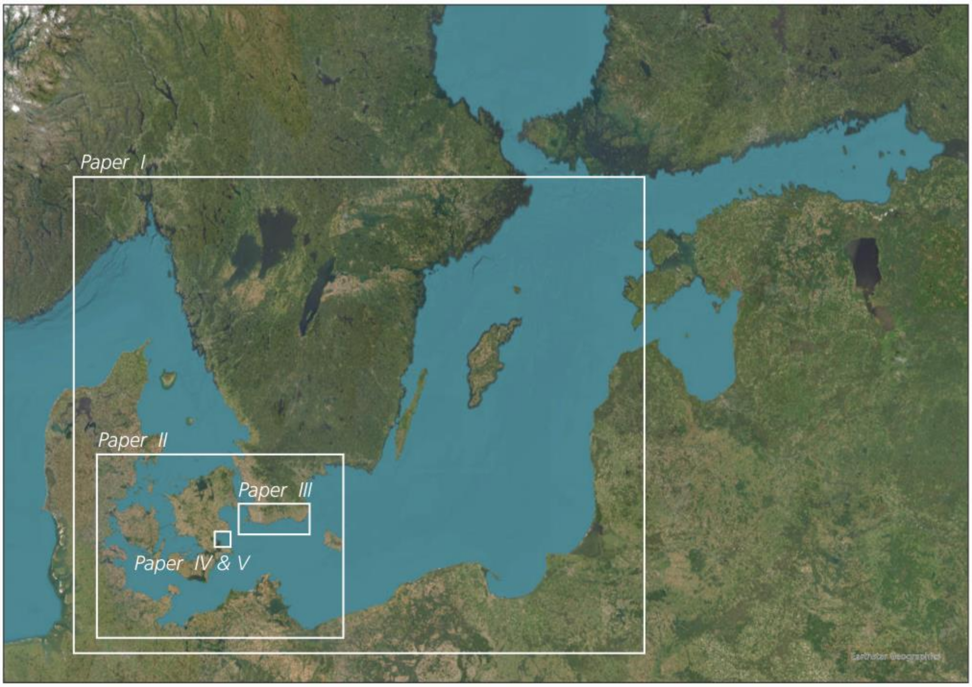


Figure 1.2: A visual representation of the different spatial scales and geographical setting considered in the appended papers that constitute this thesis.

1.5 Thesis structure

This compilation thesis is based on the research presented in the appended papers, summarized in Section 1.4. It consists of nine chapters, beginning with an Introduction. Chapter *2 Background* provides the context for the research, followed by Chapter *3 Study areas*. The core structure aligns with the research objectives (Section 1.2) and the framework in Figure 1.1 - Forcing, Response, Exposure, and Mitigation. Methods, results, and discussions from Papers I-V are integrated within: *4 Hydrodynamic conditions*, *5 Morphological response*, *6 Regional exposure analysis,* and *7 Mitigation through coastal protection*. The final chapters, *8 Discussion and outlook,* and *9 Conclusions*, offer a broader synthesis of findings. Lastly, the papers are appended presented in their published layout or as manuscript versions.

2 Background

This chapter provides an overview of the key concepts central to the scope of the thesis. It includes description of coastal processes that drive flooding and erosion, highlighting their associated risks and implications for coastal roads. Additionally, the chapter introduces general protection and adaptation strategies aimed at mitigating these risks, with a particular focus on hybrid solutions and small-scale beach nourishments, which are the primary focus of the case study.

2.1 Coastal flooding and erosion

Coastal flooding and erosion are dynamic processes that shape the morphology of coastlines and can make coastal areas vulnerable to impact (Wong et al., 2014). Coastal flooding occurs primarily due to extreme sea level (ESL) events, which arise from a combination of meteorological and hydrodynamic factors. Storm surges, driven by intense winds and low atmospheric pressure, or tides, are dominant contributors to ESLs. These processes can temporarily elevate water levels, with the risk of causing coastal flooding (inundation) and allow waves to reach further inland. Seasonal and longer-term sea-level fluctuations, influenced by climate variability, can also modulate the frequency and severity of flooding events. In addition, wave processes can cause coastal flooding through wave runup and overtopping.

Waves and wave-induced currents drive littoral processes in the coastal zone and can drive morphological change which can cause erosion (Davidson-Arnott, 2010). Sediment transport processes play a significant role in reshaping beaches, dunes, and other coastal landforms. Prolonged periods of elevated water levels can intensify these processes, leading to the loss of sediment and a reduction in natural coastal defences. Additionally, human activities, such as shoreline modification and the construction of coastal engineering works (harbours, hard coastal protection, or infrastructure), can disrupt sediment transport and exacerbate localized erosion. The interplay between coastal flooding and erosion creates a feedback loop where flooding weakens coastal systems, and erosion diminishes their capacity to mitigate future flooding impacts.

2.2 Impacts on coastal roads

Roads located in coastal areas are exposed to the impact of waves and coastal processes that can damage the road structure and threaten the operation. The impact and exposure of coastal processes on infrastructure can be categorized into two types. The first includes hazards directly caused by physical processes, such as wave overtopping, runup, and inundation, while the second arises from shoreline response in relation to the acting physical processes, including storm erosion, scour, and long-term shoreline retreat (McGillis & MacCallum, 2010).

The images in Figure 2.1 shows examples of road damages caused by coastal processes. The impact on the transport infrastructure and traffic flow also differs depending on the hazard, where the direct impact of e.g., waves can affect serviceability and traffic temporarily during extreme events. The indirect impacts of the physical process may disrupt the operation of the roads; for example, if a road is undermined due to erosion, it may require repairs that cause longer disruptions (Douglass & Webb, 2020).

Figure 2.1: Hazards that can impact coastal roads. (a) Wave overtopping at Rågeleje, Denmark during storm Bodil in December 2013, Photo: Keld Navntoft/Ritzau Scanpix. (b) Receding shorelines, cliff erosion at Tunstall beach, UK in August 2022, Photo: Andy Medcalf/Shutterstock. (c) Road damaged due to undermining following storm erosion during storm Babet October 2023, Photo: Sønderborg Kommune. (d) Inundated intersection in Malmö, Sweden during storm Malik in January 2022, Photo: Johan Nilsson/TT Nyhetsbyrån. (e) Undermining of road at Kåseberga, Sweden, caused by wave runup during storm Babet October 2023, Photo: Caroline Hallin. (f) Local scour caused by weir flow mechanism, Photo: FHWA, 2008.

Inundation is caused by an elevated water surface, and the risk of inundation is greater if the infrastructure is in a low-lying area. Inundation will compromise the operation and serviceability of roads by large amounts of water occupying the road (Pregnolato et al., 2017). There is also a risk of local scour caused by flowing water and the weir flow mechanism (Figure 2.1f).

Wave runup and overtopping are risks in exposed areas, and the greater forces can potentially damage the road structure and induce erosion and undermining of the road structure. There are established limits for overtopping discharges (EurOtop, 2018) that indicate at which levels the wave impact and volumes can compromise the use of the road by posing a risk to vehicles and traffic. During extreme events, the risk of transport of debris is also important to consider.

Coastal erosion can be caused by individual events or long-term chronic erosion if the sediment budget is not in balance. Erosion that is impacting the road can cause undermining or destabilisation of the slope in front of the road structure. In the case if the road structure is undermined or damaged, it might require repairs that can cause longer disruptions and periods when the road is out of use and traffic may have to be re-directed.

Given the long-expected lifetime and long planning horizons, in combination with the societal importance of transport infrastructure, it is important to understand these processes and associated risks on varying time scales. For continued use and operation of coastal roads it is important to assess the risks in future climate conditions when sea level rise will be an important component. It is important to account for both when adapting the existing infrastructure and planning construction of new facilities.

2.3 Climate change effects

Climate change is driving the rise in global mean temperatures and warming of the world's oceans. Consequently, there is increased melting of ice sheets and glaciers, which is contributing to global sea level rise. The main driver for observed global sea level rise since the 1970s has been anthropogenic emissions of greenhouse gases (Slangen et al., 2016). As established by the International Panel on Climate Change (IPCC), the rate of change is accelerating for the period 2006-2018, corresponding to a rate of an average 3.7 mm/yr compared to an average of 2.3 mm/yr for the period 1971-2018 (Fox-Kemper et al., 2021). Global mean sea level is expected to continue to rise, and future projections are indicating average rises of between 0.38 [0.28 to 0.55] m (SSP1-1.9) to 0.77 [0.68 to 1.01] m (SSP5-8.5) by 2100 (Fox-Kemper et al., 2021).

The uncertainty levels presented in brackets correspond to a likely range and do not consider ice-sheet-related processes that are concerned with deep uncertainty. There is great uncertainty related to the ice-sheet processes with great potential for extreme sea level rise past 2100 driven by deep-ocean heat uptake and mass loss from the Greenland and Antarctic ice sheets (Fox-Kemper et al., 2021).

The IPCC projections concern eustatic sea level change, i.e., absolute sea level change, and is driven by the combination of thermal expansion and ice melt. The contribution from ice melt has now been identified as the dominating driver for global mean sea level rise (Oppenheimer et al., 2019). Regional assessment is needed as the global mean sea level changes are not expected to impact the whole globe in a uniform manner. The melting of the Greenland and Antarctic ice sheets also influences the gravitational field, which means relative sea level falls in the vicinity of glaciers and ice sheets (Mitrovica et al., 2001). This is due to a combination of weakened gravity but also the movement of the Earth's crust following postglacial rebound.

For estimation of relative sea level change, the global mean sea level rise projections must be downscaled to local levels through assessment considering local conditions (Durand et al., 2022). To further downscale the IPCC projections to local estimations, the absolute sea level change must be converted to relative sea level change by accounting for local isostatic adjustments in relation to the eustatic sea level. Local impacts on isostatic sea level can, for example, be postglacial uplift or land subsidence due to extraction of resources such as groundwater, oil, or natural gas.

Climate change driven sea level rise is expected to aggravate risks of coastal flooding and erosion in the future, posing a significant threat to coastal transport infrastructure and other functions in coastal zones (Hinkel et al., 2014; Nicholls & Cazenave, 2010; Oppenheimer et al., 2019). In addition, the projections also concerns increased magnitude and frequency of storms, which impact the wave climate conditions (Anderson et al., 2018; Bricheno & Wolf, 2018). This increases the risk of dynamic processes like wave runup and erosion, which may further increase the vulnerability of coastal roads in the future. These changes are likely to increase both the frequency and magnitude of coastal hazards, such as the extent of road networks impacted by flooding and erosion and the severity of damages (Pal et al., 2023). The projected development of risks for coastal hazards in the future increases the need for coastal management and coastal protection to mitigate the risks and limit negative societal impacts (Brown et al., 2014; Lincke & Hinkel, 2018).

2.4 Coastal protection solutions

Conventional coastal protection solutions mainly concern hard structures such as groins, revetments, seawalls, dikes, and breakwaters. They are built in the coastal zone to protect against flooding and mitigate erosion. Coastal roads are rarely designed with consideration for wave impact; even if placed in the coastal zone, they typically need to be combined or reinforced with coastal protection structures (McGillis & MacCallum, 2010). In addition to protection, other adaptation strategies for coastal transport infrastructure include, maintenance, increased redundancy, accommodation, or relocation (Douglass & Webb, 2020). Corresponding solutions for example include increasing the road elevation, relocating the road, redirecting traffic, or temporarily closing the road during extreme events.

An assessment conducted by the UN, focusing on climate change risks for transport infrastructure, found that coastal protection and adaption solutions of coastal transport infrastructure have been dominated by hard rather than soft solutions (Asariotis et al., 2020). This has also been the general trend for coastal protection historically. Although there is a risk of having negative impacts on sediment budgets by restricting sediment supply, and while maybe solving the problem locally, there is the potential of moving the erosion problems to adjacent coastlines (Dean, 1986; Manno et al., 2016).

Considering the known negative effects that hard coastal protection structures can have on the coastal system, there has been a shift in recent decades to work with soft coastal protection solutions as an alternative (Hanson et al., 2002; Schoonees et al., 2019; Sutton-Grier et al., 2015; Temmerman et al., 2013). These include sand nourishments, planting vegetation, and dune restoration, among others. The benefits of using soft coastal protection measures are that they resemble the natural coastal features and thereby support more ecological and recreational functions (Sutton-Grier et al., 2015). The solutions are dynamic, and there is potential for self-recovery after storm impact, and they can be adapted to increasing sea level rise. In contrary to hard structures that typically have an established design level and are rigid to sea level rise.

For some applications, it may be beneficial to consider combinations of different types of solutions to accommodate a wider range of functions that are desired with the protection and to leverage potential benefits from both hard and soft measures (Sutton-Grier et al., 2015). These can be considered hybrid solutions and are being increasingly more applied to mitigate coastal challenges and increase resilience. The general definition of hybrid coastal protection is a solution combines a resistant core to provide defence against flooding with a nature-based soft element that provides reinforcement or offers alternative benefits to the protection (Almarshed et al., 2020; Boers, 2011;

Nordstrom, 2019). Therefore, the benefits of both conventional hard and soft solutions can be combined into one coherent framework or solution. The soft elements can be considered compensation for the shortcomings and negative impacts on sediment budgets that hard structures are known to have. While the hard solution may offer a stricter and higher protection level during extreme conditions. The benefits and drawbacks related to the different strategies are presented in Table 2.1, along with some examples of solutions.

Table 2.1: Summary and overview of different protection and adaptation strategies with listed benefits and drawbacks, some examples also provided for each strategy, but the list is not exhaustive. Table information from Sutton-Grier et al., (2015).

	HARD	**HYBRID**	**SOFT**
BENEFITS	• Less maintenance • Smaller footprint • Established design guidelines • Global experience of implementation	• Combining benefits from both hard and soft solutions • Innovative design alternatives	• Dynamic natural development • Promotes self-recovery • Adaptable with SLR • Recreation, tourism • Habitat and ecology • Can be cheaper to construct
DRAWBACKS	• Repairs can be costly • Rigid for SLR • No dynamics • Potentially impacts on sediment budgets	• Design guidelines are lacking and complex • Risk for scour	• Requires large spatial footprint • Regular assessment and maintenance needed
EXAMPLES	• Seawall, revetments • Groins, breakwaters • Riprap • Dike • Sheet piling	• Dunes with resistant cores, • Dune restoration or beach in front of hard structures • Artificial reefs	• Dunes • Planting vegetation • Sand nourishments • Sand fences

2.4.1 Examples of hybrid coastal protection solutions

Many of the hybrid solutions exemplified in literature have typically become hybrid solutions as soft elements were added to reinforce existing hard structures or flood defences. For example, cases where dunes were constructed in front of an existing dike or seawall (Kroon et al., 2022; Perk et al., 2019; Strypsteen et al., 2024), where the design relied on a combination of nourishments and planting vegetation. Other examples exist where dunes were constructed to cover hard protection (Tomlinson et al., 2016; Winters et al., 2020) or where seawalls got buried with sand over time (Irish et al., 2013; Smallegan et al., 2016; Yang et al., 2012). There are also examples where beach nourishments were implemented in front of seawalls to increase resilience without altering the hard protection structure (Blott & Pye, 2004; Ravens & Sitanggang, 2007; Ton et al., 2023). Extensive nourishment can then allow for natural dune growth, and vegetation can be established (Irish et al., 2013; Nordstrom, 2014). Hybrid designs can allow for innovative approaches, and typically, the protection may resemble a more natural system and provide associated positive benefits (Table 2.1) (Sutton-Grier et al., 2015), and the hard resistant core is needed for extra protection particularly during storm conditions.

2.4.2 Small-scale beach nourishments

The scale and type of nourishment (e.g., beach fill, shoreface, channel wall, mega nourishment) depends on the dynamics and setting at the site where it is to be implemented. For example, beaches on open coastlines are typically dynamic and show a distinct seasonal variability in the morphology. The morphology can be impacted by variations in tide, swell, and wind-waves. Nourishments in these environments are typically in the order of >100 m^3 per m alongshore. On the contrary, beaches in more sheltered coastal environments typically have a smaller active zone and hence require smaller nourishment volumes, generally <100 m^3 per m alongshore.

There are examples of implementation and analysis of small-scale nourishment projects in more sheltered coastal environments such as inland seas, estuaries, and lakes (Andrade et al., 2006; Basterretxea et al., 2007; Corradi et al., 2008; Jackson & Nordstrom, 1994; Karasu et al., 2023; Lowe & Kennedy, 2016; O'Brien et al., 1999; Ojeda & Guillén, 2008; Pupienis et al., 2014; Ton et al., 2021). In general, the morphodynamics of beaches in sheltered coastal systems have received less attention in research (Vila-Concejo et al., 2024). That also goes for nourishment projects on sheltered coastlines, as small-volume projects typically have fewer resources available for monitoring and evaluation of the effectiveness of design.

3 Study areas

This chapter provides an overview of the geographical scope of the research, focusing on the study areas where the work was conducted. The study areas are presented in the following order: first, the regional scale setting of the Southern Baltic Sea; followed by more local scales for the south coast of Sweden and the case study site in Faxe Ladeplads in Denmark.

3.1 Southern Baltic Sea

The Baltic Sea is a marginal sea located in northern Europe, it extends over latitudes 54-66° N and longitudes 10-30° E. The Baltic Sea is composed of a series of sub-basins, illustrated in the map in Figure 3.1. Water exchange from the North Atlantic to the Baltic Sea is limited through the shallow Danish straits (The Belts and Öresund); further water exchange between the different sub-basins is restricted due to complex bathymetry and confining geometry. Since the basin covers a relatively large area (392 978 km^2), there is a great spatial variation both in terms of characteristics of the sub-basins and physical- and environmental conditions, such as surface salinity and sea-ice conditions (Leppäranta & Myrberg, 2009). Winter sea ice conditions are rare in the southern Baltic Sea, contrary to the north- and northeastern parts (i.e., Bay of Bothnia, and the Gulf of Finland), where sea ice is forming annually. Although sea ice extent has declined in recent decades due to climate change and milder winter temperatures (Hünicke et al., 2015).

