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Nature-based Solutions for sandy coasts as sustainable adaptation measures to climate change

A contribution to the broadened conceptual understanding of NbS from an engineering as well as a societal perspective

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A contribution to the broadened conceptual understanding of NbS from an engineering as well as a societal perspective

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Vorwort des Herausgebers

Küstenzonen sind die am dichtesten besiedelten Gebiete der Erde. Entsprechend sind die Küsten vielfach anthropogen überprägt und entwickeln sich im Allgemeinen nicht natürlich. Die Form und der Umfang der anthropogenen Überprägung ist abhängig von der Intensität der Nutzung der küstennahen Bereiche durch Menschen und reicht von Naturräumen oder naturnahen Räumen mit nur geringer Überprägung über naturnahe Kulturräume und Kulturräume bis hin zu anthropogen vollständig überprägten und befestigten Küstenzonen. Hierbei sind zudem die vollständig anthropogen überprägten Gebiete zumeist urban geprägt und dicht bis sehr dicht besiedelt.

Mit der zunehmenden Besiedlung der Küsten wuchs und wächst das Bedürfnis nach Sicherheit und nach dem Schutz vor Stürmen und Hochwasser. Hierzu wurden in den letzten 1000 Jahren entlang der Küsten umfangreiche Küstenschutzbauwerke errichtet - vielfach mit dem Ziel, die Kraft des Meeres und des Wassers durch massive Bauwerke zu bezwingen. Entlang der deutschen Nordseeküste wurden beispielsweise über hunderte von Kilometern Deiche errichtet und über die Zeit immer weiter verstärkt und den gestiegenen Sicherheitsbedürfnissen angepasst. Auch auf den dem Festland vorgelagerten Inseln wird umfassend Hochwasserschutz und Küstenschutz betrieben mit dem Ziel, die Inseln vor Hochwasser zu schützen aber auch mit dem Ziel, die Inseln als indirekten Schutz für das Festland vor Erosion zu schützen und zu erhalten.

Im Küstenschutz spielten und spielen Sturmflutkatastrophen wie beispielsweise die Sturmflut im Februar 1962 an der deutschen Nordseeküste eine wesentliche und treibende Rolle. Nach 1962 kam es zu einem kompletten Umdenken im Küstenschutz sowohl aus organisatorischer und technisch-baulicher Sichtweise als auch aus wissenschaftlicher Sicht. Nach 1962 wurden Konzepte zunehmend vorsorgend, d.h. unter Abschätzung der zukünftig wahrscheinlichen und / oder möglichen Veränderungen entworfen und umgesetzt.

Neben den geänderten Sicherheitsansprüchen haben sich in den letzten Jahrzehnten ebenfalls die gesellschaftlichen Sichtweisen auf Umwelt und auf umweltbezogene Fragen stark verändert. Der Schutz von Umwelt, Natur und natürlichen Ökosystemen wurde gesellschaftlich zunehmend als extrem wichtig erachtet. Dies hat dazu geführt, dass umweltbezogene Fragestellungen und Auswirkungen von geplanten Maßnahmen auf die Umwelt umfassend in Planungsprozesse einbezogen werden. Zudem sind Fragen des Klimawandels und der Anpassung an die Folgen des Klimawandels in der Gesellschaft angekommen. Diese werden in Deutschland seit etwa 20 Jahren explizit und seit mindestens 50 Jahren implizit über den Bemessungshochwasserstand in Planungen zum Küstenschutz einbezogen.

Als Folge des Klimawandels werden sich zukünftig die hydro-meteorologischen Bedingungen an den Küsten ändern. Steigender Meeresspiegel mit veränderten mittleren aber auch extremen Wasserständen, veränderte mittlere und extreme Windbedingungen mit resultierend veränderten Wasserständen, Strömungs- und Seegangsbedingungen sorgen dafür, dass sich die Küsten den veränderten Randbedingungen anpassen. Viele Küstenabschnitte und hier insbesondere die leicht verformbaren Küsten aufgebaut aus kiesigem, sandigem, feinsandigem oder schluffigem Material werden zukünftig zurückweichen. Zudem werden in Zukunft die Belastungen auf die Küstenschutzbauwerke im Vergleich zu heute zunehmen.

Hieraus resultiert die Frage, welche Art von Küstenschutz zukünftig möglichst effizient die Herausforderungen, die aus den verschiedenen Ansprüchen – Sicherheit und intakte Umwelt – vor dem Hintergrund des Klimawandels zu lösen imstande ist. Hier versprechen naturbasierte Lösungen (NbS / Nature-based Solutions) sowohl die Lösung der Küstenschutzfragestellung als auch Anpassungsfähigkeit an geänderte Randbedingungen und daneben ebenfalls positive Effekte hinsichtlich der Umwelt und der Gesellschaft.

Hier setzt die in diesem 26. Band der Hamburger Wasserbauschriften veröffentlichte Arbeit von Herrn Dr. Philipp Jordan an. Mit seiner Arbeit hat er das Ziel verfolgt, das konzeptionelle Verständnis von Nature-based Solutions (NbS) im Küstenschutz (und teilweise des Küstenschutzes im Allgemeinen) sowohl aus technischer als auch aus gesellschaftlicher Sicht zu erweitern. Hierbei spielen insbesondere die Stakeholder und Akteure im Küstenschutz und deren Sichtweise auf und Einschätzung zu NbS eine wesentliche Rolle als Grundlage für die Akzeptanz von Lösungen im Küstenschutz generell aber insbesondere auch für NbS. Diese werden in der Arbeit eingebunden in die historische Entwicklung des Küstenschutzes, der (aus heutiger Sicht) naturbasierte Ansätze bereits seit Jahrhunderten mitverfolgt – auch wenn diese nicht explizit so benannt wurden.

Die Dissertation ist ein Ergebnis der Arbeiten[1] des Instituts für Wasserbau im Vorhaben C3 „Sustainable Adaptation Scenarios for Coastal Systems“ des Exzellenzclusters CLICCS „Climate, Climatic Change, and Society“ der Universität Hamburg und entstand in enger Kooperation insbesondere mit Prof. Beate Ratter und Dr. Martin Döring vom Geographischen Institut der Universität Hamburg.