While the tidal range in the Baltic Sea is very small (<10 cm) and can often be neglectable (Arns et al., 2020), sea level fluctuations can arise from other processes. This is mainly through wind-driven setup and influence by variance in atmospheric pressure. In addition, internal basin oscillations occur in the form of seiches (Weisse et al., 2021). The nodal point of the seiche oscillation is located at the Landsort deep (58.13° N; 18.13° E) in the Northern Baltic Proper; from there, the amplitude increases in each direction north and south (Hellström, 1941). Additionally, long periods of westerly and north-westerly winds can increase the inflow to the basin from the North

Sea and lead to increased filling levels and increase in sea surface elevation up to 0.5 m (Hünicke et al., 2015; Weisse & Weidemann, 2017). The combined effect of seiches and filling level influence extreme sea levels (ESL) in the Baltic Sea.

There is large spatial variability in the frequency and persistence of ESLs between the different sub-basins in the Baltic Sea due to the complex basin geometry (Wolski & Wiśniewski, 2023). Water masses can be pushed up by onshore winds giving a funnelling effect in the narrow and shallow bays and gulfs, for example, in the Gulf of Riga and the Gulf of Finland during westerly and south-westerly winds and in Kiel Bay in the southwestern Baltic Sea during easterly winds (Wolski & Wiśniewski, 2023).

Regarding water level fluctuations in the Arkona Basin, westerly winds push water towards the eastern part of the Baltic Proper, which lowers the water levels within the study area. When the wind then ceases, the water masses return to the western part of the Baltic Sea, and thereby, water level variations are altering in relation to the wind direction with a varying time delay (Bendixen et al., 2013). High water levels in the Arkona Basin are driven by easterly winds when water is being pushed from the east Baltic Sea to the Arkona Basin.

Coastlines in the southern Baltic Sea have complex and irregular appearance, and the basin is lined with many separate embayed parts, and forcing conditions fall within the wave-dominated microtidal regime (Weisse et al., 2021). There is a range of different coastal types, e.g., rocky coasts, sedimentary cliffs, sandy beaches, coastal meadows, spits, gravel- and boulder beaches (Łabuz, 2015). The region is subsiding as the post-glacial uplift is limited, which makes the coastlines susceptible to change compared to the north (Harff et al., 2017).

The dominance of westerly winds over the region creates a gradient in mean annual erosion rates that increase towards the east, with larger erosion for the Polish, Latvian, Russian, and Lithuanian coastlines compared to the German, Swedish, and Danish coastlines (Łabuz, 2015). In addition, the complex basin geometry provides conditions where the shoreline orientation can vary greatly over small spatial scales (around 10 km). The system is also characterized by that sediment input is low, i.e., negligible sediment input from river systems and in general, input to the sediment budgets relies on erosion of the coast and eroding buffs (Harff et al., 2017; Łabuz, 2015).

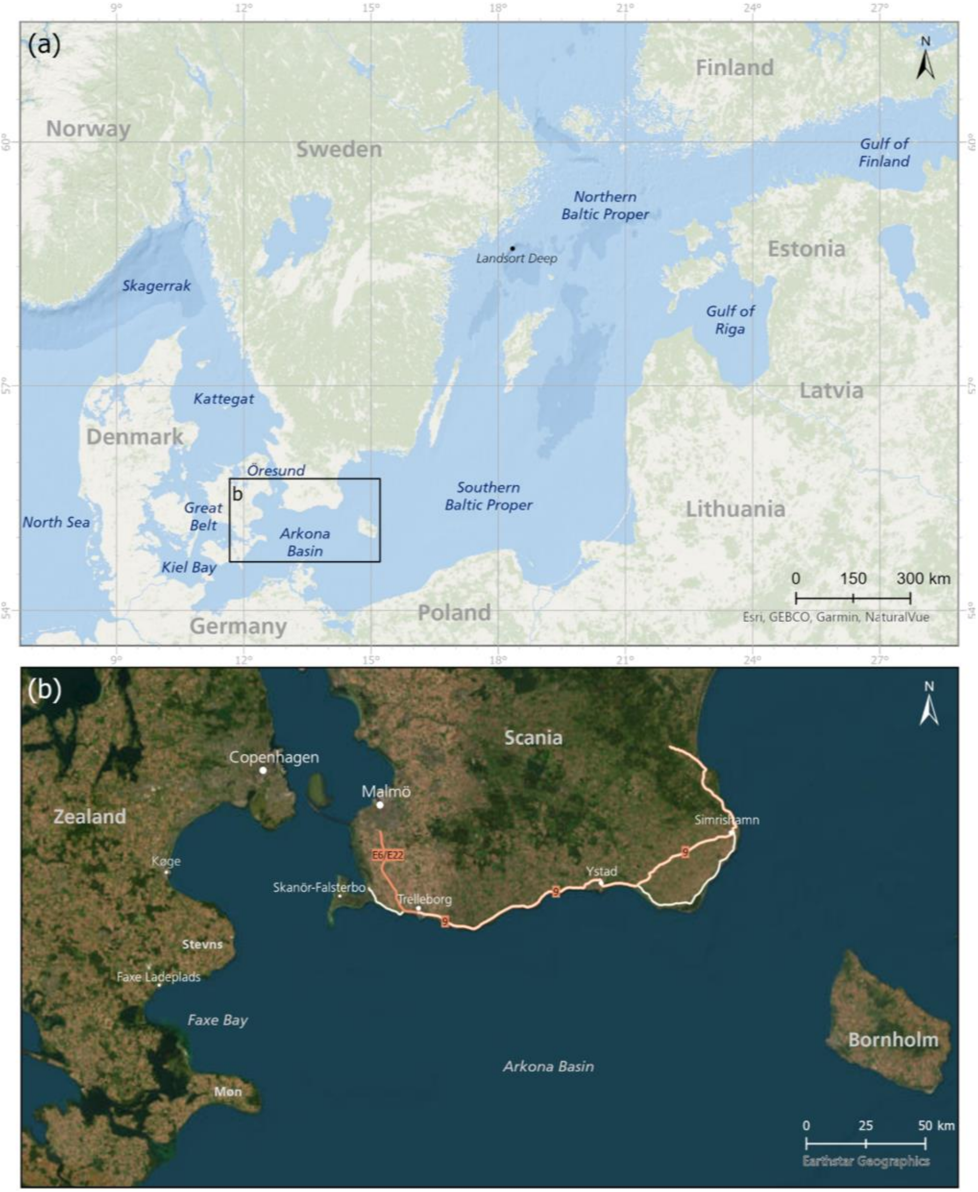


Figure 3.1: (a) Overview map of the southern Baltic Sea, and (b) zoomed in view of the study area, main focus for the research is the south coast of Sweden and Riksväg 9 and Faxe Ladeplads in the east coast of Denmark.

3.2 The south coast of Sweden

In **Papers I**, **II**, and **III**, the south coast of Sweden is the main subject for investigation. The coastal areas of Scania and Halland Counties has been identified as risk areas for coastal flooding and erosion in a national assessment (SGI & MSB, 2021). This includes the south coast of Sweden, namely the south coast of Scania County, which is an area that exemplifies a lot of the coastal issues that are facing the Swedish and the southern Baltic Sea coastlines today. The coastline is characterized by a varying coastal landscape that hosts many important functions and unique values, such as nature, recreation, trade, harbours, tourism, and critical infrastructure. The coastline is oriented in the east-west direction and faces the Arkona Basin, which is one of the shallowest parts of the Baltic Sea (Figure 3.1b). The coastline mainly consists of sandy beaches and eroding bluffs. Protruding headlands and harbours divide the coastline into separate embayments and disrupt the sediment transport, and the shoreline orientations vary. In some places, there are hard coastal protection measures in place, dominated by revetments, breakwaters, and dikes. At two locations in Ystad municipality, regular nourishments have been conducted, which started in 2011.

In a national climate and vulnerability assessment presented by Trafikverket (2020), the southern part of Sweden is identified as a vulnerable region, particularly highlighting increasing impacts on near-coastal transport infrastructure in the future due to sea level rise and increased storminess. The national road *Riksväg 9* stretches along the coastline and connects the cities of Trelleborg, Ystad, and Simrishamn. Both Ystad and Trelleborg have two large commercial harbours that transport goods and ferries departing to other locations in the Baltic Sea including the island of Bornholm. The road is therefore part of an important network which is vital for supporting transport from ships and ferries onto the roads to further distribute goods within Scandinavia. *Riksväg 9* is one of the main subjects for investigation in the research conducted in this thesis project, used to exemplify the impacts and apply models for risk assessment to demonstrate the methodology.

The Swedish Metrological and Hydrological Institute (SMHI) has downscaled the IPCC projections for future sea level rise to local estimates for all Swedish coastal municipalities, by considering the rate of land uplift (Hieronymus & Kalén, 2020). The result is summarized and available in a national database where future sea levels can be retrieved for every coastal municipality in Sweden for the different SSP scenarios and at intervals every 10 years for the period 2030-2150 (SMHI, 2020).

3.3 Faxe Ladeplads, Denmark

The case study site presented in **Papers IV** and **V** is located in Faxe Ladeplads on the east coast of Zealand in Denmark. The coastal protection solution at the site has been investigated as a potential strategy to reinforce the protection of the coastal road and reduce wave overtopping. Faxe Ladeplads is a coastal town situated along the central of Faxe Bay, an embayment of the southwestern Baltic Sea. The mean depth in the bay is approximately 15 meters, and the bay is confined between the two limestone headlands Stevns and Møn (Figure 3.1b). The opening of the bay is facing towards the Arkona Basin to the east. The net longshore drift is directed from north to south in the bay. At the end of the littoral system, there is Feddet spit where longshore transported sediment is deposited in beach ridges (Bendixen et al., 2013).

The construction and development of the harbour in Faxe Ladeplads have been motivated by the industrial activities related to the nearby limestone quarry and chalk production (Aasbjerg, 2002). However, the protruding harbour has impacted the sediment transport and thereby influenced shoreline development over time. Figure 3.2 shows this development illustrated in historical maps and more recent aerial photos. Since the construction of the two initial harbour piers in the late 1800s, the coastline has transitioned from having a uniform orientation backed by eroding bluffs to being two separate sediment cells where the transport is disrupted by the harbour. Thereby, the updrift side of the harbour is characterized by sediment accumulation, and here, the shoreline position has moved seaward approximately 100-150 meters since the construction of the harbour. At the same time, the downdrift area has been subject to chronic erosion due to the lack of sediment input to the system through longshore transport processes in the direction of net longshore drift.

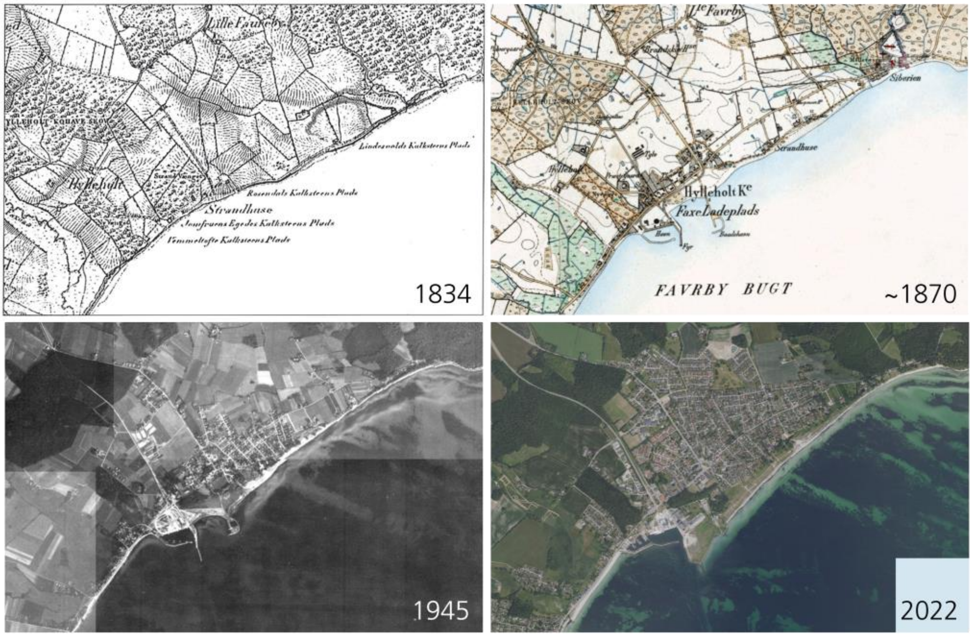


Figure 3.2: Historical development of the coastal town Faxe Ladeplads, Denmark, clearly showing the development of the harbour and the shoreline response. Image sources: 1834 (Aasbjerg, 2002), 1870 and 1945 (obtained from Danmarks Arealinformation, Miljøportal - https://danmarksarealinformation.miljoeportal.dk/), 2022 (contains data from the Danish Agency for Data Supply and Infrastructure, Orthophoto 2022 geodenmark_2022_12_5cm, WMS).

In Faxe Ladeplads, erosion has historically been managed with hard structures like groins and seawalls. Along the investigated stretch, ten groins were in place, but by the early 2000s, they had severely worn down. Additionally, the adjacent coastal road, Strandvejen, experienced wave overtopping during storms when large waves coincided with elevated water levels. Instead of repairing the groins, the municipality switched to a beach nourishment scheme.

A rock revetment existed adjacent to the road, and the nourishment was placed in front of it, confined by the harbour mole to the north and a small terminal groin near the creek outlet to the south (Figure 3.3). The developed design thereby combines hard and soft elements in a hybrid protection solution. The reinforcement with the nourishment aimed both to reduce overtopping onto the road during storms and to restore a recreational beach (Danish Coastal Authority, 2021). The nourished stretch extends about 650 m alongshore and has been nourished twice: initially in 2018 (70 000 m^3) and with a maintenance nourishment in 2021 (20 000 m^3). From an international perspective, these volumes are relatively small and are classified as small-scale nourishments.

Figure 3.3: (a) Cross-shore schematic illustration of the combined coastal protection solution. (b) Overview of the coastal protection solution at Faxe Ladeplads, Denmark. The nourishment is placed between the harbour mole and the groin with the objective to reduce wave impact on the coastal road Strandvejen. Photo: Danish Coastal Authority, July 2021.

4 Hydrodynamic conditions

Risk analysis should be based on the best possible data to generate as robust and detailed results as possible. Thereby, the initial part of the work presents the efforts in conducting numerical modelling to generate detailed time series of decadal hindcast wave climate with sufficient spatial resolution to be used in continued analysis. Analysis of the data is then performed to outline the spatial and temporal variability in the wave climate in the study area.

4.1 Wave hindcast modelling and observations

4.1.1 Model setup

Paper I presents the methodology used to set up a comprehensive multi-scale numerical wave model that has been calibrated and validated for offshore and nearshore performance based on existing records and new nearshore wave observations. The model is based on the open-source software Simulating Waves Nearshore (SWAN), a third-generation spectral wave model (Booij et al., 1999), which computes wave dynamics based on information about wind, current, and bathymetry input. In the model, the propagation of wave energy is described according to the spectral action balance equation (Booij et al., 1999). The model can resolve both deep-water processes (i.e., energy transfer from wind to waves, wave propagation, dissipation, and white capping) and shallow-water processes (i.e., refraction, shoaling, and wave-breaking).

The extent of the model is shown in Figure 4.1. The grid cell size is coarser in the deeper offshore parts of the model domain and gradually gets finer at the coast to resolve complex wave transformation processes. Hence, the resolution of the model grid cells ranges from a maximum of 25 km in offshore regions to 0.2 km in the nearshore coastal areas of south Sweden and parts of Zealand in Denmark, see Figure 4.1. The bathymetry used as input to generate the computational grid constitutes a combination of EMODnet Bathymetry (EMODnet, 2021) with a resolution of approximately 115 m, and for the nearshore areas of southern Sweden, there is a 2x2 m multibeam bathymetry (Malmberg-Persson et al., 2016). The model is forced with wind at 10-m elevation from the ERA5 reanalysis dataset (Hersbach et al., 2020), and simulations used as a basis for the analysis in **Paper I** cover the period 1959-2021 with a temporal resolution of 3 hours. Later, the temporal resolution was increased to 1 hour (Sukchaiwan, 2023), and the simulation was extended until December 2023 to also include the storm surge Babet, and analysis of the data is disclosed in **Paper II**.

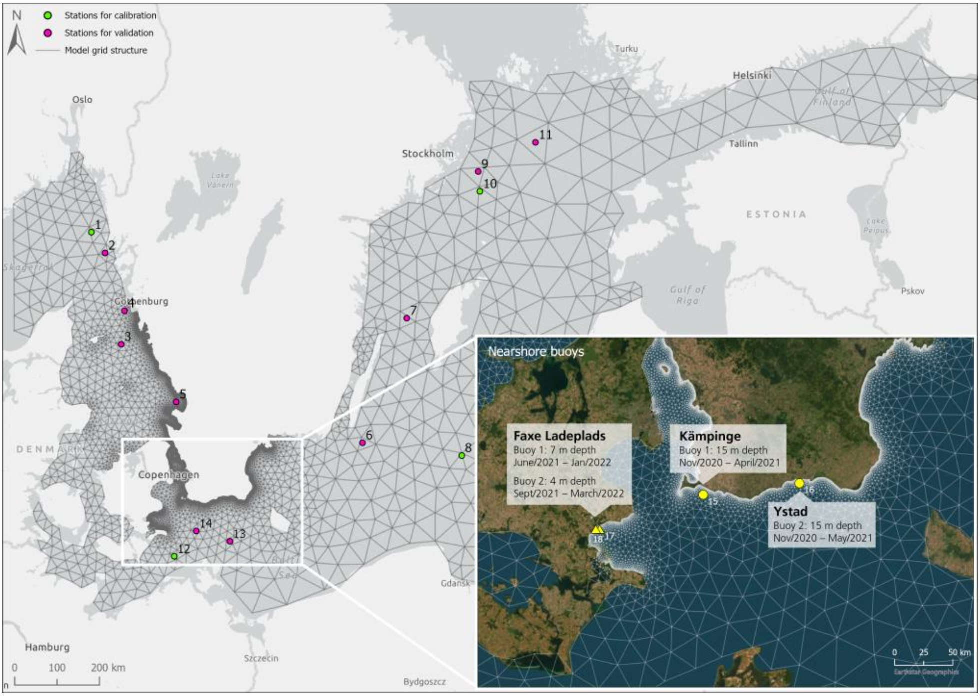


Figure 4.1: SWAN model grid and extent along with the distribution of wave buoys used for the calibration (green) and validation (pink). The zoomed in map shows the location of the surface acceleration buoys deployed along the south coast of Sweden and in Faxe Ladeplads, Denmark.