Herr Dr. Philipp Jordan hat eine komplexe Dissertation zu einer inter- und transdisziplinären Thematik mit sehr schönen Ergebnissen abgeliefert und eine aktuelle Thematik (NbS) im Zusammenhang mit Küstenschutz und Risikomanagement an Küsten einen klaren Schritt nach vorne gebracht. Die Arbeit enthält viele wichtige Aspekte zur Thematik NbS im Küstenwasserbau und wird sicher auf ein breites Interesse in der Fachwelt stoßen.

Hamburg, 25. August 2024

Peter Fröhle
Leiter des Instituts für Wasserbau der Technischen Universität Hamburg

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Hamburg, June 2024

Philipp Jordan

Keywords:

Nature-based Solution, NbS, Nature-based adaptation, Coastal protection, Sandy coast, Coastal ecosystems, Conceptual understanding, Socio-technical endeavour, Engineering Scope in NbS, Societal Scope in NbS, interdisciplinary

Abstract

For centuries, coastal protection was characterised by the fight against nature. Nowadays it enables a safe life and economic activity along the coast, but climate change poses new challenges to the existing coastal protection and requires substantial adaptations. In combination with a paradigm shift in society's view of the coastal landscape and nature in general, a discourse on future technically possible, sustainable and sensible coastal protection is stimulated. Nature-based Solutions (NbS) represent promising adaptations for sandy coasts, providing ecological and societal benefits in addition to protection. In order for these to find their way into future common practice and to fully exploit their potential for Water, Nature and People, a broadened understanding of NbS from both engineering and societal perspectives is needed to facilitate cooperation at all levels.

The present thesis starts off at this point. Adopting an inter- and transdisciplinary approach allows the issues to be considered and analysed from different scientific disciplines as well as actors' perspectives. By combining a broad spectrum of analytical tools, insights can be generated that go beyond the spectrum of the disciplines involved. Exemplary for sandy coasts, the North Frisian islands of Amrum and Föhr are selected as investigation area. An insight into the evolution of coastal protection and its characterising rationale is obtained through a systematic literature review. How this rationale is anchored in the minds of people is investigated with an analysis of the assessment of protective measures based on conducted semi-structured interviews. In combination, both analyses reveal a dynamic evolution characterised by experimenting and tinkering with various types of coastal protection. Well-established measures like diking or stalk plantings in dunes, are prevailingly assessed as useful, adequate and trustworthy for the time being. Supposedly new concepts like NbS are initially often met with scepticism as they cannot be readily placed in the existing category system of coastal protection. The conducted review of coastal ecosystems as NbS discloses that they offer a chance to close this gap. Thanks to their inherent resilience, in addition to the existing coastal protection, NbS represent a sustainable adaptation option to climate change. To broaden the understanding of NbS from an engineering perspective, a conceptual analysis of the underlying processes within coastal ecosystems reveals and analyses the properties of NbS which can be fine-tuned and their role and interrelationships with regard to service, resistance and resilience. To broaden the understanding of NbS from a societal perspective, a socio-scientific analysis identifies the coastal dwellers' key requests towards coastal protection. The Key Societal Requests can help coastal dwellers to contextualise NbS in their established category system of coastal protection and highlight the importance and the potential of societal aspects to coastal engineers.

Both perspectives add to a broadened conceptual understanding of NbS, so that NbS can find way into common practice as sustainable adaptation measures to climate change and, thus, ultimately contribute to the re-diversification of coastal protection for an increased coastal resilience.

Zusammenfassung

Jahrhunderte lang war der Küstenschutz geprägt vom Kampf gegen die Natur. Heute ermöglicht er ein sicheres Leben und Wirtschaften an der Küste. Der Klimawandel aber stellt neue Herausforderungen an den Bestand und erfordert erhebliche Anpassungen. In Kombination mit einem Paradigmenwechsel in der gesellschaftlichen Sicht auf die Küstenlandschaft und die Natur wird ein Diskurs über technisch möglichen, nachhaltigen und sinnvollen Küstenschutz der Zukunft angeregt. Naturbasierte Maßnahmen (NbS) stellen eine vielversprechende Anpassungsoption für sandige Küsten dar, weil sie neben dem reinen Schutz auch einen ökologischen und gesellschaftlichen Mehrwert bieten. Damit diese in der Küstenschutzpraxis etabliert werden und ihr Potenzial für Wasser, Natur und Mensch voll ausschöpfen können, ist ein erweitertes Verständnis von NbS sowohl aus ingenieurwissenschaftlicher als auch aus gesellschaftlicher Perspektive notwendig.

Die vorliegende Dissertation setzt mit einem inter- und transdisziplinärer Ansatz an diesem Punkt an, um die Fragestellungen aus unterschiedlichen Disziplinen und Akteursperspektiven zu betrachten und über das Spektrum der einzelnen Disziplinen hinaus zu bearbeiten. Beispielhaft für sandige Küsten werden die Inseln Amrum und Föhr als Untersuchungsgebiet ausgewählt. Mittel einer systematischen Literaturrecherche wird ein Einblick in die Entwicklung des Küstenschutzes und sein charakterisierendes Rational gewonnen. Wie dieses in den Köpfen der Menschen verankert ist, wird durch die Analyse durchgeführter, halbstrukturierter Interviews untersucht. Es zeigt sich eine dynamische Entwicklung, die durch das Experimentieren mit verschiedensten Küstenschutzmaßnahmen gekennzeichnet war. Während bewährte Maßnahmen wie der Deichbau oder die Dünenbepflanzung überwiegend als sinnvoll und vorläufig vertrauenswürdig bewertet werden, wird vermeintlich neuen Konzepten wie NbS zunächst oft mit Skepsis begegnet. Sie lassen sich nicht ohne Weiteres in das etablierte Kategoriensystem des Küstenschutzes einordnen. Die strukturierte Analyse und Hinterfragung der Grundannahmen hinsichtlich Küstenökosystemen als NbS zeigt, dass diese eine Chance bieten, bestehende Konflikte zu überwinden. Dank ihrer natürlichen Resilienz stellen NbS ergänzend zum bestehenden Küstenschutz eine nachhaltige Anpassungsoption an den Klimawandel dar. Um das Verständnis von NbS aus einer ingenieurwissenschaftlichen Perspektive zu erweitern, werden durch eine konzeptionelle Analyse die Eigenschaften der NbS, die die ingenieurtechnischen Stellschrauben darstellen, identifiziert und ihre Rolle sowie Wirkungsketten in Bezug auf Leistung, Beständigkeit und Resilienz herausgearbeitet. Um das Verständnis von NbS aus gesellschaftlicher Sicht zu erweitern, wird eine sozialwissenschaftliche Analyse der Kernanforderungen der Küstenbewohner an den Küstenschutz durchgeführt. So können Küstenbewohner NbS in ihr etabliertes Kategoriensystem Küstenschutz einordnen und mit ihren Wertvorstellungen verknüpfen. Küsteningenieuren verdeutlicht das Konzept außerdem die Bedeutung und das Potenzial gesellschaftlicher Aspekte für die effektive Kommunikation und Realisierung von Maßnahmen.