4.1.2 Model validation

Existing wave measurement records are available from stations that are operated by different authorities active in the Baltic Sea region. These data were used in the calibration procedure and validation of the deep-water wave conditions in the model. The distribution of the stations is shown on the map in Figure 4.1, and details are given in Table 4.1. For Swedish locations (stations 1-11) the responsible organisation is the Swedish Hydrological and Metrological Institute (SMHI). In the western Baltic Sea, stations (12-14) are operated by the Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschifffahrt und Hydrographie, BSH).

Table 4.1: Results of model validation assessing the performance based on metrics R^2 and RMSE, content from Adell et al., (2023), i.e. Paper I. The station numbers correspond to the numbers disclosed in Figure 4.1, (*) mark the stations also used in model calibration with data from the period July 2005 - June 2009 that has then been excluded from the validation period.

Nr.	Station name	Validation period	Parameter	R^2	RMSE
1	Väderöarna WR*	July 2009 – Dec 2021	H_s (m)	0.83	0.36
2	Brofjorden WR	Feb 2017 – Dec 2021	H_s (m)	0.83	0.33
3	Läsö-Ost	May 2001 – Feb 2009	H_s (m)	0.75	0.25
4	Turbanen	Oct 1978 – Oct 2003	H_s (m)	0.71	0.29
5	Laholmsbukten	Mar 1984 – Oct 1985	H_s (m)	0.88	0.17
6	Ölands S grund	Oct 1978 – Mar 2004	H_s (m)	0.83	0.29
7	Knolls grund	Nov 2011 – Dec 2021	H_s (m)	0.84	0.26
8	Södra Östersjön*	July 2009 – April 2011	H_s (m)	0.93	0.24
9	Almgrundet	Oct 1978 – Sept 2003	H_s (m)	0.58	0.49
10	Huvudskär Ost*	May 2001 – June 2005; July 2009 – Dec 2021	H_s (m)	0.87	0.23
11	Svenska Björn	Nov 1982 – Nov 1986	H_s (m)	0.85	0.30
12	Darsser Sill*	Feb 1991 – June 2005; July 2009 – May 2020	H_s (m)	0.83	0.20
13	Arkona	June 2013 – Dec 2021	H_s (m)	0.89	0.21
14	FINO2 platform	May 2011 – Sept 2020	H_s (m)	0.88	0.21
15	Kämpinge	Nov 2020 – April 2021	H_s (m)	0.86	0.18
			T_p (s)	0.48	0.93
			θ (deg.)	0.65	30.6
16	Ystad	Nov 2020 – May 2021	H_s (m)	0.90	0.16
			T_p (s)	0.57	0.93
			θ (deg.)	0.61	25.1
17	Faxe (7m)	June 2021 – Jan 2022	H_s (m)	0.80	0.11
18	Faxe (4m)	Sept 2021 – Mar 2022	H_s (m)	0.79	0.11

To validate the model performance for nearshore wave conditions, two separate field campaigns were conducted using two surface acceleration buoys (Obscape WaveDroid Block III). One campaign was initiated on the south coast of Sweden, where the buoys were deployed at similar depth (i.e., 15 m) but covering different sections of the coast. Deployment locations are Kämpinge and Ystad, and the campaign ran from November 2020 until May 2021 (details are provided in Figure 4.1 and Table 4.1). One campaign was initiated in Faxe Bay, where the buoys were deployed at 7 and 4 m depth, respectively, at the site in Faxe Ladeplads. These operated from June 2021 – January 2022 and September 2021 – March 2022. The buoys measure the sea surface elevation with a frequency of 5.82 Hz and in 23-minute bursts. Bulk wave climate parameters (H_s, T_p, T_m, direction (θ) are processed and are available every 30 minutes.

The model performance was evaluated by comparing observed and simulated levels and using statistical measures, i.e., Coefficient of Determination (R^2) and Root-Mean-square-Error (RMSE). In addition, a visual comparison between the simulated and observed time series was used. The time series comparison between simulated and observed significant wave height for two locations along the south coast of Sweden, is presented in Figure 4.2. The same type of comparison was performed for the buoys in Faxe Ladeplads. The results indicate that the calibrated model can reproduce the observed response in terms of the timing and magnitude of the peaks in the record.

The model was also verified for additional output parameters, and observed values were plotted together with the simulated levels in scatterplots for comparison. The results show good agreement for significant wave height, H_s, with R^2 of 0.86 and 0.9 for Kämpinge and Ystad, respectively. For the buoys deployed in Faxe Ladeplads, the corresponding comparison yielded R^2 of 0.80 and 0.79 for H_s. For wave period, T_p, and wave direction (θ), the result is acceptable, but slightly lower R^2 values are obtained as the data present more scatter (Figure 4.3).

The model with the assigned parameter settings is able to reproduce the wave climate conditions and yield good performance for both offshore and nearshore conditions. The regional coverage of the model produces reliable results for hindcast wave conditions that can be applied in further analysis. By adopting numerical modelling, the coverage is extrapolated from in-situ measurements from individual wave buoys in some points to a model with regional coverage and with detailed temporal (3 h) and spatial (200 m) in the nearshore coastal areas.

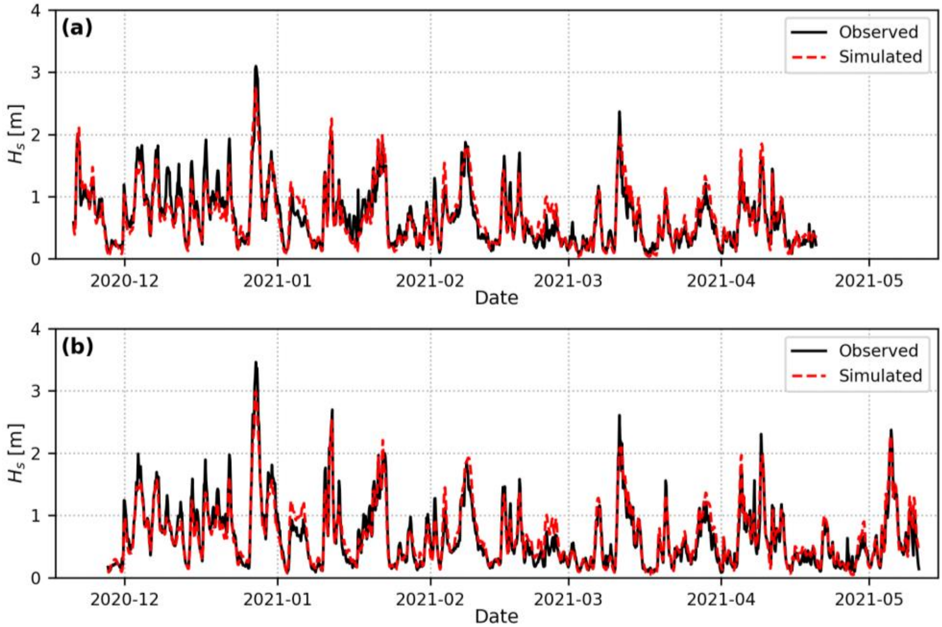


Figure 4.2: Time series comparison between simulated and observed significant wave height for stations Kämpinge (a) and Ystad (b).

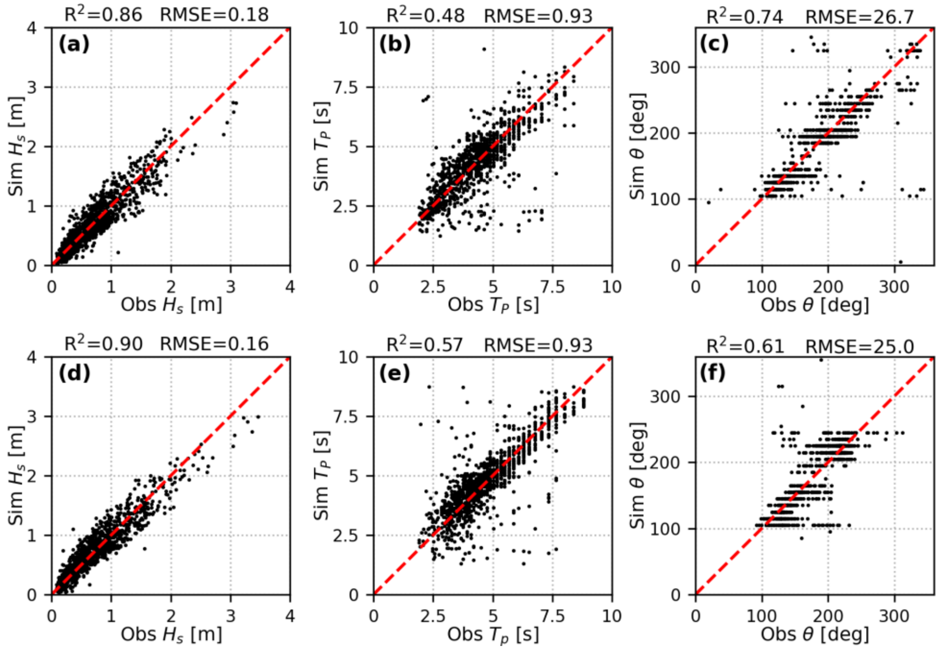


Figure 4.3: Validation result showing the model performance for parameters H_s, T_p and direction (θ) for the two stations Kämpinge (a-c) and Ystad (d-e).

4.2 Wave climate variability

The wave climate display large spatial variability of local wave conditions within in the study area (Figure 4.4). Wave time series data was extracted at approximately 10 m depth, from the wave model covering the period 1959-2023. The western parts (locations a and b) are more sheltered and shallower while the eastern parts (locations c and d) are more exposed to larger waves from longer fetch lengths.

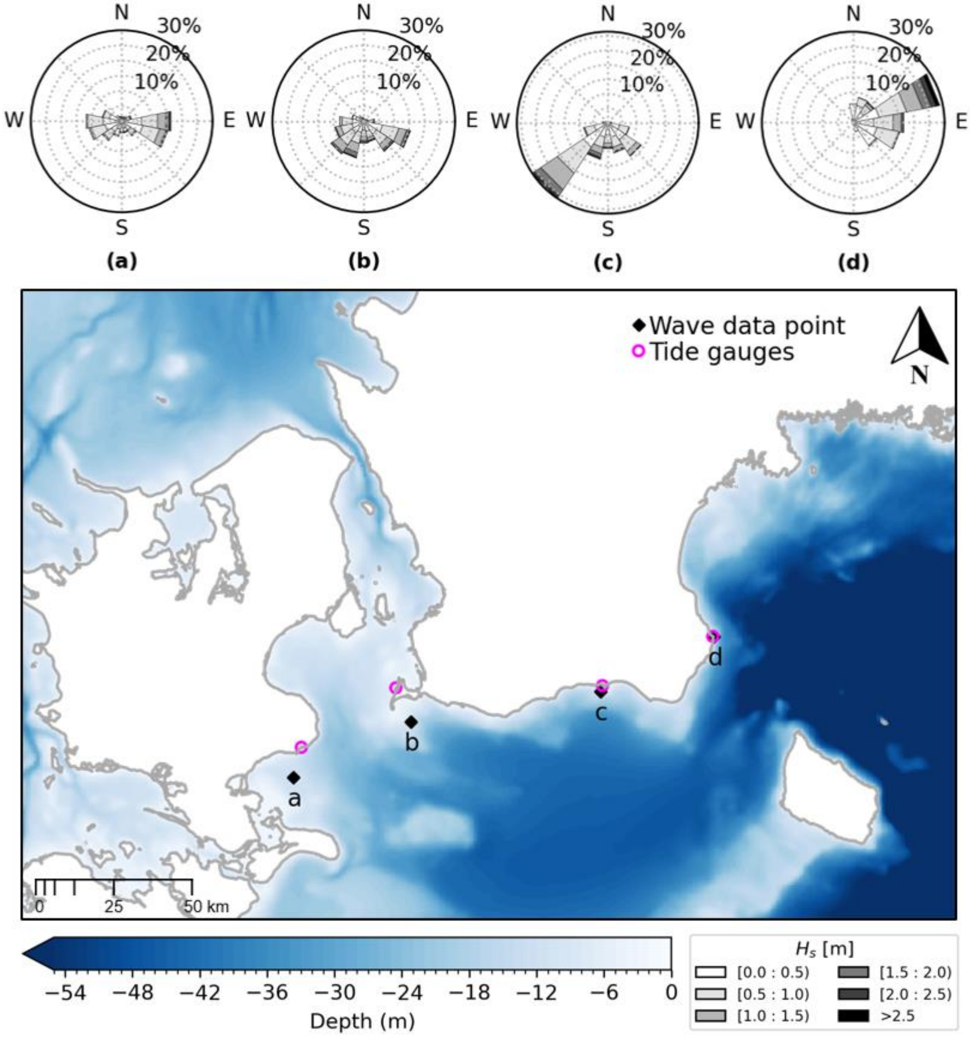


Figure 4.4: Wave conditions in the study area illustrated in wave roses generated based on data extracted from the hindcast wave model, at 10 m depth in four locations (a-d). Data from tide gauges (magenta-coloured circles) are available from Danish Meteorological Institute (DMI) and Swedish Hydrological and Meteorological Institute (SMHI), respectively.

Based on the hindcast wave time series produced in **Paper I**, an analysis was conducted to investigate the intra- and inter-annual variability in the wave climate. Storm wave conditions are more frequent in the winter months, so for the analysis, the year is divided from July to June. This division is used to assess inter-annual variability, where wave conditions are expressed as cumulated annual wave energy. Figure 4.5a shows the annual cumulated wave energy with respect to direction for the Arkona Basin.

The analysis found that the magnitude and direction of annual cumulated wave energy correlate with the NAO DJFM index. A positive NAO phase coincides with dominant westerly winds -the prevailing wind direction in the region- while the negative phase corresponds to increased easterly winds. This correlation confirms that NAO variability is reflected in annual wave climate conditions. Additionally, variations in annual cumulated wave energy show that in some years (e.g., 1960, 1969, 1979, 1996, and 2003), energy from the eastern sector surpasses that from the west (Figure 4.5b).

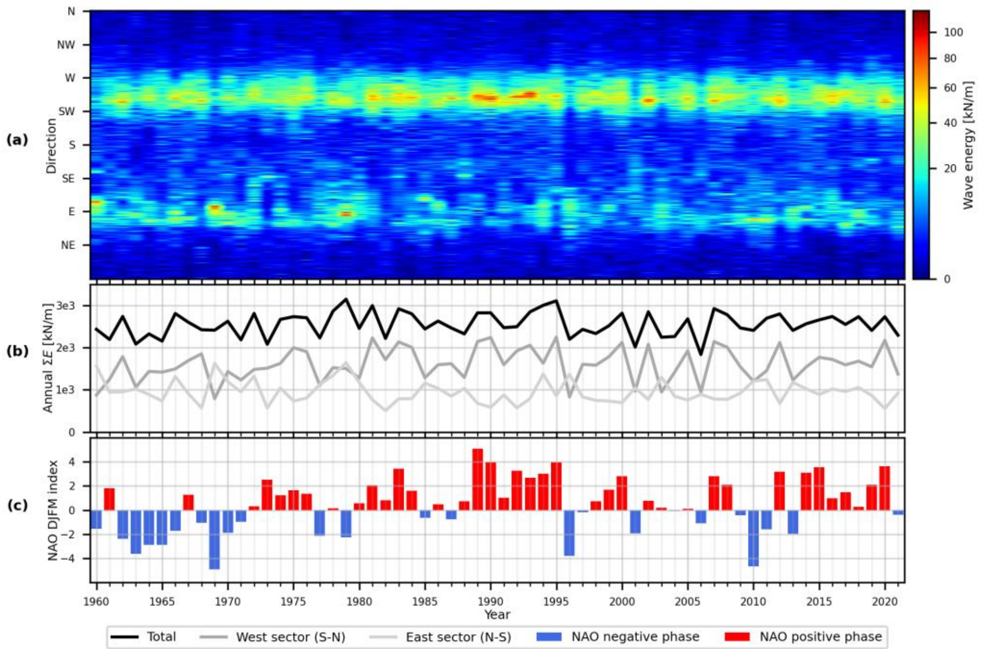


Figure 4.5: Directional wave energy distribution (a), and time series of cumulative annual wave energy (b) for the period 1959-2021, for the Arkona Basin in the southern Baltic Sea. (c) Time series of the NAO DJFM station-based index (NCAR, 2023).

The plot in Figure 4.5 is generated with data from the Arkona Basin and represents the general pattern. Regarding the contribution to annual wave energy, waves equal to or greater than the long-term 50th percentile H_s on average contribute 90% of the total annual wave energy, and waves equal to or greater than the 90th percentile H_s on average contribute 42% of the total annual wave energy. Of course, the exact values vary between individual years, but the numbers illustrate the dynamics of the system. The contribution of wave energy is dependent on a few energetic events per year. Similar descriptions have been made to characterize the wave climate conditions in other parts of the Baltic Sea (Eelsalu et al., 2022).

4.3 Extreme events

For the study area, waves and water levels are typically uncorrelated, as extremes in each component are driven by different meteorological conditions. Consequently, large waves and elevated water levels rarely occur simultaneously (Hanson & Larson, 2008; Kudryavtseva et al., 2020). However, when they do coincide, they create the highest potential for morphological change and coastal flooding (Bendixen et al., 2013; Hanson & Larson, 2008; Orvikut et al., 2003).

The scatter plots in Figure 4.6 illustrate the joint occurrences of wave and water level dynamics at the locations indicated in Figure 4.4: (a) Faxe Bay, (b) Skanör, (c) Ystad, and (d) Simrishamn. Observed water levels are recorded from tide gauges operated by DMI and SMHI, while simulated wave conditions come from the hindcast model. Spatial variability in wave heights, as seen in the wave roses (Figure 4.4), is also evident in the scatter plots. Locations c and d, which are more exposed, show a higher potential for larger wave heights compared to a and b. However, additional variability emerges when sea level is considered. Locations a and d show more tendency to experience large waves alongside elevated water levels due to their coastline orientation, which allows onshore waves from the east to contribute to higher water levels.

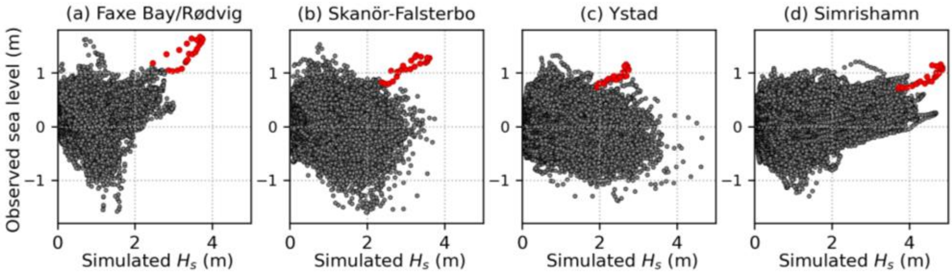


Figure 4.6: Scatter plots showing the relationship between waves and water level occurrences at the four locations a-d indicated in Figure 4.4. (a) Faxe Bay/Rødvig, 2012-2023, (b) Skanör/Falsterbo, 1992-2023, (c) Ystad, 1959-1987; 2014-2023, and (d) Simrishamn, 1982-2023. Observed sea levels are obtained from the nearest tide gauge to the wave data extraction point. Note that the displayed time period varies between the locations, and this is depended on the length of observed record from the tide gauges obtained from DMI and SMHI. Red points correspond to levels during peak of storm Babet on 20-21 October 2023.

The red points in Figure 4.6 represent the levels during storm Babet in October 2023, the event that was the focus of **Paper II**. Babet was a rare event where elevated sea levels and large waves, driven by strong easterly winds, coincided. The event followed a period of consistent westerly winds that raised the background sea level in the Baltic Sea. On 18 October, the wind shifted east, intensifying and pushing water to the southwest, while large waves were generated.

Through Generalized Extreme Value analysis (GEV), the 100-year return levels for H_s were estimated based on the generated hindcast data for the locations a-d (Table 4.2). These are presented along with the estimated 100-year return levels for water level based on assessment from SMHI and DMI. The results show an increase in H_s towards the east compared to the west, while the water level shows the opposite. The westernmost locations (a and b) are more sheltered, but the funnelling effect is more pronounced, impacting extreme sea levels.

Table 4.2: Extreme values for water level and significant wave height for some location in the study area. Information about water level return periods is retrieved from DMI (Rødvig) and SMHI (Skanör, Ystad and Simrishamn), while the levels of for wave height are based on the hindcast data from 1959-2023.

ID	Station	Water level (m) 100 yr return (GPD)	Significant wave height (m) 100 yr return (GEV)
a	Rødvig/Faxe	1.64	3.66
b	Skanör	1.48	3.93
c	Ystad	1.41	4.46
d	Simrishamn	1.15	4.90

An additional SWAN model simulation was conducted specifically for the storm surge Babet. A shorter time period was simulated considering both time-varying wind conditions and sea surface height (SSH) for the event as input. This simulated time series was used as input for further simulations of nearshore hydro- and morphodynamics in XBeach, and the details are presented in **Paper V**. Comparison between the initial wave model setup and the version considering water level input is presented in Figure 4.7 by showing data at two locations, at 38.5 and 6.45 m rel. MSL, respectively. It illustrates that the nearshore wave conditions possibly are underestimated if water level input is not considered for the simulation of extreme surge conditions. However, due to the lack of in-situ observations during the storm surge Babet, it is not possible to validate the updated simulated time series. For the presented long-term hindcast data, information about SSH is not applied as input to the model simulations. Therefore, it is recommended to be aware of this limitation in the procedure, and care should be taken when extracting data for nearshore locations, depending on the intended application of the data.

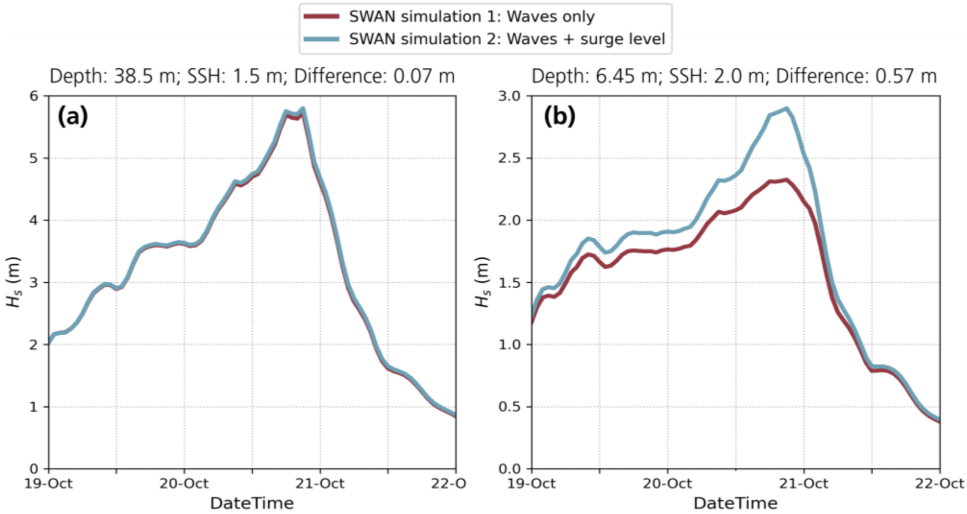


Figure 4.7: Difference in simulated significant wave height during storm Babet when including variable sea surface height as input. (a) Deep location (38.5 m) in the Arkona Basin and (b) nearshore location (6.45 m) in Faxe Bay.

It can be possible that the slight discrepancy between observed and simulated H_s for the nearshore stations presented as part of the validation (Figure 4.3 a and d) could be related to the exclusion of the water level data in the model forcing. However, water level varies over smaller spatial scales and requires more detailed resolution compared to wind input hence, there is a trade-off between computational time and desire for a long hindcast simulated time series. However, as discussed in **Paper I** the observed discrepancy can also be related to the quality of the ERA5 wind input. It is always important to validate the hindcast dataset against real observations, but for extreme events, this can prove difficult if observations are lacking (Bosom & Jiménez, 2011).

5 Morphological response

Variability in the hydrodynamic conditions drives morphological change. This chapter examines the morphological response within the study area across various temporal and spatial scales. The focus is primarily on the local assessment of nourishment development at the site in Faxe Ladeplads, based on observations. In addition, display of the regional response and consequences to the road along the south coast of Sweden caused by storm Babet.

5.1 Inter-annual variability of nourishment development

Field measurements at Faxe Ladeplads were conducted to monitor the nourishment's morphological evolution. A total of 21 evenly spaced transects (every 50 m) were assessed (Figure 5.1). The survey area covered the nourished section between the harbour mole and terminal groin (P1-P13), and extending 400 m downdrift (P14-P21). Topographic and bathymetric data were collected using RTK-GNSS covering the beach and shallow nearshore, while deeper profiles were measured with a single-beam echo sounder mounted on a zodiac boat. Details of the field campaign are provided in **Paper IV**.

Morphological development was analysed across different timescales, including initial adjustment, long-term changes over three years, and response to storm surge Babet. Figure 5.2 presents volumetric changes for each transect (P1–P21), covering both the nourished and downdrift sections. The objective was to study sediment redistribution after nourishment and assess the protection's performance over time, particularly during extreme storm events.

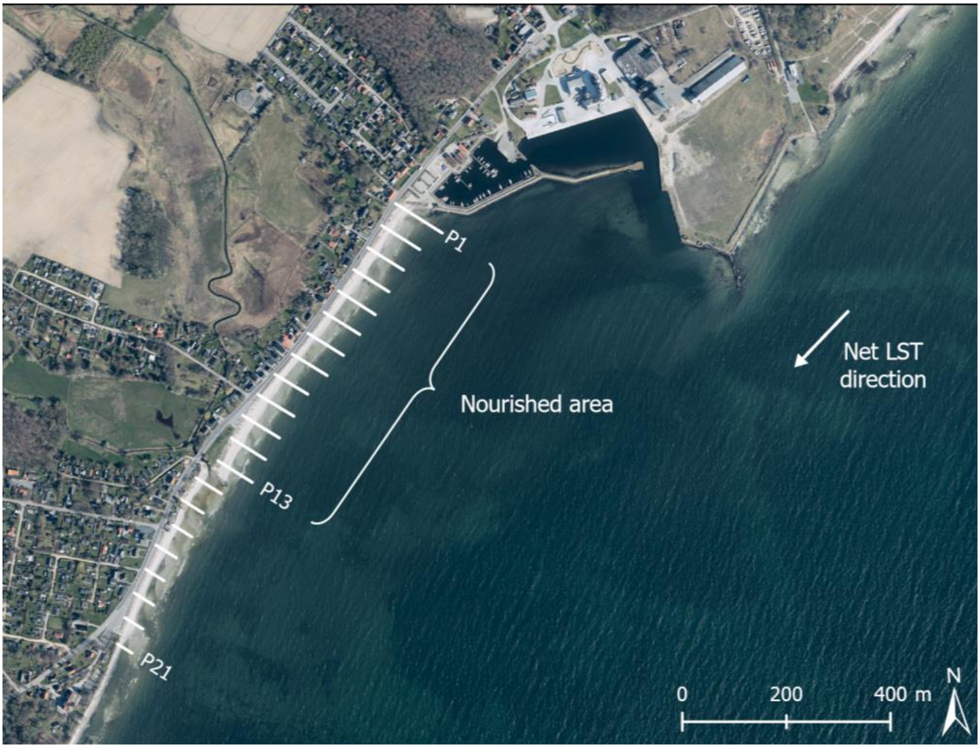


Figure 5.1: Map showing the study site and the location of the survey transects P1-P21. The nourishment is placed between the harbour mole and the terminal groin covering transects P1-P13.

The assessment of morphological change over a three year period identified the centre section as the most vulnerable both in terms of wave impact and for rapid displacement of sediment along the coastal stretch and transport offshore. The protective beach width disappeared following both initial profile adjustments and erosion was aggravated by individual storm events. Dynamic sections do display some potential for self-recovery during low-energy conditions. However, since there is no natural input of sediment to the section, neither through erosion of dunes or hinterland since the hard protection and the infrastructure is limiting sediment input from the hinterland nor from longshore sediment input from the north as the harbour blocking input in the dominant direction of the longshore drift.

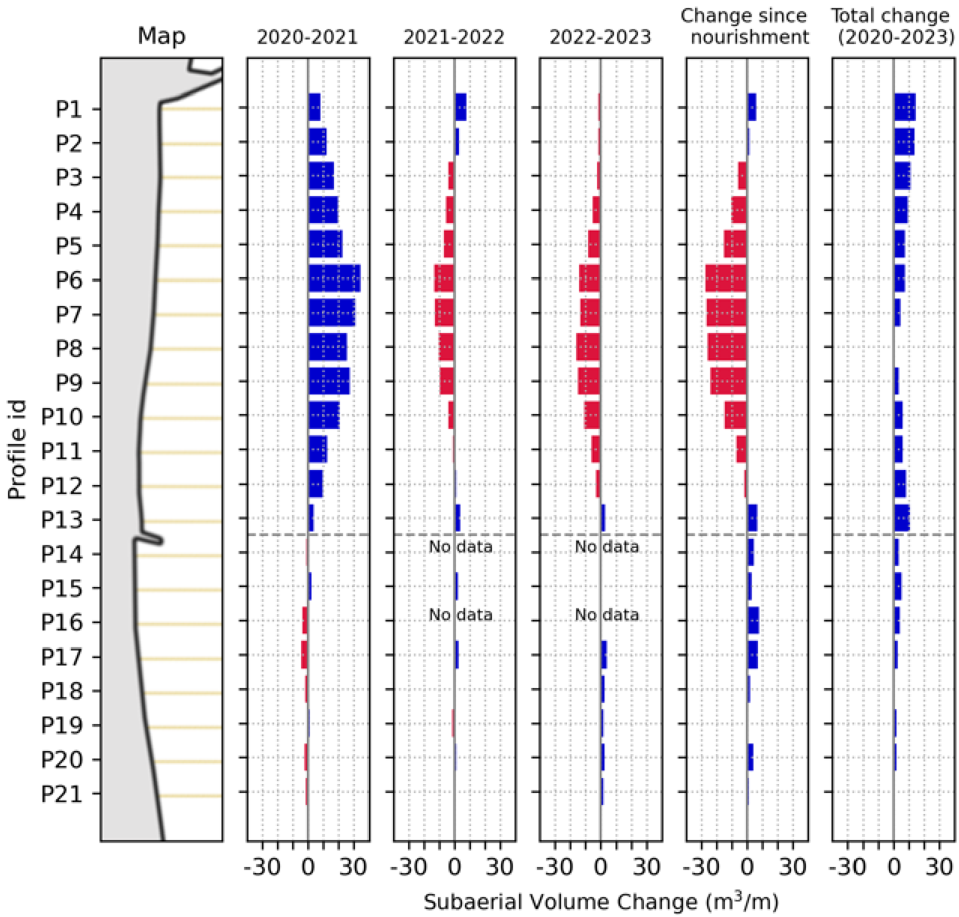


Figure 5.2: Subaerial volume changes of beach nourishment over time since implementation in July 2021 and until June 2023. Change given in volume per cross-shore distance (m^3/m) and red bars indicate erosion and blue indicate deposition.

5.2 Storm response

The impact due to the October 2023 storm surge Babet was characterized by widespread erosion and flooding in southern Sweden, and for the Danish and German Baltic Sea coasts. The storm propagated from the east, and atmospheric and oceanographic processes converged causing extreme surge in the southern Baltic Sea basin. Thereby, the event marked a rare occurrence where high waves and extreme surge levels coincided (Figure 4.6).

Paper IV showcase the storm response at the nourished site in Faxe Ladeplads, which was generally characterized by erosion of the subaerial beach, scouring at the tow of the revetment and material deposited in a storm bar, formed at the lower beach during high water level. The post-storm configuration displayed alongshore variability in the extent and dimensions of the deposition feature, Figure 5.3.

Figure 5.3: (a) Drone image to show an overview of the protection at the site after impacted by storm Babet (Photo: Gregor Luetzenburg, 23 October 2023), water level was +30 cm MSL. (b) Post-storm DEM, black dashed line corresponds to +30 cm MSL and thereby highlight the emerged areas shown in (a).

The varying response is illustrated as pre- and post-storm conditions from survey transects presented in Figure 5.4. The least reduction in beach elevation was observed at transects closest to the harbour mole, e.g., beach width for transect P1 increased by 13.5 m due to sediment accretion (Figure 5.4a). The centre section, illustrated in transects P7 and P9 (Figure 5.4b and c), displays scouring at the toe of the revetment, forming a trench approximately 10 m wide and scour depth of about -0.6 m rel. MSL. The elevation of the bar gradually decreases towards the south and becomes completely washed out at transect P11 (Figure 5.4d). Potentially due to a return current or strong undertow currents over a large area during high water level.

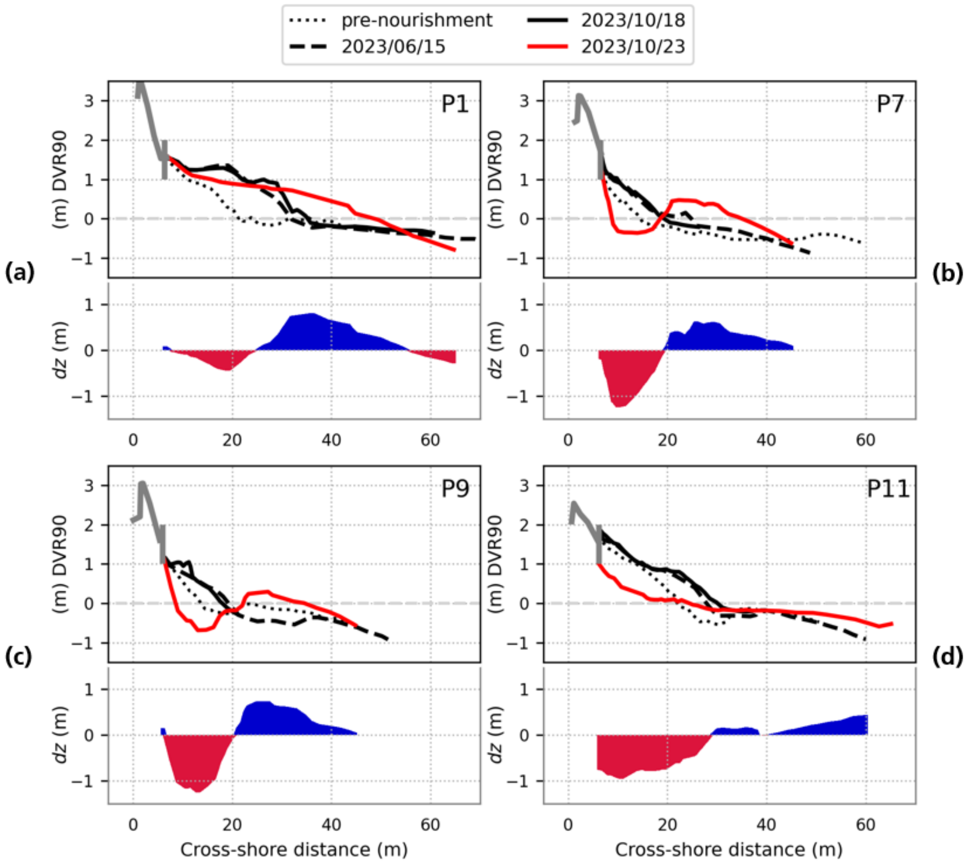


Figure 5.4: Pre- and post-storm conditions to illustrate the morphological response to the storm for transects P1 (a), P7 (b), P9 (c) and P11 (d).