Beide Perspektiven tragen zu einem erweiterten konzeptionellen Verständnis von NbS bei, damit sie als nachhaltige Anpassungsmaßnahmen an den Klimawandel in der allgemeinen Praxis etabliert werden können, und so letztlich zur Re-Diversifizierung des Küstenschutzes für eine erhöhte Resilienz beitragen.

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Glossary

Actor Actors are persons, groups, or organisations acting within a system of interest. (...) Often, the terms ‘actors’ and ‘stakeholders’ are used interchangeably (Buser, n.d.).

Adaptation The process of adjustment to actual or expected climate and its effect. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects (IPCC, 2019).

Angiosperms Seed-bearing vascular plants.

Boundary Conditions In the context of this thesis, the term is understood from the coastal engineering perspective as environmental conditions or environmental forcing, e.g. waves or currents.

Confidence Interval (95% CI) 95% probability that the value lies in the interval.

Diachronic Approach In a diachronic approach, development is described in relation to time.

Dynamics (I) [in physics / mechanics] The study of forces and their effects on motion, in contradictory meaning to statics.

Dynamics (II) [as a characterising feature of people/processes] Driving, advancing force; inner movement.

Ecosystem Properties The size, biodiversity, stability, degree of organization, internal exchanges of materials and energy among different pools, and other properties that characterise an ecosystem (Watson and Zakri, 2003).

Engineering Intervention An anthropogenic (engineering) intervention selectively influences or alters one or more properties of a coastal ecosystem to achieve or trigger a desired effect regarding services, resistance or resilience of the ecosystem.

Gat / Tidal Inlet A strait that is constantly eroded by currents flowing back and forth.

Glycophytes Non-salt-tolerant plants.

Hazard The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources (IPCC, 2019).

Indicator A variable providing specific information on the existence or condition of something.

Interdisciplinarity Cross-disciplinary scientific cooperation and combination and inclusion of methods and ways of thinking from different disciplines.

Key Societal Requests (KSR) KSR make tangible and clarify what requests or demands there are on the part of the coastal population for coastal protection. KSR reveal which values and standards are important to the local society in relation to coastal protection and can therefore play a decisive role in the participatory conceptualisation, planning and communication of future measures, for example incorporating NbS in coastal protection concepts.

Multi-disciplinarity Side-by-side investigation of a scientific question by scientists from independent disciplines, with no significant exchange between the disciplines.

Nature-based Solutions Within the scope of this thesis, Nature-based Solutions are defined as measures that use characteristics and effects of natural features like coastal ecosystems for climate adaptation and to promote nature while simultaneously providing protective, ecological and societal functions or benefits.

Paradigm Shift A dramatic or fundamental change in the framework (basic concepts and practices) of a scientific community or discipline.

Participation Involvement of different actors in collective decisions consisting of different forms like public participation, engagement of civil society as well as co-determination.

Rationale The fundamental reasons serving to account for something, or a reasoned exposition of principles.

Resilience The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation (IPCC, 2019). Resilience is the capacity to recover from eventual damage (Temmerman et al., 2023).

Resistance Resistance is the capacity to avoid damage (Temmerman et al., 2023).

Rhizome Subterranean plant stem.

Risk Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence (IPCC, 2019).

Sandy coasts Sandy coasts are by the classical definition coasts that are characterised by an abundance of sand-size sediments (A. D. Short, 2005). Within the scope of this thesis, the term is understood more broadly to include muddy coasts, which can be located in the immediate vicinity of sandy beaches. Thus, various coastal protection options can be considered for sedimentary differently dominated but coherent and interacting coastal sections.

Scenario A plausible description of how future may develop on a coherent and internally consistent set of assumptions about key driving forces (e.g. rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecast, but are used to provide a view of the implications of developments and actions (IPCC, 2019).

Scleractinian Corals Hard / reef-building corals.

Social Representation (SR) SRs are *'a system of values, ideas and practices with a twofold function: first, to establish an order which will enable individuals to orientate themselves in their material and social world and to master it; and secondly to enable communication to take place among members of a community by providing them with a code for social exchange and a code for naming and classifying unambiguously the various aspects of their world and their individual group history'* (Moscovici, 1973).

Stakeholder *'Stakeholders are people who are influenced by or can influence the activities of others. (. . .) Stakeholders can also be inanimate and can take many forms such as future generations, plants, animals, our homes, or even dead people'* (Franklin, 2020).

Stakeholder Engagement Stakeholder engagement is a strategic management function, that features processes to identify different stakeholder perspectives deliberately and to facilitate interactions and develop relationship to gather representative preference by design. The concept of stakeholder engagement is defined as a process where the organization strategically promotes these values when interacting with stakeholders: representative, transparent, accessible, responsive, and accountable (Franklin, 2020).

Stressor Parameter, process or event that affect humans, animals, vegetation and/or materials. For people, stressors can harm the living conditions (e.g, health conditions or the emotional level in a positive or negative way, or by damages to buildings, infrastructure). Multi-stressors are described as at least two stressors acting in parallel. Multi-stressors can interact with each other.