5.3 Storm response to coastal roads in Sweden

The documented damages and assessment of response strategies in relation to storm Babet in Sweden are presented in **Paper II**. In Sweden, the coastlines that were impacted by the event were the south and east coasts of Scania. The combination of high water levels and large waves caused significant changes to the coastal landscape, for example, extensive dune and cliff erosion. Documented damages concern damages to private properties, buildings, beach houses, harbours, and roads. In many places along the coast in Scania, roads or bike paths are the most seaward infrastructure. During Babet, a lot of this infrastructure got damaged, there were cases of both state, municipal, and privately owned roads that got damaged to varying degrees and by different processes. The map in Figure 5.5 shows the locations where road damages have been documented (a total of 10 incidents), along with some images to illustrate the impact. Location A is a private road that got destroyed but has since been repaired and constructed in the same location. Locations B and D correspond to locations of state-owned roads that were impacted and undermined due to the large surge levels and wave runup. As shown in the image of location D, emergency repairs were already well underway just the day after the peak of the storm; the photo was taken at noon on the 21st of October 2023. The road and protection at location B have also been repaired. Location C is a state-owned road that got overwashed by sand deposits, which did not damage the road but rather compromised its accessibility.

In many places, the protective volume between the shoreline and the road got eroded in the event, but not to the degree that the road suffered impact. The morphological changes in response to the storm have been assessed in **Paper II** and comprise difference-DEM analysis between a post-storm lidar scan (Dec-2023) and the most recent national DEM (2019). The confidence in the quantified volume changes is low since there are only two datasets, and thereby, the temporal frequency is low. Consequently, it is difficult to quantify volume changes that are only attributed to the specific event. However, Babet was very extreme and the recorded data can be used in combination with long-term change trends derived from shoreline position change to help interpret the general patterns of erosion and deposition.

Figure 5.5: Documented damages to roads caused by storm Babet in October 2023. (A) Beddingestrand - Private owned road damaged by storm erosion, photo: Sweco. (B) Kåseberga - State owned road undermined due to storm erosion following wave runup on the structure, photo: Bradley Goodfellow. (C) Kivik – road impacted by flooding and overwash, photo: Gunnar Österlund. (D) State owned road between Kivik and Vitemölla damaged through storm erosion, photo: Carola Wingren.

6 Regional exposure analysis

To analyse the probability of risks for coastal flooding and erosion that can impact coastal roads at regional scale, a framework was developed. The content presented in Section 5.3 illustrates potential damages and impacts to coastal roads documented in the study area caused by storm Babet. They highlight a few of the acting processes as declared in the background section and motivate the structure of the modelling framework to include relevant processes, considering both hydrodynamics and morphology. The use of the framework is demonstrated by applying it to the main coastal road along the south coast of Sweden.

6.1 Description of the framework

Paper III presents the framework RoadRAT which is designed to calculate the probability of a road segment to be impacted by inundation, wave runup, and erosion, and is intended as a screening tool to identify vulnerable road segments. It is set up to use readily available data, like time series of waves and water level and geographical data sourced from aerial or satellite images. The methodology can treat large extents of roads (>100 km) where frequency of computations nodes can be placed with a desired density. In each node along the road segment, the probability of impact of inundation and wave runup is computed by fitting a Generalized Extreme Value distribution (GEV) to relevant data. To estimate annual storm erosion, simulated data is fitted to the distribution proposed by Hallermeier & Rhodes (1988). The model structure is presented in Figure 6.1, and shows the various modules that compose the model, which include hydrodynamics (inundation and wave runup) and morphology (long-term coastal evolution and storm erosion). The tool can assess the impact in today's conditions and future conditions by accounting for the SLR.

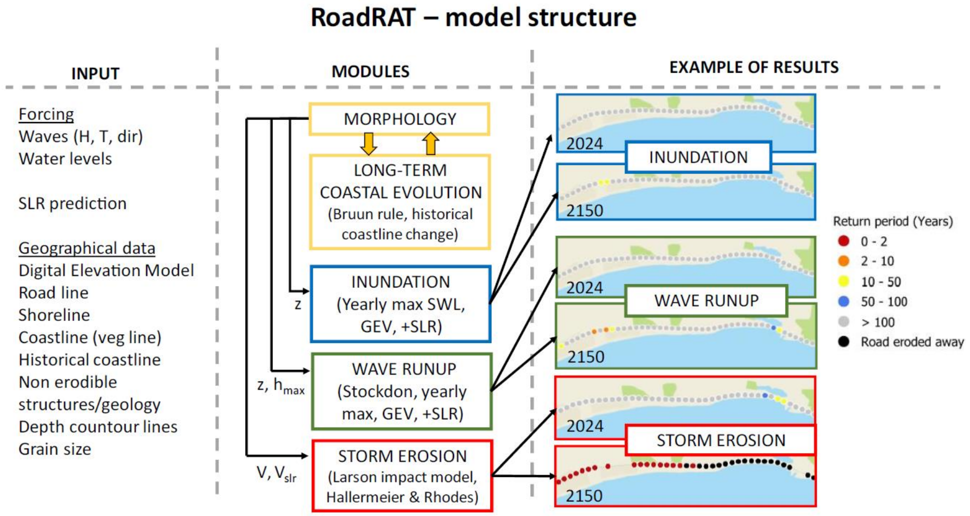


Figure 6.1: RoadRAT model structure showing the content of the different modules including a summary of the required input data. Right panel shows and example of the output.

For the investigation of inundation, the GEV distribution is fitted to the yearly maxima from observed water level time series. The probability of inundation is defined as the probability of the still water line (SWL) to be greater than the road elevation. For the specific case study along the south coast of Sweden, the water level data is available from SMHI tide gauges located within the study area.

Calculations of runup are done according to the Stockdon equations (Stockdon et al., 2006). Together with the SWL and the computed runup level, these are added to get the total water level (TWL). Then the GEV distribution is fitted to the yearly maxima of TWL and the probability of the road being impacted by wave runup if the maximum elevation of the road or the highest point between the road and the coastline is exceeded.

Long-term erosion is estimated to account for future coastal change in the assessment of future risks in the framework. The long-term coastal evolution trends are derived from aerial images and thereby assumes that historical trends in coastal evolution will continue in the future. The historical coastal evolution then represents the background erosion, and to account for coastal change in response to SLR, the tool makes the assessment based on the Bruun Rule concept (Bruun, 1954, 1962). Storm erosion estimation is based on the Larson impact formula (Larson et al., 2004), and the eroded volume is related to the protective volume available between the shoreline and the road segment.

6.2 Application on the south coast of Sweden

RoadRAT was used to analyse the probability of impact on the main coastal road along the south coast of Sweden, which includes *Riksväg 9* from Trelleborg to Ystad and some minor municipal roads. The analysis is focused on investigating the impact on the roads by inundation, wave runup, and erosion.

6.2.1 Present-day conditions

The results indicate that the probability for all impacts, inundation, wave runup, and storm erosion are low when present-day conditions are considered. The problems are concentrated to some local "hotspots" identified by the model. The resulting output from the RoadRAT analysis is exemplified in Figure 6.2. Sections of the road where there is existing coastal protection are excluded from the model, and probability is not computed for these stretches. The framework is designed to identify previously unknown risk areas, based on the assumption that protected areas have already been recognized as in need of management. For the south coast of Sweden, the sections that may experience problems in present conditions amount to between 0-500 meters and for return periods typically >50 years for both inundation, wave runup, and storm erosion. The identified hotspots correspond to areas where there are known problems today, and the impacts observed for storm Babet and other events with extreme water levels (like the event in 2017) are a way to validate the model results.

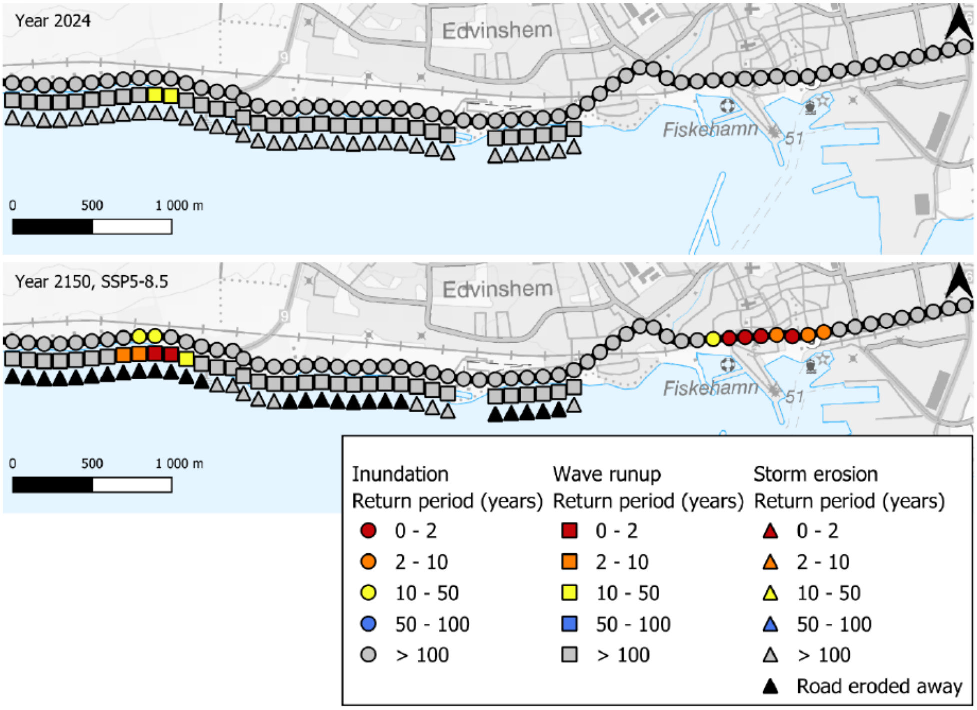


Figure 6.2: Example output from the screening analysis in RoadRAT for today's condition (top) and in 2150 with emission scenario SSP5-8.5 considered for projected SLR (bottom).

6.2.2 Future conditions

Analysis of the development of the risks in future conditions considers various projections for SLR. It should be noted that the framework does not consider increased storminess as a potential impact of climate change. The risks are assessed for future conditions, considering SLR projections according to the SSP5-8.5 emission scenario, and in years 2050, 2100, and 2150; the results are presented in Figure 6.3. The results indicate that the risks of the road stretch being subject to inundation, wave runup, and storm erosion are increased, and the total length of the impacted stretch of the road increase to several kilometres, see Figure 6.3. The most striking result is the risk of storm erosion. By the end of the century, shoreline retreat at many locations along the main coastal road of Sweden's south coast could result in the future shoreline extending landward from the road's present-day position. These results indicate that adaptation measures will have to be implemented to protect the road to ensure continued use and service of the function in the future.

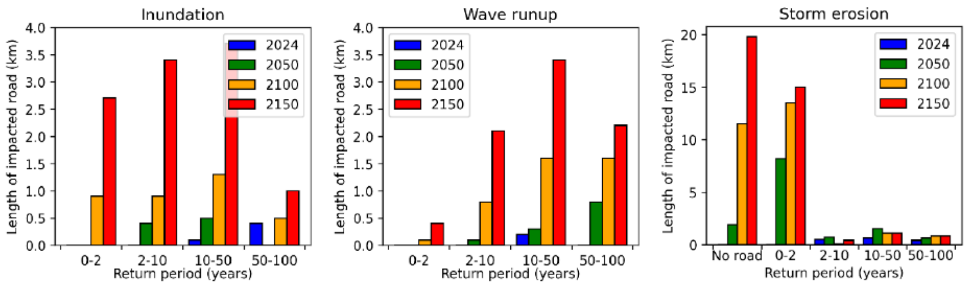


Figure 6.3: Result showing the development of total road stretches (in km) impacted by coastal processes, inundation, wave runup and storm erosion, over time. Future assessment is considering SLR and long-term coastal evolution.

When risk areas are identified by the RoadRAT framework, the result can be used to motivate local assessment and possibly design and implement coastal protection solutions. More complex models could be applied to analyse the site-specific conditions where more detailed assessments of local impacts can be conducted, such as detailed process-based models like XBeach. The probability of risk is just one part of the risk assessment, and additional analysis should focus on assessing the potential cascading effects or consequences of the road being temporally or frequently out of use. This should also guide or motivate the design and objectives for intended adaptation solutions.

7 Mitigation through coastal protection

The option to adapt coastal road infrastructure to mitigate the risks of flooding and erosion through coastal protection solutions is investigated in a case study in Denmark. The protection at the site constitutes a combination of a rock revetment and beach nourishment implemented to reduce wave overtopping on the adjacent coastal road.

7.1 Numerical modelling of hybrid coastal protection

If a road stretch is identified as a potential hotspot in the RoadRAT analysis presented in Section 6, a detailed assessment of the local conditions at the site may be needed. Such assessment relies on the use of more complex models and access to monitoring data. This approach is demonstrated through the presented case study at the site in Faxe Ladeplads, where nearshore hydrodynamics and local morphological response were simulated in XBeach 2DH Surfbeat (**Paper V**). The hydrodynamic conditions at the site are similar to the conditions along the south coast of Sweden. Therefore, the protection solution at Faxe Ladeplads can be a possible and suitable measure to be implemented at other sites to mitigate impacts of coastal hazards.

To resolve the nearshore hydrodynamics and morphological response at the site, a model was set up in XBeach Surfbeat 2DH, and the simulations focused on replicating the response observed due to storm Babet. XBeach (Roelvink et al., 2009) is an open-source processed-based model that solves equations for wave propagation, flow, sediment transport, and bed level changes. The model was initially developed for the purpose of simulating nearshore morphological changes during storms, and since then the model has been widely used by researchers and practitioners in the coastal community and for a range of applications globally.

The hard structures at the site are represented as non-erodible layers in the model. The post-storm observations described in Section 5.2 were used to calibrate the model with regard to morphological output. Erosion- and deposition patterns are illustrated as difference in bed level between the first and last timesteps in the simulations. The results are presented as 2D difference maps in Figure 7.1, where blue corresponds to deposition and red is erosion. The 2D variable erosion- and deposition patterns are reasonably well represented using calibrated model settings (Figure 7.1). However, the magnitude of morphological change is underestimated in the model, and the post-storm layout presents a more longshore uniform appearance compared to the observed (Figure 7.1 a and b). Particularly, the scour depth at the toe of the revetment is not replicated in the model simulation, which results in the erosion being underestimated by about 0.5 m in the vertical.

An additional simulation was conducted where the non-erodible layer was disabled, thereby eliminating the hard structures at the site. This gives a more longshore uniform and more pronounced deposition pattern, suggesting that the hard revetment back barrier and the confinement between the harbour mole and the terminal groin influence the resulting response. In addition, when disabling the hard features, the road and part of the hinterland completely erode, indicated by a landward retreat of the system of approximately 40 m. This shows that some coastal protection is needed at the site to mitigate potential negative erosion impacts on the road structure.

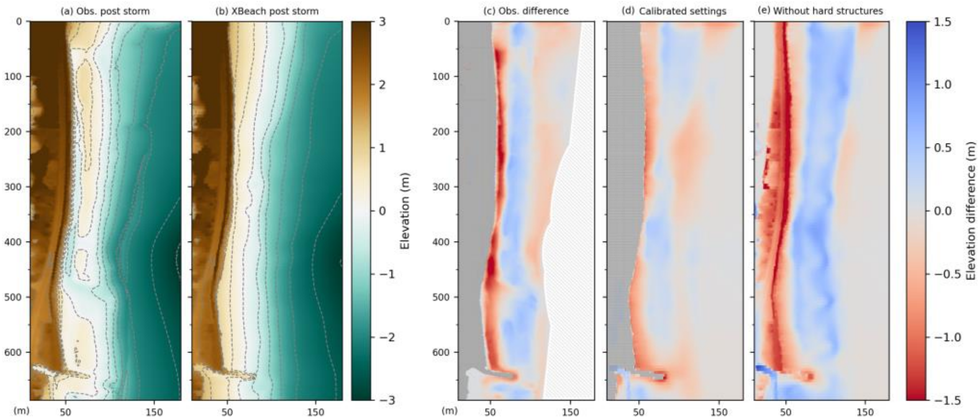


Figure 7.1: Observed response (a, c) and XBeach simulated (b, d, e) results of morphological change at the nourished site in response to storm surge Babet.

7.2 Small-scale beach nourishment design

The calibrated XBeach model setup was used at the site in Faxe Ladeplads to investigate alternative beach nourishment designs and evaluate the effectiveness in reducing the impact of coastal processes on the road. The input bed levels were modified to create six different design cases, representing initial beach widths of 5, 10, 20, 30, 40, and 50 m. Beach width is defined as the cross-shore distance from the toe of the revetment until the 0-m depth contour. Then, the same time series input corresponding to conditions during storm Babet was used in the simulation to assess and compare the effect of nourishment beach width on reducing wave impact. Wave impact was investigated in terms of wave height at the toe of the structure and overtopping discharges. Figure 7.2 a and b show the maximum H_{m0} at the revetment's toe and the maximum overtopping discharge as a function of initial beach width. Figure 7.2c shows the maximum H_{m0} at the toe of the revetment for the 13 transects (P1-P13) spaced every 50 m along the protection. The results indicate that a wider initial beach width of the nourishment reduces wave heights at the toe of the revetment and, hence, effectively decreases overtopping. Although, at the cost of larger downstream losses during the event with larger added nourishment volumes.

The results demonstrate that the effect of the added nourishment in front of the rock revetment is twofold. A wider protective beach can reduce wave impact on the revetment and coastal road by increasing wave dissipation over the nourished profile while also helping to maintain a higher beach elevation at the toe of the structure. However, the effectiveness does not only rely on the dimensions of the soft part of the protection but also the crest height of the revetment. The southernmost transects have a lower crest height compared to the rest of the protection and, thus, a smaller freeboard (difference between SWL and crest height), which influences overtopping.

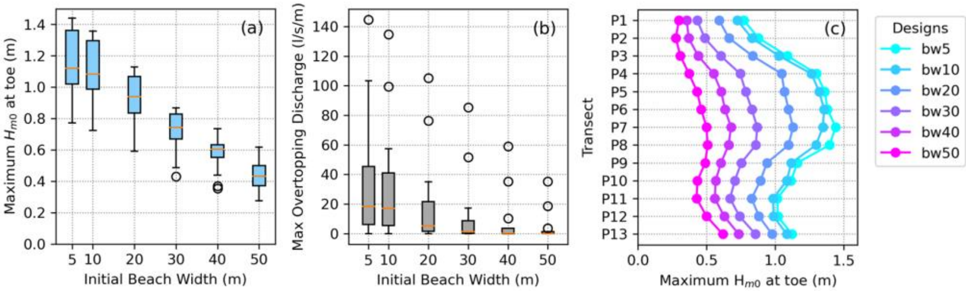


Figure 7.2: Panels (a) and (b) show the distribution of maximum H_{m0} and overtopping discharge, respectively, as a function of initial beach width. The orange line represents the median, the boxes indicate the interquartile range, error bars show the spread in the data and circles represent outliers. Panel (c) display the spatial variation of H_{m0} indicated for each of the design cases bw5-bw50.

The results from the XBeach modelling in combination with the observed response of the nourishment over time, highlight specific vulnerable sections along the protection under the impact of varying conditions. For example, the centre section is most susceptible to rapid redistribution of the sediment from the subaerial beach to the nearshore and adjacent areas. At the same time, the southern end is more vulnerable to overtopping and inundation due to the lower crest height of the revetment. The results can help the management of the protection at the site but also highlight some complexities and valuable information to keep in mind when designing hybrid coastal protection that can be exposed to a range of forcing conditions.

The solution at Faxe Ladeplads illustrates how a combination of approaches within the same design can be applied to meet different objectives or achieve different functions. The soft solution can provide more recreational and aesthetic value and offer a smooth transition between land and water, while the resistant revetment is there as the final line of defence to protect against flooding and erosion during extreme events.

8 Discussion and outlook

The following chapter presents a general discussion and outlook in relation to the work presented in the thesis. Aspects related to the presented content – forcing, response, exposure and mitigation – are discussed and the impact of climate change is explicitly addressed.

8.1 Forcing

This research presents a comprehensive regional dataset (sub-basin scale) with decadal wave hindcast conditions validated for both offshore and nearshore performance. Previous hindcast modelling efforts at basin scale in the Baltic Sea generally show good agreement with observations, and state-of-the-art models typically have a spatial resolution of 1-3 nautical miles (e.g., Björkqvist et al., 2018; Soomere, 2023). However, nearshore dynamics remain a challenge. With the current research, the coverage and quality of detailed nearshore wave conditions for the south coast of Sweden and parts of Zealand's coast have been presented and validated against new wave buoy observations and show good agreement. Future research should focus on assessing the impact of extreme sea levels on model performance in the nearshore, where the model has not explicitly been validated for storm surge conditions. This is expected to have the most influence on shallow nearshore regions and coastal areas with N-S orientation and are thereby more likely to be exposed to events where elevated water levels coincide with large onshore waves.

The Baltic Sea seasonal wave climate is driven by the wind climate, with larger significant wave heights in the winter period. Wind climate variability driven by large scale atmospheric circulation also influence inter-annual variability in the wave climate. The results presented in this thesis (**Paper I**) for the southern Baltic Sea specifically shows this through the established correlation between annual cumulated wave energy and the NAO DJFM station-based index. The relationship implies sensitivity in the inter-annual wave climate conditions to changes in the wind field.

Baltic Sea regional climate is strongly dependent on large-scale atmospheric circulation. Hence, in the assessment of future climate conditions, it is important to consider changes in circulation that are potentially driven by global warming (Kjellström et al., 2018). Yet, it is uncertain how large-scale atmospheric circulation will respond to climate change (Deser et al., 2017; Rutgersson et al., 2022). Although, it is likely that the NAO index will continue to display similar variability in the future as it has in the past. According to Knudsen et al. (2011), it is likely that the NAO will become slightly more positive in the future due to global warming (Knudsen et al., 2011), which increases the possibility of extreme waves in the Baltic Sea (Mentaschi et al., 2017). In addition, other environmental conditions associated with the positive phase of the NAO in winter include increased basin filling due to periods of stronger and more frequent westerly winds, more precipitation, milder temperatures, and hence less sea ice extent (Wolski & Wiśniewski, 2023). These factors have the potential to contribute to an increase in extreme sea levels in the basin (Wolski & Wiśniewski, 2023) and potentially increase in mean and extreme significant wave heights, particularly in the north (Bonaduce et al., 2019).

Projections for future wave conditions in the Baltic Sea are inconclusive as there is a lot of uncertainty in projected wind speeds and direction (Meier et al., 2022). Groll et al. (2017) estimated an increase of as much as 15% in median significant wave height in the Baltic Sea associated with increased wind speeds and dominance of westerly winds. Bonaduce et al. (2019), on the other hand, projected a decrease in future mean significant wave height in the southern Baltic Sea and an increase in the northern part of the basin related to diminishing sea ice extent. Future changes in the wave field in the Baltic Sea will also arise from slight changes in the wind direction. This is because fetch lengths vary with direction in relation to the geometry of the basin (Meier et al., 2022) and thereby can give large spatial variability in extreme significant wave heights across the basin.

Regarding the future development of storm surges in the southwestern Baltic Sea, Gräwe & Burchard (2012) concluded that an increase in mean sea level has a larger influence on future surge levels compared to an increase in wind speed. However, historic storm surges are known to have been caused by different factors converging and generating unprecedented extremes. In a series of simulations, Andrée et al. (2023) show the role of preconditioning for extreme storm surges in the western Baltic Sea. The authors investigated the effect of alternative preconditioning of the 1872 storm surge. They considered varying levels of infilling and wind speed extremes based on levels derived from conditions of the known similar events, namely the 1904 storm surge and the 2017 "silent storm". The results showed, for example, an increase of 36 cm in peak water level at Køge close to Copenhagen and thereby showcase how variability may exaggerate the extreme levels. These types of compound events are difficult to project for future conditions. It is therefore suggested that future work should focus on assessing the potential in contribution of compound events in relation to projected SLR for the Baltic Sea, as it can be an important aspect in future evolution of natural hazards.

8.2 Response

The highly intermittent wave climate in the Baltic Sea impacts the morphological evolution of the coastlines, which is characterised by extended periods of limited change (stable conditions) and a lot of potential for erosion during storms. This variability was, for example, observed at the site in Faxe Ladeplads (**Paper IV**), where it was found to impact the development of the nourishment. Generally, limited change and limited possibility for accretion features to develop in low energy periods followed by significant sediment redistribution in high energy events.

The potential implication for the coastal evolution and sediment transport patterns along the south coast of Sweden, in relation to the varying wind-wave patterns in the Arkona Basin, is briefly discussed in **Paper I** but not explicitly analysed. Future research should focus on investigating how the coast responds to the variability exhibited by the NAO index. Previous studies have been able to correlate long-term shoreline change in e.g., Poland, France, and the UK, to the NAO index (Masselink et al., 2023; Robinet et al., 2016; Rozyński & Szmytkiewicz, 2012; Thomas et al., 2010). In addition, the complex layout of the Baltic Sea and varying shoreline orientations make alongshore transport at certain sections sensitive to the incident wave angle and thereby be sensitive to even slight changes in wind direction (Viška & Soomere, 2013). Soomere et al. (2017) found that a 10° shift in wind direction could generate a complete shift in the longshore sediment transport patterns at sites in Latvia and Lithuania. Understanding such vulnerabilities conceptually and in relation to future plausible wind projections will be key for predicting future coastal change.

In addition, the complex geometry of the basin and varying shoreline orientations can give that storm waves approach the coast at relatively large angles then resulting in large alongshore transport during storms. Characteristics of Baltic Sea storm surges impact the coastal erosion along the coast. Future research should also focus on the joint impact of high waves and elevated water levels in the basin and the effect on sediment transport. Storm surges in the Baltic Sea are characterised by relatively long duration; in the absence of tides, there is no process that can ease the peak storm levels. This typically increases the time of contact erosion of, for example, dune toes or cliff faces (Różyński, 2023). These principles are relevant to analyse further with the aim to quantify potential impacts on sediment budgets and to design coastal protection works.

There is a large knowledge gap related to sediment transport dynamics, and a comprehensive sediment budget for the Baltic Sea shores does not exist (Harff et al., 2017). Due to the prevailing westerly wind conditions over the Baltic Sea region, counterclockwise alongshore transport dominates the southern Baltic Sea. Secondary transport modes, under easterly and northerly conditions, are less well understood (Weisse et al., 2021). There are also knowledge gaps in understanding sediment dynamics at national scales. A comprehensive sediment budget for the Swedish and Danish Baltic Sea coastlines is yet not available. Therefore, it has not been quantified how much sediment is derived from eroding cliffs during storms, as was observed during Babet (**Paper II**). Cliff retreat has been identified as a major sediment source for the nearby German Baltic Sea shores (Averes et al., 2021). Storms in the Baltic Sea cause severe coastal erosion, but the contribution to the sediment budget from eroding sandy dunes and soft glacial cliffs has not been quantified, although large potential. Future research should focus on assessing how important storm surges are for mobilising sediment and making it available in the system.

8.3 Exposure

In the presented research, the exposure assessment framework RoadRAT (**Paper III**) is designed as a bottom-up approach where the road is defined as the main asset to evaluate, and thereby, the geographical and functional extent of the road limits the scope. Other regional risk assessment approaches that RoadRAT shares similarities with (Bosom & Jiménez, 2011; Christie et al., 2018; Jiménez et al., 2018) focus on risk assessment in a broader sense and exposure is rather assessed per coastal section, which allows consideration of more assets or functions within the coastal zone. RoadRAT is different as it does not use prescribed probabilities or scenarios for specific processes to identify vulnerabilities. The framework assigns the road as a starting point and explores probabilities of the impact of multiple coastal processes. The idea with the tool is that concentrating the analysis to focus on the road extent can reduce the complexity and allow for the detailed discretisation of the road segment and apply a wider range of processes and SLR scenarios. The purpose of the tool is to provide support for transport managers in their planning process and potentially facilitate stepwise adaptation by considering different timescales.

The results of the case study along the south coast of Sweden showed the risk of the road being completely eroded in some sections by 2150, thereby making coastal erosion the main threat to the asset in the future. This assessment is crude due to the simplifications assumed in the Bruun rule that have been widely criticized (Cooper et al., 2020; Cooper & Pilkey, 2004; Le Cozannet et al., 2016). However, although the exact quantification may be uncertain, the results and spatial patterns can provide some indication of the system vulnerability. Prediction of future coastline changes in relation to SLR is a challenge for sandy coastal systems globally, and the Baltic Sea is no exception (Jiménez et al., 2024; Luijendijk et al., 2018). In the case the main road along the south coast of Sweden erodes completely by 2150, it inevitably implies larger impacts for society and the environment than just the negative impact for the coastal roads, such as risk for private properties, decreased flood safety, loss of nature and recreation values etcetera.

The framework considered SLR projections for assessment of future development of the probability of impact and does not consider impacts of increased storminess or changes in wave climate. As discussed, projections for changes in future wave climate and storm surges in the Baltic Sea are inconclusive, but due to the system's sensitivity, it will respond to any changes. The analysis in RoadRAT is based on hindcast wave data, historic tide gauge records, and historic trends in long-term coastal evolution, which then all assume that the trends and levels observed in the past will continue in the future. The system is likely to exhibit the same type of variability, but mean and extreme levels are difficult to accurately project and account for. Further research should focus on simulating artificial changes in wave conditions and extremes to get a more comprehensive view of possible boundary conditions in the future.

8.4 Mitigation

The future development of coastal hazards is dependent on the increase in the magnitude of acting forces, like SLR and storms. However, it is equally important to consider the development of future risks following infrastructure development in the coastal zone. Rutgersson et al. (2022) state that Baltic Sea cities are likely responsible for the future development of coastal flood risks due to the high concentration of people, infrastructure, and valuable assets. If this development continues in the future and is not managed properly, it will be a significant driver for the increase in coastal flood risks. The presented findings and other literature suggest that an increase in future coastal protection is needed to reduce the impacts of coastal processes on coastal roads and increase resilience (Hinkel et al., 2014; Koks et al., 2019; Pal et al., 2023; Pregnolato & Dawson, 2018).

Coastal protection measures can have unintended negative impacts, and human activities in the coastal zone have become a significant driver for coastal change (Weisse et al., 2021). Hard coastal protection structures, such as seawalls and revetments, restrict sediment input, exacerbating erosion by disrupting natural sediment transport pathways (Dean, 1986; Nawarat et al., 2024a). In addition to storms, coastal engineering structures are a significant driver for coastal change in the Baltic Sea (Weisse et al., 2021). There are cases of increased private initiatives and implementation of hard coastal protection following storm impact at least in Sweden (Hallin et al., 2024; Norrman et al., 1981). The effect on sediment budgets from armouring the coastline and anthropogenic influence on the sediment system is overlooked. To improve knowledge of the sediment budget in the Baltic Sea, research should focus on quantifying the anthropogenic impacts of coastal management solutions and their role in altering sediment dynamics and driving coastal change. For vulnerable sections, research should investigate how management strategies can focus on restoring sediment budgets in a way that uses resources effectively, perhaps through sediment bypass.

Hybrid solutions could be a good alternative for mitigation as the design combines benefits from both hard and soft solutions (Sutton-Grier et al., 2015). The soft design element can serve as compensation for the potential negative impacts of the sediment budget following hard coastal protection solutions. Hybrid solutions may be a good alternative particularly in urban areas and for coastal roads as there is often limited space for implementation of adaptation solutions. Hybrid solutions may prove beneficial as they require less spatial footprint than if only a soft solution would be implemented (Schuerch et al., 2022). The soft design provides reinforcement for existing protection works, as demonstrated by the protection at the site in Faxe Ladeplads (**Papers IV** and **V**). In addition, hybrid solutions can support a variety of positive benefits, like assuring beach accessibility and may facilitate stepwise adaptation to sea level rise.

The maintenance of hybrid solutions differs from that of traditional hard structures. While offering potential cost savings in repairs, these systems demand more frequent maintenance, monitoring, and safety assessments to address seasonal variations and operational limits. A deeper understanding of their long-term performance is essential to maximise their protective benefits. Further research should focus on case studies, physical modelling, and detailed monitoring to develop robust design guidelines and enhance our understanding of the interactions between hard and soft elements, particularly during storm events. These efforts can prove very valuable in improving the effectiveness and reliability of hybrid coastal defences and their potential as coastal management strategies in a changing climate.

9 Conclusions

The work compiled in this thesis presents a methodology to study the impact of flooding and erosion on coastal roads. The geographical scope of the work has been limited to the southern Baltic Sea and, more specifically, to the south coast of Sweden and the east coast of Denmark, where case studies have been conducted. The conditions in the semi-enclosed Baltic Sea differ from conditions along the open coasts. Thereby, the findings are considered important to improve the knowledge of these types of coastlines that are characterised by episodic wave conditions and low sediment input to the coastal systems. The presented findings can be transferable to systems with similar conditions as the Baltic Sea, such as e.g. other marginal seas, sheltered coastal environments like estuaries and bays, or even large lakes. The results have particularly contributed to the field of risk assessment and beach nourishment development for these types of coastal landscapes. Thereby, the presented findings contributed to fulfilling the overall aim of the thesis. By presenting a methodology for the investigation of coastal-related risks that can impact coastal roads and presenting alternatives for management solutions to adapt the infrastructure to limit the negative impacts of coastal processes.

The work resulted in the presentation of a detailed high-resolution dataset of decadal hindcast wave data for the southern Baltic Sea, as outlined in objective (i). The dataset constitutes a multi-scale wave modelling approach where one set of calibration settings gives satisfactory performance for both offshore and nearshore conditions when compared to observations. The long, validated time series offer robust data for wave statistics and data that can be used both in risk assessment and design of coastal infrastructure. The dataset covers the period from 1959-2023 and enables analysis of the variability in the wave climate across temporal and spatial scales. The analysis of inter-annual variability showed that the direction and magnitude of cumulated annual wave energy are correlated to the NAO DJFM index.

The characteristic episodic wave climate in the Baltic Sea dictates the morphological evolution of the coastal systems. The morphological evolution of a small-scale beach nourishment was assessed at varying temporal scales and under varying hydrodynamic impact in accordance with objective (ii). The results show that the redistribution of sediment is largely event-driven where the combined effects of waves and water levels have the potential to activate a larger part of the nourished profile. In addition, the protruding hard structures and layout of the coastal stretch contributed to more sediment redistribution from the central section toward the sides. Consequently, the centre section is more exposed and vulnerable to wave action and narrowing of the beach in front of the revetment.

Objective (iii) was addressed through the development of the RoadRAT framework, which was designed to assess the exposure of coastal roads to flooding and erosion. The framework constitutes an efficient screening tool that can treat both hydrodynamic and morphological processes and assess future development by considering SLR. The analysis can be set up to investigate exposure at regional scales (spatial scales >100 km) but still outputs detailed results (100 m) to identify specific hotspots through discretization or the road segment. The case study of the southern Swedish coast combines results from the RoadRAT analysis and the observed impacts on the infrastructure caused by storm Babet. The findings highlight risks for infrastructure both in today's conditions and in the future under SLR. For future scenarios, coastal erosion is identified as the most destructive hazard that can impact long stretches of the main coastal road along the south coast of Sweden. Thereby, there will be an increased need for mitigation of coastal hazards in the next 130 years to limit negative impacts to the transport system.

Lastly, the work related to objective (iv) focused on evaluating the potential of small-scale beach nourishment for the protection of coastal roads in an approach to mitigate the risks through decreased exposure to coastal processes on the road infrastructure. The investigated site constitutes a solution that is a combination of a rock revetment and a beach nourishment in a hybrid solution that combines the design of both hard and soft elements. The design can be a beneficial option for mitigating impacts by coastal processes on coastal roads, and the nourished beach contributes to reducing the wave impact on the revetment and the road. However, the extreme surge levels during Babet were very high in relation to the crest height of the hard structure, where some sections where the hybrid solution did not provide sufficient protection.