Sustainability The concept of sustainability is usually based on the three pillars of social, economic and environmental sustainability (Purvis et al., 2019). The IPCC (2019) defines sustainability as a dynamic process that guarantees the persistence of natural and human systems in an equitable manner. In the context of this thesis, coastal protection measures are referred to as sustainable if their existence and functionality as well as their acceptance can be ensured now and, against the background of possible changes, also in the future.

Synchronic Approach A synchronic approach attempts to describe a state, i.e. the relationship of things to a time.

Systems Approach *'The Systems Approach (...) is essentially a way of perceiving and thinking through a problem by identifying and focusing on the critical elements pertaining thereto'* (Chen, 1975).

Tidal Creek / Tidal Channel Tributary watercourse in the mudflats.

Transdisciplinarity An integrative research approach that also involves non-scientific and, in particular, societal actors.

Acronyms

AR Assessment Report

BSH Bundesamt für Seeschifffahrt und Hydrographie

CBD Convention on Biological Diversity

CI Confidence Interval

DKK Deutsches Klima-Konsortium e.V.

DWD Deutscher Wetterdienst

EI Engineering Intervention

EP Ecosystem Property

EPA U.S. Environmental Protection Agency

ES Ecosystem Service

ESL Extreme Sea Level

FAO Food and Agriculture Organization of the United Nations

GCM Global Climate Model

GIZ Deutsche Gesellschaft für Internationale Zusammenarbeit

GMSLR Global Mean Sea Level Rise

IPCC Intergovernmental Panel on Climate Change

IUCN International Union for Conservation of Nature

KDM Konsortium Deutsche Meeresforschung e.V.

KSR Key Societal Request

LKN.SH Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein

MELUND Ministerium für Energiewende, Landwirtschaft, Umwelt, Natur und Digitalisierung des Landes Schleswig-Holstein

MELUR Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein

MHW Mean High Water

MLW Mean Low Water

MN Mean Range of Tide

MSLR Mean Sea Level Rise

MTL Mean Tide Level

NbS Nature-based Solution

NSR North Sea Region

PIANC Permanent International Association of Navigation Congresses

PSU Practical Salinity Units

RCP Representative Concentration Pathway

SLR Sea Level Rise

SR Social Representation

SRES Special Report on Emission Scenarios

SSP Shared Socioeconomic Pathway

UNEP WCMC United Nations Environment Programme World Conservation Monitoring Centre

USACE U.S. Army Corps of Engineers

WWF World Wide Fund For Nature

1 Introduction

Globally, about one third of the ice-free shoreline can be characterised as sandy (Luijendijk et al., 2018; Vousdoukas et al., 2020). Along these sandy coasts[1], healthy coastal ecosystems, such as dunes, coral reefs or salt marshes play important roles with respect to various ecological and societal needs as well as natural protection from coastal hazards (Spalding et al., 2014). In addition to these natural coastal ecosystems and their inherent dynamic processes, however, it is mainly human activities that shape the coastal zone today. In various scientific publications or reports, a multitude of different figures circulate on a wide variety of reference horizons, e.g.

- half of the world's population lives within 60 km of the coast (Morris et al., 2018),
- 1.2 billion people are at flood risk today (United Nations World Water Assessment Programme / UN-Water, 2018),
- the low-lying coastal zone is home to 680 million people today (IPCC, 2019),
- one fifth of the EU population lives within 10 km of the coast (Doswald and Osti, 2011), or
- the North Sea Region is home to 50 million people (Sündermann and Pohlmann, 2011),

but they all document the same fact: the coastal zone is a highly stressed area that will be even more so in the future as a result of human activities (e.g. the low-lying coastal zone will be home to over 1 billion people in 2050 (IPCC, 2019); 1.6 billion people will be at flood risk in 2100 (United Nations World Water Assessment Programme / UN-Water, 2018)).

Fighting over the limited space there is along the coasts, ecosystems have to compete with settlements and cities, ports, industry, fisheries, farming, tourism, recreation and of course coastal protection (cf. Fröhle and Kohlhase (2004)). Coastal protection is the expression of the coastal dwellers' historically grown desire to protect themselves as well as their property to preserve all the values that were created in the coastal zone (Hofstede, 2019a). Ever since the natural dangers of the sea became a technically solvable problem, residential and industrial development on the coast increased, which in turn raised the risk of loss of values in the event of a storm surge and thus again demanded more coastal protection - the so-called 'safe development paradox' (Bulleri and Chapman, 2010; Jakubowski-Tiessen, 2011). So far, in the short term, armouring the coastline has

[1] In this thesis, the term is understood more broadly to include muddy coasts as well (cf. Glossary).

been working well at most locations (J. L. Gutiérrez et al., 2011), and people do feel safe and trust the existing protection (González-Riancho et al., 2015; González-Riancho et al., 2017). Built coastal protection infrastructure usually performs as desired upon completion, but weakens over time and lacks the ability to adapt on its own (Sutton-Grier et al., 2015).

In the light of climate change, the adaptation of the current coastal protection is the pressing issue at sandy coasts around the world. According to IPCC (2019), the frequency, severity and duration of coastal hazards will increase by the end of the century. Due to permanent submergence, land loss, salinisation, ecosystem loss or more frequent flooding, humanity might face the displacement of 1.6 to 5.3 million people and annual coastal flood damages could increase by 2 - 3 orders of magnitude in 2100.
Although there are still some *'coulds'* and *'mights'* in the equation, the tendency is clear. The sea level at the end of the century will be higher than today - no matter which actions are taken (IPCC, 2019). Thus, coastal protection needs to be adapted to these changing conditions. The good news is - not all is already lost. Changes in extreme sea levels (ESL) until 2050 are small, so there is still sufficient time left to adapt (IPCC, 2019). Nevertheless, coastal risks are increasing. As climate change and concerns about its consequences have reached society (e.g. González-Riancho et al. (2015)), this serves as a door-opener in terms of coastal protection adaptation, stimulating discourse about technically feasible and sensible sustainable concepts and solutions.