References

Aasbjerg, A. (2002). *Fakse Ladeplads - Lidt om havnenes historie.*

Adell, A., Almström, B., Kroon, A., Larson, M., Uvo, C. B., & Hallin, C. (2023). Spatial and temporal wave climate variability along the south coast of Sweden during 1959–2021. *Regional Studies in Marine Science*, *63*, 103011. https://doi.org/10.1016/j.rsma.2023.103011

Almarshed, B., Figlus, J., Miller, J., & Verhagen, H. J. (2020). Innovative Coastal Risk Reduction through Hybrid Design: Combining Sand Cover and Structural Defenses. *Journal of Coastal Research*, *36*(1), 174–188. https://doi.org/10.2112/JCOASTRES-D-18-00078.1

Anderson, T. R., Fletcher, C. H., Barbee, M. M., Romine, B. M., Lemmo, S., & Delevaux, J. M. S. M. S. (2018). Modeling multiple sea level rise stresses reveals up to twice the land at risk compared to strictly passive flooding methods. *Scientific Reports*, *8*(1), 1–14. https://doi.org/10.1038/s41598-018-32658-x

Andrade, A. C., Lira, F., Pereira, M. T., Ramos, R., Guerreiro, J., Freitas, M. C., Andradef, C., Lirafj, F., Pereiraj, M. T., Ramosj, R., & Freitasf, J. G. C. (2006). *Monitoring the Nourishment of Santo Amaro Estuarine Beach (Portugal)*. *II*(39), 776–782.

Andrée, E., Su, J., Dahl Larsen, M. A., Drews, M., Stendel, M., & Skovgaard Madsen, K. (2023). The role of preconditioning for extreme storm surges in the western Baltic Sea. *Natural Hazards and Earth System Sciences*, *23*(5), 1817–1834. https://doi.org/10.5194/nhess-23-1817-2023

Arns, A., Wahl, T., Wolff, C., Vafeidis, A. T., Haigh, I. D., Woodworth, P., Niehüser, S., & Jensen, J. (2020). Non-linear interaction modulates global extreme sea levels, coastal flood exposure, and impacts. *Nature Communications*, *11*(1), 1–9. https://doi.org/10.1038/s41467-020-15752-5

Asariotis, R., Kruckova, L., & Mohos-Naray, V. (2020). Climate Change Impacts and Adaptation for Coastal Transport Infrastructure: A Compilation of Policies and Practices | UNCTAD. In *Transport and Trade Facilitation Series* (Issue 12). https://unctad.org/webflyer/climate-change-impacts-and-adaptation-coastal-transport-infrastructure-compilation

Averes, T., Hofstede, J. L. A., Hinrichsen, A., Reimers, H. C., & Winter, C. (2021). Cliff retreat contribution to the littoral sediment budget along the baltic sea coastline of Schleswig-Holstein, Germany. *Journal of Marine Science and Engineering*, *9*(8). https://doi.org/10.3390/jmse9080870

Basterretxea, G., Orfila, A., Jordi, A., Fornós, J. J., & Tintoré, J. (2007). Evaluation of a small volume renourishment strategy on a narrow Mediterranean beach. *Geomorphology*, *88*(1–2), 139–151. https://doi.org/10.1016/j.geomorph.2006.10.019

Bendixen, M., Clemmensen, L. B., & Kroon, A. (2013). Sandy berm and beach-ridge formation in relation to extreme sea-levels: A Danish example in a micro-tidal environment. *Marine Geology*, *344*, 53–64. https://doi.org/10.1016/j.margeo.2013.07.006

Björkqvist, J. V., Lukas, I., Alari, V., van Vledder, G. P., Hulst, S., Pettersson, H., Behrens, A., & Männik, A. (2018). Comparing a 41-year model hindcast with decades of wave measurements from the Baltic Sea. *Ocean Engineering*, *152*(April 2017), 57–71. https://doi.org/10.1016/j.oceaneng.2018.01.048

Blott, S. J., & Pye, K. (2004). Morphological and sedimentological changes on an artificially nourished beach, Lincolnshire, Uk. *Journal of Coastal Research*, *20*(1), 214–233. https://doi.org/10.2112/1551-5036(2004)20[214:mascoa]2.0.co;2

Boers, M. (2011). *Technisch Rapport Duinwaterkeringen en Hybride Keringen 2011*. 140.

Bonaduce, A., Staneva, J., Behrens, A., Bidlot, J. R., & Wilcke, R. A. I. (2019). Wave climate change in the North Sea and Baltic Sea. *Journal of Marine Science and Engineering*, *7*(6). https://doi.org/10.3390/jmse7060166

Booij, N., Ris, R. C., & Holthuijsen, L. H. (1999). A third-generation wave model for coastal regions 1. Model description and validation. *Journal of Geophysical Research: Oceans*, *104*(C4), 7649–7666. https://doi.org/10.1029/98JC02622

Bosom, E., & Jiménez, J. A. (2011). Probabilistic coastal vulnerability assessment to storms at regional scale - Application to Catalan beaches (NW Mediterranean). *Natural Hazards and Earth System Science*, *11*(2), 475–484. https://doi.org/10.5194/nhess-11-475-2011

Bricheno, L. M., & Wolf, J. (2018). Future Wave Conditions of Europe, in Response to High-End Climate Change Scenarios. *Journal of Geophysical Research: Oceans*, *123*(12), 8762–8791. https://doi.org/10.1029/2018JC013866

Brown, S., Nicholls, R. J., Hanson, S., Brundrit, G., Dearing, J. A., Dickson, M. E., Gallop, S. L., Gao, S., Haigh, I. D., Hinkel, J., Jiménez, J. A., Klein, R. J. T., Kron, W., Lázár, A. N., Neves, C. F., Newton, A., Pattiaratachi, C., Payo, A., Pye, K., … Woodroffe, C. D. (2014). Shifting perspectives on coastal impacts and adaptation. *Nature Climate Change*, *4*(9), 752–755. https://doi.org/10.1038/nclimate2344

Bruun, P. (1954). Coastal erosion and the development of beach profiles. In *Beach Erosion Board Technical Memorandum*.

Bruun, P. (1962). Sea level rise as a cause of shore erosion. *Journal of Waterways and Harbors Division ASCE 88*, 117–130.

Christie, E. K., Spencer, T., Owen, D., McIvor, A. L., Möller, I., & Viavattene, C. (2018). Regional coastal flood risk assessment for a tidally dominant, natural coastal setting: North Norfolk, southern North Sea. *Coastal Engineering*, *134*(May 2017), 177–190. https://doi.org/10.1016/j.coastaleng.2017.05.003

Cooper, J. A. G., Masselink, G., Coco, G., Short, A. D., Castelle, B., Rogers, K., Anthony, E., Green, A. N., Kelley, J. T., Pilkey, O. H., & Jackson, D. W. T. (2020). Sandy beaches can survive sea-level rise. *Nature Climate Change*, *10*(11), 993–995. https://doi.org/10.1038/s41558-020-00934-2

Cooper, J. A. G., & Pilkey, O. H. (2004). Sea-level rise and shoreline retreat: Time to abandon the Bruun Rule. *Global and Planetary Change*, *43*(3–4), 157–171. https://doi.org/10.1016/j.gloplacha.2004.07.001

Corradi, N., Ferrari, M., & Schiaffino, C. F. (2008). Evaluation of the effectiveness of a seasonal nourishment programme of the pocket beaches of the city of Genoa. *Chemistry and Ecology*, *24*(1), 215–223. https://doi.org/10.1080/02757540801965472

Danish Coastal Authority. (2021). *Beach Nourishment Effects - Faxe Ladeplads*.

Davidson-Arnott, R. (2010). *Introduction to Coastal Processes and Geomorphology*. Cambridge University Press.

Dean, R. G. (1986). Coastal Armoring: Effects, Principles and Mitigation. In Https://doi.org/10.9753/icce.v20.135 (Ed.), *Coastal Engineering Proceedings* (pp. 1843–1857). ASCE Publishing. https://doi.org/https://doi.org/10.9753/icce.v20.135

Defeo, O., McLachlan, A., Schoeman, D. S., Schlacher, T. A., Dugan, J., Jones, A., Lastra, M., & Scapini, F. (2009). Threats to sandy beach ecosystems: A review. *Estuarine, Coastal and Shelf Science*, *81*(1), 1–12. https://doi.org/10.1016/j.ecss.2008.09.022

Demirel, H., Kompil, M., & Nemry, F. (2015). A framework to analyze the vulnerability of European road networks due to Sea-Level Rise (SLR) and sea storm surges. *Transportation Research Part A: Policy and Practice*, *81*, 62–76. https://doi.org/10.1016/j.tra.2015.05.002

Deser, C., Hurrell, J. W., & Phillips, A. S. (2017). The role of the North Atlantic Oscillation in European climate projections. *Climate Dynamics*, *49*(9–10), 3141–3157. https://doi.org/10.1007/s00382-016-3502-z

Douglass, S. L., & Webb, B. M. (2020). Highways in the Coastal Environment. *Hydraulic Engineering Circular Number 25 - Third Edition, October 2014*.

Durand, G., van den Broeke, M. R., Le Cozannet, G., Edwards, T. L., Holland, P. R., Jourdain, N. C., Marzeion, B., Mottram, R., Nicholls, R. J., Pattyn, F., Paul, F., Slangen, A. B. A., Winkelmann, R., Burgard, C., van Calcar, C. J., Barré, J. B., Bataille, A., & Chapuis, A. (2022). Sea-Level Rise: From Global Perspectives to Local Services. *Frontiers in Marine Science*, *8*(January). https://doi.org/10.3389/fmars.2021.709595

Eelsalu, M., Parnell, K. E., & Soomere, T. (2022). Sandy beach evolution in the low-energy microtidal Baltic Sea: Attribution of changes to hydrometerological forcing. *Geomorphology*, *414*(July), 108383. https://doi.org/10.1016/j.geomorph.2022.108383

EMODnet. (2021). *EMODnet Bathymetry*. https://www.emodnet-bathymetry.eu/

EurOtop. (2018). *Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application.* (J. . Van der Meer, N. W. . Allsop, T. Bruce, J. De Rouck, A. Kortenhaus, T. Pullen, H. Schüttrumpf, P. Troch, & B. Zanuttigh (eds.)). www.overtopping-manual.com

Fox-Kemper, B., H.T. Hewitt, C., Xiao, G., Aðalgeirsdóttir, S. S., Drijfhout, T. L., Edwards, N. R., Golledge, M., Hemer, R. E., Kopp, G., Krinner, A., Mix, D., Notz, S., Nowicki, I. S., Nurhati, L., Ruiz, J.-B., Sallée, A. B., Slangen, A., & Yu, Y. (2021). Ocean, Cryosphere and Sea Level Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1211–1362). Cambridge University Press. https://doi.org/10.1017/9781009157896.011

Gräwe, U., & Burchard, H. (2012). Storm surges in the Western Baltic Sea: The present and a possible future. *Climate Dynamics*, *39*(1–2), 165–183. https://doi.org/10.1007/s00382-011-1185-z

Groll, N., Grabemann, I., Hünicke, B., & Meese, M. (2017). Baltic sea wave conditions under climate change scenarios. *Boreal Environment Research*, *22*, 1–12.

Hallermeier, R. J., & Rhodes, P. E. (1988). Generic treatment of dune erosion for 100-year event. *Coastal Engineering Proceedings*, 1197–1211. https://doi.org/10.9753/icce.v21.89

Hallin, C., Knaggård, Å., Alexanderson, H., Zander, U., Persson, A., Sahlin, U., Wingren, C., & Thorén, H. (2024). De värsta konsekvenserna av Babet ligger framför oss. *Sydsvenskan*. https://www.sydsvenskan.se/2024-02-28/de-Varsta-Konsekvenserna-Av-Babet-Ligger-Framfor-Oss

Hanson, H., Brampton, A., Capobianco, M., Dette, H. H., Hamm, L., Laustrup, C., Lechuga, A., & Spanhoff, R. (2002). Beach nourishment projects, practices, and objectives - A European overview. *Coastal Engineering*, *47*(2), 81–111. https://doi.org/10.1016/S0378-3839(02)00122-9

Hanson, H., & Larson, M. (2008). Implications of extreme waves and water levels in the southern Baltic Sea. *Journal of Hydraulic Research*, *46*(2), 292–302. https://doi.org/10.1080/00221686.2008.9521962

Harff, J., Deng, J., Dudzińska-Nowak, J., Fröhle, P., Groh, A., Hünicke, B., Soomere, T., & Zhang, W. (2017). *What Determines the Change of Coastlines in the Baltic Sea?, in: Coastline Changes of the Baltic Sea from South to East* (J. Harff, K. Furmanczyk, & H. VonStorch (eds.); pp. 15–36). Springer International Publishing. https://doi.org/10.1007/978-3-319-49894-2_6

Hellström, B. (1941). Vattenståndsvariationerna i Östersjöbäckenet. In *Väg- och Vattenbyggnadskonst Husbyggnadsteknik*.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., … Thépaut, J. N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hieronymus, M., & Kalén, O. (2020). Sea-level rise projections for Sweden based on the new IPCC special report: The ocean and cryosphere in a changing climate. *Ambio*, *49*(10), 1587–1600. https://doi.org/10.1007/s13280-019-01313-8

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C., & Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3292–3297. https://doi.org/10.1073/pnas.1222469111

Hünicke, B., Zorita, E., Soomere, T., Madsen, K. ., Johansson, M., & Suursaar, Ü. (2015). Recent Change - Sea Level and Wind Waves. In BACC II Author Team (Ed.), *Second Assessment of Climate Change for the Baltic Sea Basin. Regional Climate Studies* (pp. 131–144). Springer, Cham. https://doi.org/https://doi.org/10.1007/978-3-319-16006-1_9

Irish, J. L., Lynett, P. J., Weiss, R., Smallegan, S. M., & Cheng, W. (2013). Buried relic seawall mitigates Hurricane Sandy's impacts. *Coastal Engineering*, *80*, 79–82. https://doi.org/10.1016/j.coastaleng.2013.06.001

Jackson, N. L., & Nordstrom, K. F. (1994). The mobility of beach fill in front of a seawall on an estuarine shoreline, Cliffwood Beach, New Jersey, USA. *Ocean and Coastal Management*, *23*(2), 149–166. https://doi.org/10.1016/0964-5691(94)90062-0

Jiménez, J. A., Sanuy, M., Ballesteros, C., & Valdemoro, H. I. (2018). The Tordera Delta, a hotspot to storm impacts in the coast northwards of Barcelona (NW Mediterranean). *Coastal Engineering*, *134*(June 2017), 148–158. https://doi.org/10.1016/j.coastaleng.2017.08.012

Jiménez, J. A., Winter, G., Bonaduce, A., Depuydt, M., Galluccio, G., Van Den Hurk, B., Meier, M. H. E., Pinardi, N., & Pomarico, L. G. (2024). *Chapter 3 – Sea Level Rise in Europe : 1st Assessment Report of the Knowledge Hub on Sea Level Rise Sea Level Rise in Europe : Knowledge gaps identified through a participatory approach.*

Karasu, S., Marangoz, H. O., Gülkaya, E., Akpınar, A., Ceylan, Y., & Yılmaz, E. (2023). Performance based assessment of a small-scale artificially nourished beach. *Ocean and Coastal Management*, *244*(August). https://doi.org/10.1016/j.ocecoaman.2023.106827

Kjellström, E., Nikulin, G., Strandberg, G., Bøssing Christensen, O., Jacob, D., Keuler, K., Lenderink, G., Van Meijgaard, E., Schär, C., Somot, S., Lund Sørland, S., Teichmann, C., & Vautard, R. (2018). European climate change at global mean temperature increases of 1.5 and 2 °C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models. *Earth System Dynamics*, *9*(2), 459–478. https://doi.org/10.5194/esd-9-459-2018

Knudsen, M. F., Seidenkrantz, M. S., Jacobsen, B. H., & Kuijpers, A. (2011). Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years. *Nature Communications*, *2*(1). https://doi.org/10.1038/ncomms1186

Koks, E. E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S. A., Hall, J. W., & Hallegatte, S. (2019). A global multi-hazard risk analysis of road and railway infrastructure assets. *Nature Communications*, *10*(1), 1–11. https://doi.org/10.1038/s41467-019-10442-3

Kroon, A., De Schipper, M., De Vries, S., & Aarninkhof, S. (2022). Subaqueous and Subaerial

Beach Changes after Implementation of a Mega Nourishment in Front of a Sea Dike. *Journal of Marine Science and Engineering*, *10*(8). https://doi.org/10.3390/jmse10081152

Kudryavtseva, N., Räämet, A., & Soomere, T. (2020). Coastal Flooding: Joint Probability of Extreme Water Levels and Waves along the Baltic Sea Coast. *Journal of Coastal Research*, *95*(sp1), 1146–1151. https://doi.org/10.2112/SI95-222.1

Łabuz, T. A. (2015). Environmental Impacts—Coastal Erosion and Coastline Changes. In *Second Assessment of Climate Change for the Baltic Sea Basin (BACCII)* (pp. 381–393).

Larson, M., Erikson, L., & Hanson, H. (2004). An analytical model to predict dune erosion due to wave impact. *Coastal Engineering*, *51*(8–9), 675–696. https://doi.org/10.1016/j.coastaleng.2004.07.003

Le Cozannet, G., Oliveros, C., Castelle, B., Garcin, M., Idier, D., Pedreros, R., & Rohmer, J. (2016). Uncertainties in sandy shorelines evolution under the bruun rule assumption. *Frontiers in Marine Science*, *3*(APR), 1–14. https://doi.org/10.3389/fmars.2016.00049

Leppäranta, M., & Myrberg, K. (2009). Physical Oceanography of the Baltic Sea. In *Paper Knowledge . Toward a Media History of Documents*.

Lincke, D., & Hinkel, J. (2018). Economically robust protection against 21st century sea-level rise. *Global Environmental Change*, *51*(June 2017), 67–73. https://doi.org/10.1016/j.gloenvcha.2018.05.003

Lowe, M. K., & Kennedy, D. M. (2016). Stability of artificial beaches in port Phillip Bay, Victoria, Australia. *Journal of Coastal Research*, *1*(75), 253–257. https://doi.org/10.2112/SI75-51.1

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., & Aarninkhof, S. (2018). The State of the World's Beaches. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-24630-6

Malmberg-Persson, K., Nyberg, J., Ising, J., & Rodhe, L. (2016). *Skånes känsliga stränder – erosionsförhållanden och geologi för samhällsplanering. SGU-report 2016:17*.