Coastal ecosystems serving as Nature-based Solutions (NbS) in coastal protection may be some of these adaptive solutions that provide the additional services needed and many more (Bouma et al., 2014). Adaptive measures accept the reality of sea level rise (SLR) (Defeo et al., 2009). Since one can not yet be certain about the changes to come, flexible and adaptive solutions are needed (Koks et al., 2023; Sündermann and Pohlmann, 2011). In order to tackle the challenges opposed upon coastal protection by climate change, local but holistic approaches have to be developed. With sufficient lead time until 2050, relationships and trust with all involved actors in the field should be established and maintained to cooperatively use the required time for the design and implementation of sustainable adaptation strategies (van den Hurk et al., 2022).
Engineered structures will, of course, remain an important part of future coastal protection, but NbS can be a potential complementary, multi-benefit strategy for the coastal protection's adaptation to climate change (Temmerman et al., 2023).

1.1 Motivation

For hundreds of years the forces of the sea have determined life along the coasts. Natural disasters were regarded punishment by a higher power and the experiences with storm surges shaped the collective memory of coastal dwellers (Jakubowski-Tiessen, 2011; Rheinheimer, 2003). At the European coasts, in relation to the feeling of being at the mercy of nature, an important paradigm shift took place from the 17^{th} to the 18^{th} century. Thanks to technical progress in coastal protection, nature, which was seen as an adversary, an opponent of society, could now be fought and dominated (Jakubowski-Tiessen,

2011; Knottnerus, 2005). The North Frisian dogma *'God created the sea, the Frisian the coast'* captures this time of upheaval well and still has an echo to the present day. Comparable to developments in inhabited coastal areas around the world, the German North Sea coast was tamed and a rather cultural than natural landscape developed until today. The dike, which in general perception ultimately made this possible, long represented the main achievement and success story of coastal dwellers dominating over nature (Holzhausen and Grecksch, 2021).
Nowadays, we find ourselves at another turning point or paradigm shift in coastal protection. It was slowly initiated in the 19th century with the aestheticisation of the landscape (Rheinheimer, 2003), and changing societal values in combination with the beginning of the consideration of environmental concerns in the 20th century (Thorenz, 2014). Finally, in the 21st century, the knowledge and recognition of multiple ecological processes and forces that need to be accommodated in coastal protection while also helping it (Brière et al., 2018), led to a lively debated amongst experts, in politics and last but not least in society as a whole about the future of coastal protection. Since it is known today, that the coastal protection heritage is no pure success but also had negative consequences to natural coastal processes (Niemeyer et al., 1996), and it is widely recognised that certain coastal problems are man-made, one solution could be to turn back to nature to learn and benefit from 'natural' coastal protection (Jakubowski-Tiessen, 2011). The Dutch adage *'Don't fight the sea with brute force, but with soft persuasion'* (Bijker, 1996) might represent the new dogma under which future coastal protection should operate, or as Bruun already pointedly captured it in 1972:

> 'By good luck nature has not only demonstrated how to erode but also how to protect. It may safely be said that there is no protection initiated by man which has not beforehand been invented by nature, and nature obtained all the good results as well as all the bad results before man did. Consequently we can learn from nature if we will only make the effort of opening our eyes and looking.' (Bruun, 1972)

Of course, nature-based measures have long been and still are used alongside built structures in coastal protection, but it is only through recent societal developments that people have come to appreciate the benefits beyond coastal protection and are learning to recognise the connections between coastal protection, society and ecology. This multi-faceted character of NbS is very beneficial in an increasingly interconnected world, as interests in the coastal zone become more diverse and competition for the limited space is fierce. Regarding coastal protection, apart from the technical functionality that requires an in depth understanding of the processes and properties of NbS, above all else, the sustainability of adaptation measure is of crucial importance. Sustainability can only be achieved when working aligned with nature, of course, and especially with the locals. Coastal dwellers understand their environment through local and regional experiences and are naturally investigated in its preservation (Döring and Ratter, 2018). A mere information-based policy, however, will not create trust in and openness towards nature-based approaches, since the credibility regarding effectiveness is still much higher towards structural measures than nature-based ones amongst coastal dwellers (González-Riancho et al., 2017). Nor will an information-based policy achieve sustainable support in the long run. Locals need to be truly integrated in the development and implementation of adaptation measures, or as German philosopher Harald Welzer puts it:

> 'Perhaps it would simply be better, instead of offering even more information and knowledge, to think about where the willingness to change is to be found - because it does not lie in knowledge. Such willingness must exist and play a role in people's lives [...]. So, if someone is to set out on the path to change, it simply has to have something to do with him or her, otherwise you can beat him or her like a dead horse.' (loosely translated from Welzer (2019))

The multi-faceted context of the coast requires active collaboration between all involved actors (d'Hont and Slinger, 2022), and adaptation measures can only be successful if they are community-supported and science-based whilst also incorporating local knowledge and experiences (IPCC, 2019). Therefore, this interdisciplinary thesis is set at the interface between engineering and the social. Its motivation is to functionally understand the processes and properties of NbS to facilitate their implementation in a more natural adaptation of coastal protection to climate change - socially accepted and well embedded in the evolution of coastal protection and the development of the coastal society.

1.2 Objective

This thesis provides a theoretical, critical analysis of coastal protection concepts applicable to traditional structural measures and approaches as well as nature-based measures for coastal protection alike. Setting the spotlight on NbS for coastal protection, the basic assumptions of NbS and whether they are reasonable and correct are investigated in depth. The main objective is to expand the conceptual understanding of NbS (and partly coastal protection in general) from an engineering as well as a societal perspective.

On the one hand, in demonstrating the engineering scope in NbS, nature-based approaches become more tangible for coastal engineers, experts and alleged laymen alike. NbS are to be put into context within the existing coastal protection rationale. The adjustable parameters and the underlying and interconnected processes within the coastal ecosystems that can serve as NbS will be elaborated, outlined, and contextualised in engineering terms.

On the other hand, societal concerns represent a central part of coastal engineering. Nevertheless, societal concerns are often neglected and unknown to the discipline of coastal protection. In demonstrating the societal scope in NbS and coastal protection in general, the relevance of societal concerns and requests, and the potential and benefit of societal support will be analysed and highlighted.

For coastal dwellers, the insights of this thesis can help to place NbS within their established image of coastal protection and their coastal environment. An enhanced comprehension of the potential and multiple processes as well as services of NbS, in turn, advances the acceptance of and openness to these 'new' or better different ways of coastal protection. To coastal engineers, nature conservationists and other experts the outcome of this thesis can facilitate them to better place NbS in their professional context and to recognise their scope of action in their work with NbS. In addition, the versatility as well

as the importance and role of societal concerns will be illustrated and made more tangible to them.
As such, this thesis aims to contribute to the diversification of coastal protection in the joint effort of all involved actors in terms of a sustainable, resilient adaptation to climate change (Jongman, 2018; Reguero et al., 2017).

1.3 Structure and addressed research questions

An illustrative overview of the structure of this thesis, that sets out the common thread and places the individual chapters within, is given in figure 1.1.

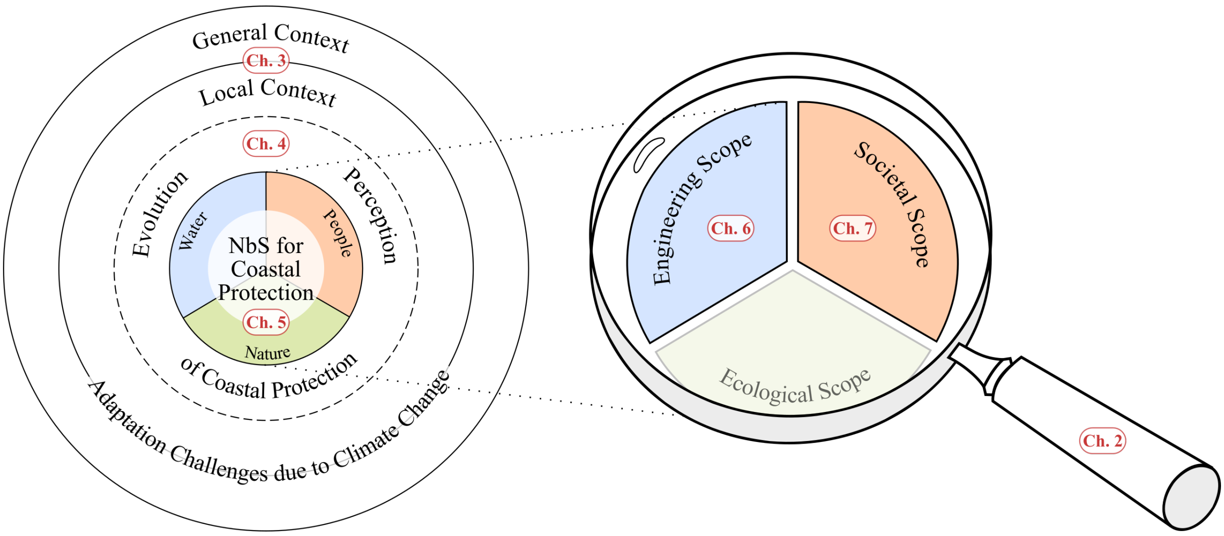

Figure 1.1: Thesis overview and indication of respective chapters with the core of this work under closer scrutiny.

The methodology, underlying each of the following chapters as well as their interaction, is described in chapter 2.

Chapter 3 sets the general as well as the local context, regarding the formation and processes of sandy coasts, and the description of the development as well as the current situation in the investigation area. The chapter closes with the assessment of the most relevant boundary conditions, illustrating which changes are projected and to be expected.

Knowing that current coastal protection is working well but against the backdrop of anticipated changes outlined in the previous chapter, a need for adaptation becomes apparent. Using the investigation area as an example, chapter 4 analyses the historical evolution of coastal protection to learn how changes were handled in the past. In combination and by contrast with an analysis of the perception of coastal protection in the past, present and future, answers to the following research questions will be provided:

- Is the history of protecting the islands against the sea characterised by a rigid and confronting rationale, or can a more dynamic rationale be disclosed that displays a more experimental evolution of coastal protection?
- In what way and to what extent is the prevailing rationale of coastal protection anchored in the minds of the people, and what role do past experiences and memories play in the present?
- What role can the analysis undertaken here play in the context of future coastal adaptation with regard to NbS?

Building up on this analysis, chapter 5 focuses on Nature-based Solutions to discuss whether they represent a promising and inclusive option for the adaptation of coastal protection on sandy coasts. In elaborating which natural coastal ecosystems can serve as NbS in coastal protection, where they thrive, which protective processes they provide for sandy coasts and which benefits they hold for ecology and society, the following research questions are addressed in this chapter:

- How is the relevance of NbS for future coastal protection assessed by experts?
- Do coastal ecosystems as NbS in addition to the existing coastal protection offer a chance to bridge the gap between coastal engineering and nature conservation in the land-sea transition zone?

To help fill some of the still existing gaps and further promote the consideration of NbS for the future adaptation of coastal protection amongst all actors and disclose their potential, chapters 6 and 7 aim at broadening the conceptual understanding of NbS from an engineering and a societal perspective respectively.
In chapter 6 a conceptual framework with regard to the engineering scope in NbS is developed, pertaining to the research questions:

- What properties or characteristics of a NbS are essential for it to **sustainably deliver its services**, and what are the corresponding dependencies between service and properties?
- What properties or characteristics of a NbS are essential for it to **sustainably exist at a location**, and what are the corresponding dependencies between resilience and its properties?

Chapter 7 elaborates upon the societal scope in NbS and coastal protection in general and provides insights to the following research question:

- Which aspects or needs display the key requests the coastal population has for coastal protection, and what are the underlying images or experiences, that shape and define these requests?

Subsequently, the contents and results elaborated in this thesis are discussed in chapter 8. Chapter 9 closes this thesis with a summary of the key findings and a conclusion.