Manno, G., Anfuso, G., Messina, E., Williams, A. T., Suffo, M., & Liguori, V. (2016). Decadal evolution of coastline armouring along the Mediterranean Andalusia littoral (South of Spain). *Ocean and Coastal Management*, *124*, 84–99. https://doi.org/10.1016/j.ocecoaman.2016.02.007

Masselink, G., Scott, T., Poate, T., Stokes, C., Wiggins, Ma., Valiente, N., & Konstantinou, A. (2023). Tale of two beaches: correlation between decadal beach dynamics and climate indices. *Coastal Sediments 2023*. https://doi.org/https://doi.org/10.1142/9789811275135_0031

McGillis, A., & MacCallum, I. (2010). Infrastructure risk assessment of coastal roads in Nova Scotia. *TAC/ATC 2010 - 2010 Annual Conference and Exhibition of the Transportation Association of Canada: Adjusting to New Realities*.

Meier, M., Kniebusch, M., Dieterich, C., Gröger, M., Zorita, E., Elmgren, R., Myrberg, K., Ahola, M. P., Bartosova, A., Bonsdorff, E., Börgel, F., Capell, R., Carlén, I., Carlund, T., Carstensen, J., Christensen, O. B., Dierschke, V., Frauen, C., Frederiksen, M., … Zhang,

W. (2022). Climate change in the Baltic Sea region: A summary. *Earth System Dynamics*, *13*(1), 457–593. https://doi.org/10.5194/esd-13-457-2022

Mentaschi, L., Vousdoukas, M. I., Voukouvalas, E., Dosio, A., & Feyen, L. (2017). Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. *Geophysical Research Letters*, *44*(5), 2416–2426. https://doi.org/10.1002/2016GL072488

Mitrovica, J. X., Tamisiea, M. E., Davis, J. L., & Milne, G. A. (2001). Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature*, *409*(February), 4–7.

Nawarat, K., Reyns, J., Vousdoukas, M. I., Duong, T. M., Kras, E., & Ranasinghe, R. (2024a). Coastal hardening and what it means for the world's sandy beaches. *Nature Communications*, *15*(10626). https://doi.org/10.1038/s41467-024-54952-1

Nawarat, K., Reyns, J., Vousdoukas, M., Van Ginkel, K., Mulholland, E., & Ranasinghe, R. (2024b). Coastal flood risk to European critical infrastructure. *Interational Conference on Coastal Engieneering*.

NCAR. (2023). *Hurrell North Atlantic Oscillation (NAO) Index (station-based)*. https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based

Neumann, J., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., & Martinich, J. (2021). Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. *Climatic Change*, *167*(3–4), 1–23. https://doi.org/10.1007/s10584-021-03179-w

Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science*, *328*(5985), 1517–1520. https://doi.org/10.1126/science.1185782

Nordstrom, K. F. (2014). Living with shore protection structures: A review. *Estuarine, Coastal and Shelf Science*, *150*(PA), 11–23. https://doi.org/10.1016/j.ecss.2013.11.003

Nordstrom, K. F. (2019). Coastal dunes with resistant cores. *Journal of Coastal Conservation*, *23*(1), 227–237. https://doi.org/10.1007/s11852-018-0653-6

Norrman, J., Agrell, H., & Albjär, G. (1981). *Stranderosion vid Espet i Hanöbukten*.

O'Brien, M. K., Valverde, H. R., Trembanis, A. C., & Haddad, T. C. (1999). Summary of beach nourishment activity along the Great Lakes' shoreline 1955-1996. *Journal of Coastal Research*, *15*(1), 206–219.

Ojeda, E., & Guillén, J. (2008). Shoreline dynamics and beach rotation of artificial embayed beaches. *Marine Geology*, *253*(1–2), 51–62. https://doi.org/10.1016/j.margeo.2008.03.010

Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R. M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., & Sebesvari, Z. (2019). *Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities Coordinating* (N. M. W. . IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-

Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama (ed.)).

Orvikut, K., Jaagus, J., Kont, A., Ratas, U., & Rivis, R. (2003). Increasing activity of coastal processes associated with climate change in Estonia. *Journal of Coastal Research*, *19*(2), 364–375.

Pal, I., Kumar, A., & Mukhopadhyay, A. (2023). Risks to Coastal Critical Infrastructure from Climate Change. *Annual Review of Environment and Resources*, *48*, 681–712. https://doi.org/10.1146/annurev-environ-112320-101903

Paulik, R., Stephens, S. A., Bell, R. G., Wadhwa, S., & Popovich, B. (2020). National-scale built-environment exposure to 100-year extreme sea levels and sea-level rise. *Sustainability (Switzerland)*, *12*(4), 1–16. https://doi.org/10.3390/su12041513

Perk, L., van Rijn, L., Koudstaal, K., & Fordeyn, J. (2019). A rational method for the design of sand dike/dune systems at sheltered sites; Wadden Sea Coast of Texel, The Netherlands. *Journal of Marine Science and Engineering*, *7*(9). https://doi.org/10.3390/jmse7090324

Pregnolato, M., & Dawson, D. A. (2018). Adaptation investments for transport resilience: Trends and recommendations. *International Journal of Safety and Security Engineering*, *8*(4), 515–527. https://doi.org/10.2495/SAFE-V8-N4-515-527

Pregnolato, M., Ford, A., Wilkinson, S. M., & Dawson, R. J. (2017). The impact of flooding on road transport: A depth-disruption function. *Transportation Research Part D: Transport and Environment*, *55*, 67–81. https://doi.org/10.1016/j.trd.2017.06.020

Pupienis, D., Jarmalavičius, D., Žilinskas, G., & Fedorovič, J. (2014). Beach nourishment experiment in Palanga, Lithuania. *Journal of Coastal Research*, *70*, 490–495. https://doi.org/10.2112/SI70-083.1

Ravens, T. M., & Sitanggang, K. I. (2007). Numerical modeling and analysis of shoreline change on Galveston Island. *Journal of Coastal Research*, *23*(3), 699–710. https://doi.org/10.2112/04-0191.1

Robinet, A., Castelle, B., Idier, D., Le Cozannet, G., Déqué, M., & Charles, E. (2016). Statistical modeling of interannual shoreline change driven by North Atlantic climate variability spanning 2000–2014 in the Bay of Biscay. *Geo-Marine Letters*, *36*(6), 479–490. https://doi.org/10.1007/s00367-016-0460-8

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., & Lescinski, J. (2009). Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, *56*(11–12), 1133–1152. https://doi.org/10.1016/j.coastaleng.2009.08.006

Różyński, G. (2023). Coastal protection challenges after heavy storms on the Polish coast. *Continental Shelf Research*, *266*(November 2022). https://doi.org/10.1016/j.csr.2023.105080

Rozyński, G., & Szmytkiewicz, P. (2012). Long term evolution of baltic sea sandy beach forced by winter north atlantic oscillation (NAOWI). *Proceedings of the Coastal Engineering Conference*, 1–10. https://doi.org/10.9753/icce.v33.sediment.70

Rutgersson, A., Kjellström, E., Haapala, J., Stendel, M., Danilovich, I., Drews, M., Jylhä, K., Kujala, P., Larsén, X. G., Halsnæs, K., Lehtonen, I., Luomaranta, A., Nilsson, E., Olsson, T., Särkkä, J., Tuomi, L., & Wasmund, N. (2022). Natural hazards and extreme events in the Baltic Sea region. *Earth System Dynamics*, *13*(1), 251–301. https://doi.org/10.5194/esd-13-251-2022

Schoonees, T., Gijón Mancheño, A., Scheres, B., Bouma, T. J., Silva, R., Schlurmann, T., & Schüttrumpf, H. (2019). Hard Structures for Coastal Protection, Towards Greener Designs. *Estuaries and Coasts*, *42*(7), 1709–1729. https://doi.org/10.1007/s12237-019-00551-z

Schuerch, M., Mossman, H. L., Moore, H. E., Christie, E., & Kiesel, J. (2022). Invited perspectives: Managed realignment as a solution to mitigate coastal flood risks - optimizing success through knowledge co-production. *Natural Hazards and Earth System Sciences*, *22*(9), 2879–2890. https://doi.org/10.5194/nhess-22-2879-2022

SGI & MSB. (2021). *Riskområden för ras, skred, erosion och översvämning.*

Slangen, A. B. A., Church, J. A., Agosta, C., Fettweis, X., Marzeion, B., & Richter, K. (2016). Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change*, *6*(7), 701–705. https://doi.org/10.1038/nclimate2991

Smallegan, S. M., Irish, J. L., Van Dongeren, A. R., & Den Bieman, J. P. (2016). Morphological response of a sandy barrier island with a buried seawall during Hurricane Sandy. *Coastal Engineering*, *110*, 102–110. https://doi.org/10.1016/j.coastaleng.2016.01.005

SMHI. (2020). *Framtida medelvattenstånd.* https://www.smhi.se/klimat/stigande-havsnivaer/framtida-medelvattenstand-1.165493

Smith, C. S., Rudd, M. E., Gittman, R. K., Melvin, E. C., Patterson, V. S., Renzi, J. J., Wellman, E. H., & Silliman, B. R. (2020). Coming to terms with living shorelines: A scoping review of novel restoration strategies for shoreline protection. *Frontiers in Marine Science*, *7*, 1–14. https://doi.org/10.3389/fmars.2020.00434

Soomere, T. (2023). Numerical simulations of wave climate in the Baltic Sea: a review. *Oceanologia*, *65*(1), 117–140. https://doi.org/10.1016/j.oceano.2022.01.004

Soomere, T., Viska, M., & Pindsoo, K. (2017). Retriving the signal of climate change from numerically simulated sediment transport along the eastern Baltic Sea coast, in: Coastline Changes of the Baltic Sea from South to East. In J. Harff, K. Furmanczyk, & H. von Storch (Eds.), *Coastline Changes of the Baltic Sea from South to East* (pp. 327–362). Springer International Publishing.

Stockdon, H. F., Holman, R. A., Howd, P. A., & Sallenger, A. H. (2006). Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, *53*(7), 573–588. https://doi.org/10.1016/j.coastaleng.2005.12.005

Strypsteen, G., Bonte, D., Taelman, C., Derijckere, J., & Rauwoens, P. (2024). Three years of morphological dune development after planting marram grass on a beach. *Earth Surface Processes and Landforms*, *49*(10), 2980–2997. https://doi.org/10.1002/esp.5870

Sukchaiwan, E. (2023). *Dune Erosion on the Falsterbo Peninsula* [TU Delft]. https://resolver.tudelft.nl/uuid:f392d303-dc5c-49ee-ae6c-ae9c40bd92d3

Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science and Policy*, *51*, 137–148. https://doi.org/10.1016/j.envsci.2015.04.006

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature*, *504*(7478), 79–83. https://doi.org/10.1038/nature12859

Thomas, T., Phillips, M. R., & Williams, A. T. (2010). Mesoscale evolution of a headland bay: Beach rotation processes. *Geomorphology*, *123*(1–2), 129–141. https://doi.org/10.1016/j.geomorph.2010.06.018

Tomlinson, R. B., Jackson, A. L. A., & Bowra, K. (2016). Gold coast seawall: status investigations and design review. *Journal of Coastal Research*, *1*(75), 715–719. https://doi.org/10.2112/SI75-143.1

Ton, A. M., Vuik, V., & Aarninkhof, S. G. J. (2021). Sandy beaches in low-energy, non-tidal environments: Linking morphological development to hydrodynamic forcing. *Geomorphology*, *374*, 107522. https://doi.org/10.1016/j.geomorph.2020.107522

Ton, A. M., Vuik, V., & Aarninkhof, S. G. J. (2023). Longshore sediment transport by large-scale lake circulations at low-energy, non-tidal beaches: A field and model study. *Coastal Engineering*, *180*, 104268. https://doi.org/10.1016/j.coastaleng.2022.104268

Trafikverket. (2020). *Trafikverkets klimat- och sårbarhetsanalys 2019*.

Vila-Concejo, A., Fellowes, T. E., Gallop, S., Alejo, I., Angnuureng, D. B., Benavente, J., Bosma, J. W., Brempong, E. K., Dissanayake, P., Gazi, M. Y., González-Villanueva, R., Guimarães, R., Kennedy, D. M., Largier, J. L., van der Lugt, M. A., Montes, J., Orescanin, M., Pattiaratchi, C. B., Cajueiro Carneiro Pereira, L., … Chen, Z. (2024). Morphodynamics and management challenges for beaches in modified estuaries and bays. *Cambridge Prisms: Coastal Futures*, *2*. https://doi.org/10.1017/cft.2024.7

Viška, M., & Soomere, T. (2013). Simulated and observed reversals of wave-driven alongshore sediment transport at the eastern baltic sea coast. *Baltica*, *26*(2), 145–156. https://doi.org/10.5200/baltica.2013.26.15

Vousdoukas, M. I., Ranasinghe, R., Mentaschi, L., Plomaritis, T. A., Athanasiou, P., Luijendijk, A., & Feyen, L. (2020). Sandy coastlines under threat of erosion. *Nature Climate Change*, *10*(3), 260–263. https://doi.org/10.1038/s41558-020-0697-0

Weisse, R., Dailidiene, I., Hünicke, B., Kahma, K., Madsen, K., Omstedt, A., Parnell, K., Schöne, T., Soomere, T., Zhang, W., & Zorita, E. (2021). Sea level dynamics and coastal erosion in the Baltic Sea region. *Earth System Dynamics*, *12*(3), 871–898. https://doi.org/10.5194/esd-12-871-2021

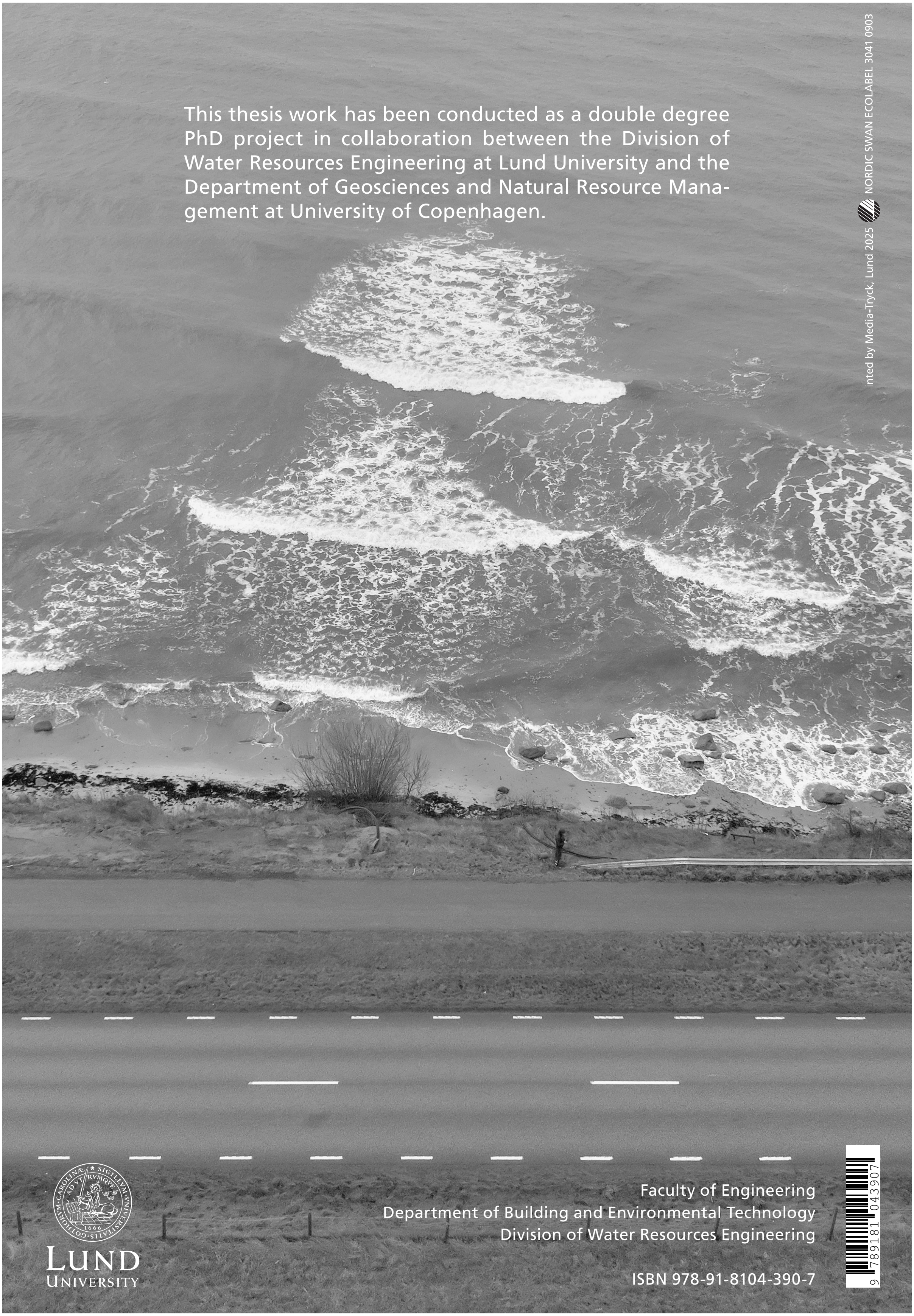
Weisse, R., & Weidemann, H. (2017). Baltic Sea extreme sea levels 1948-2011: Contributions from atmospheric forcing. *Procedia IUTAM*, *25*, 65–69. https://doi.org/10.1016/j.piutam.2017.09.010

Winters, M. A., Leslie, B., Sloane, E. B., & Gallien, T. W. (2020). Observations and preliminary vulnerability assessment of a hybrid dune-based living shoreline. *Journal of Marine Science and Engineering*, *8*(11), 1–18. https://doi.org/10.3390/jmse8110920

Wolski, T., & Wiśniewski, B. (2023). Characteristics of seasonal changes of the Baltic Sea extreme sea levels. *Oceanologia*, *65*(1), 151–170. https://doi.org/10.1016/j.oceano.2022.02.006

Wong, P. P., Losada, I. J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K. L., Saito, Y., & Sallenger, A. (2014). Coastal systems and Low-Lying Areas. In C. . Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), *Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 361–409). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Yang, B., Hwang, C., & Cordell, H. K. (2012). Use of LiDAR shoreline extraction for analyzing revetment rock beach protection: A case study of Jekyll Island State Park, USA. *Ocean and Coastal Management*, *69*, 1–15. https://doi.org/10.1016/j.ocecoaman.2012.06.007



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