2 Methodology

Parts of the applied methodology described below have already been published in Jordan and Fröhle (2022) and in Jordan et al. (2023).

This thesis adopts an inter- and transdisciplinary approach that allows the issues to be considered and analysed from different scientific disciplines as well as actor's perspectives. This requires a methodology that goes beyond the traditional boundaries of the respective scientific disciplines in order to integrate different perspectives, and to broaden the understanding of Nature-based Solutions in coastal protection.
In the interest of adequately addressing the multi-layered aspects of the research questions mentioned at the outset, a broad spectrum of analytical tools is required. Thus, the research field of NbS for the protection of sandy coasts can be illuminated from different perspectives and by combining these, insights can be generated that go beyond the spectrum of the disciplines involved.
By applying and integrating the various methodologies described hereafter, value is added to better capture the complexity of this research area and expand the conceptual understanding of NbS in coastal protection.

Description of the landscape and relevant boundary conditions, chapter 3

A variety of sources is used to describe the investigation area made up of the two North Frisian island of Amrum and Föhr in front of Germany's North Sea coast. First, the geomorphology of sandy coasts is described on the basis of a comprehensive literature review. This is followed by a description of the study area in particular on the basis of geographical information, a short introductory excursus on the formation of the region as well as geological and geomorphological features on the basis of maps and literature. The analysis of the social and economic situation on the islands is based on publicly available statistical data. The climatic and hydrodynamic boundary conditions relevant to the topic of coastal protection are analysed and processed using historical weather and measurement data as well as model-based forecasts and projections based on the climate change scenarios of the IPCC (cf. IPCC (2019)). Taken together, these analyses and observations provide a sufficiently detailed and comprehensive description of the investigation area and thus serve as a basis for the further procedure of this thesis.

Analysis of the evolution of coastal protection, section 4.1

To zoom in on the analysis, insights gathered through a systematic in-depth reading and content oriented analysis of available written sources (scientific research, project reports, political and administrative documents, and newspaper articles) led to a combined historical-qualitative approach, as it holds the potential to disclose the somewhat diachronic patterns of interpretation and social representations (SRs) pervading past, current and future-oriented mind-sets of coastal protection presently at work (J. W. Creswell and J. D. Creswell, 2018). The next methodological step consisted in the search and analysis of historical sources about measures of coastal protection on Amrum and Föhr. For the historical analyses at hand the seminal works by Müller and Fischer (1937a), Müller and Fischer (1937b) and Stadelmann (2008) were used as these publications offered a saturated and descriptive insight into the past developments of coastal protection on both islands. The historical information gathered from them (cf. appendix B) was visualised to give an overview over the variety of protective measures taken since the 15th century (cf. section 4.1).

Socio-scientific analysis of actors' perspectives on dynamics in coastal protection, section 4.3

Against this historical background, semi-structured interviews with 14 actors deeply engaged in coastal protection in North Frisia were conducted. The interview partners were identified on the basis of existing contacts and knowledge of the sector, by contacting responsible authorities and institutions active in the coastal zone, as well as through personal conversations and recommendations. A semi-structured questionnaire was developed, critically inspected, revised and re-revised after three initial interviews had been conducted (cf. appendix C). Structurally, all interviews began with questions addressing the sense of place (Casey, 1997; Malpas, 1999) or home (Ratter and Gee, 2012) to emotionally and thematically emplace the interviewees and the interviewers. This introductory section was followed by

- queries revolving around the work context of the person interviewed,
- the individual framing and assessment of climate change and its relevance for the local and regional level (Döring and Ratter, 2018),
- an interrogation about the current state of the art of coastal protection in North Frisia in times of a looming climate change and
- the relevance of NbS in this context.

The interview ended with an envisioning exercise where interviewees were asked to imagine the future development of North Frisian Islands within the period of the next 50-100 years against the background of a coming climate change. Interviews lasted between 45 minutes and 1.5 hours, were conducted in places chosen by the interviewees, transcribed verbatim and cooperatively analysed. Once central themes or topics emerged during the investigation, segments of the interview transcriptions were individually grouped in categories. These bottom-up categories were refined and reformulated in the course of the interview analysis with regard to assessing their general meaning, analytical plausibility and empirical relevance for the present work. This procedure contributed to calibrating the coding of interviews (Saldaña, 2015) resulting in a corroborated set of 23 empirical categories (see appendix D for an overview). A final step consisted in selecting those categories which analytically and empirically appeared to be of relevance for tackling the research questions discussed here. Each of the four categories selected was re-analysed with regard to its past, present and future-related visions and reflections about how the coast was, is and should be protected. This displayed a range of interconnected and sometimes opposing experiences and ideas which, besides the well-established rational of diking, brought about ideas and possibilities of how coastal protection can be done differently (cf. section 4.3).

Review of coastal ecosystems as Nature-based Solutions, section 5.2

To assess the potential of coastal ecosystems as NbS bridging the gap between coastal protection and nature conservation while also benefiting societal needs, a comprehensive literature review was conducted (see chapter 5). The review procedure is divided into the steps of (i) data collection, (ii) initial screening and finally an (iii) in-depth analysis of the selected literature.

(i) As search engines for data collection Google Scholar and Scopus databases were chosen. The search was conducted with the search terms 'nature-based solutions', 'coastal protection', 'salt marsh', 'mangrove', 'seagrass', 'beach', 'dune', 'coral reef', 'shellfish reef', and 'oyster reef' as well as all relevant combinations. For this literature review scientific publications such as peer-reviewed journal articles or conference proceedings were considered along with books and book sections, guidelines, reports, policy recommendations or strategies.

(ii) During the initial screening process, literature that was neither relevant to coastal protection nor to ecological or societal benefits of the coastal ecosystems under consideration was eliminated.

(iii) In the final in-depth analysis for each of the examined coastal ecosystems the selected literature was examined and summarised based on the overarching and comparable subjects

- general characteristics of the ecosystem,
- natural (and anthropogenically triggered) development,
- natural distribution,
- distinctive feature (regarding the ecosystem's survival in the land-sea transition zone,
- zonation,
- threats,
- coastal protection processes, and
- ecological and societal benefits.

Assessment of NbS from the coastal protection perspective, section 5.3

In light of this review, 14 of the semi-structured interviews (cf. appendix C) mentioned above were taken for a closer look into the relevance and role of NbS in coastal protection as assessed by the actors (from science and practice or authorities) deeply engaged in coastal protection. The development and structure of the semi-structured questionnaire and the interview procedure are described above. The only modification was that the interviews with actors from the scientific community started without the questions addressing the sense of place, but went straight to the topic of coastal protection asking about its meaning or a personal definition of the term and personal motivation in relation to it.
The further processing of the transcribed interviews was analogous to the procedure described above. During the analysis of the interviews, with regard to the question at hand, segments of the interview transcriptions were individually grouped, resulting in four categories. These categories display the relevance of NbS in coastal protection as evaluated by experts, and the chances as well as the obstacles and limits that are perceived (cf. section 5.3).

The role and potential of NbS in coastal protection from various perspectives

Regarding the role and potential of NbS in coastal protection, decisions have to be based on information contained in various knowledge bases (Garrido-Baserba et al., 2012), such as engineering, society and ecology (the latter of which is not further considered in this work). Drawing on the systems approach, NbS for coastal protection - hence 'the system' - is therefore being considered in parts and the respective interaction and relationships between these parts, the whole system as well as the system's environment are described and analysed (Singhvi et al., 2022). To follow this approach, this way of thinking through a problem, the nature of the goal has to be known. The crucial question then is, which entities and attributes of the system under analysis are being considered, and not whether one is dealing with the total system or just a sub-system or where the system boundary has to be drawn (Chen, 1975). Therefore, for NbS in coastal protection, in accordance with the knowledge bases mentioned above, the choice of *Water*, *Nature* and *People* and the consideration of respective criteria is of main importance.

Identification of the engineering scope, chapter 6

Based on the review of coastal ecosystems as NbS in combination with the relevant boundary conditions, the complicated system of interaction between ecosystems and boundary conditions was deconstructed into subsystems and components (Benmia et al., 2022) in order to compile an item list including all previously identified and coastal protection related

- coastal ecosystems,
- ecosystem properties,
- ecosystem services, and

- boundary conditions.

From this item list, one example of an interaction between a coastal ecosystem and a boundary conditions - e.g. the interaction between a salt marsh and waves - was further elaborated and analysed in detail, in order to identify the key processes, relations and connections between the ecosystem, its properties and services, and the boundary condition (*Downscaling*). The insights gathered through the analysis of this one exemplary interaction, thus, the identified scheme, was then tested on several other single interactions to prove its suitability as well as adaptability. In the final step, the example was then abstracted and transferred back to NbS in general in order to develop a generally applicable concept with regard to the engineering scope in NbS (*Upscaling*). Figure 2.1 illustrates the steps described above in the development of the concept with regard to the engineering scope.

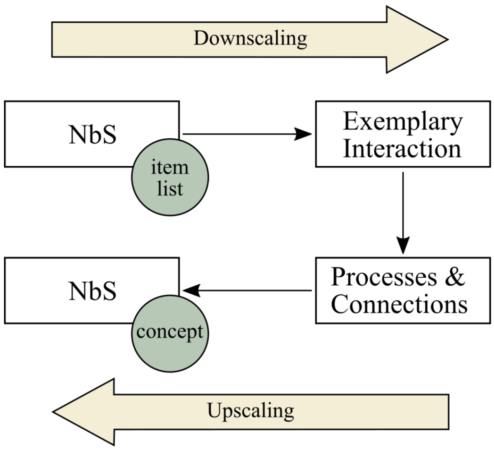

Figure 2.1: Methodology for the identification of the engineering scope in NbS.

Identification of the societal scope: socio-scientific analysis of coastal dwellers' key requests regarding coastal protection, chapter 7

In order to identify the key requests coastal dwellers bare towards coastal protection, 19 semi-structured interviews with people living on the islands of Amrum and Föhr in the investigation area in the North Frisian Wadden Sea were conducted. The interview partners were again identified on the basis of existing contacts and knowledge of the sector, by contacting organisations and institutions active in or around the islands as well as through personal conversations and recommendations. The questionnaire was developed as described in the procedure above in accordance with the other semi-structured interview questionnaire developed within the scope of this work (see appendix C). Structurally, similar to the procedure described above, all interviews began with a question addressing the sense of place (Casey, 1997; Malpas, 1999) or home (Ratter and Gee, 2012) to emotionally and thematically emplace the interviewees and the interviewers. This introductory section was followed by

- further questions on the social and emotional place attachment of the person interviewed,

- the individual framing and assessment of climate change and its relevance for the local level (Döring and Ratter, 2018) as well as personal engagement in relation to climate change,
- an interrogation regarding the knowledge about, experience with and assessment of coastal protection on the respective island and in the wider region and
- the knowledge about and idea of NbS in this context.

Corresponding to the previously described interviews, the interview ended with an envisioning exercise on the future development of the North Frisian Islands against the background of climate change. The interview procedure as well as the analysis were performed accordingly, resulting in a set of 12 key societal requests (see appendix E for an overview). In a final step, five key requests which analytically and empirically appeared to be of relevance for tackling the research questions discussed here were selected, re-analysed, and revealed a range and ranking of what coastal dwellers expect and require from coastal protection - whether in terms of traditional built structures or nature-based approaches (cf. section 7.2).

3 Description of the landscape

Coastal protection is a global issue, but when considering and discussing individual measures, it only works in a local context. Sustainable coastal protection must fit in with the local hydrological boundary conditions as well as the landscape, the natural environment and, last but not least, the local coastal population.
Therefore, this chapter focuses on the description of the landscape as well as social, economic and environmental or natural boundary conditions of the investigation area around the islands of Amrum and Föhr. First, the geomorphology of sandy coasts and relevant formation processes and classifications of coastlines are briefly described. The formation of the North Sea is examined and a description of the existing landscape of the islands, their society and economy is given. The islanders' connectedness with their natural environment, which represents their livelihood, is examined further. In relation to the coastal protection that is necessary to protect this livelihood, existing boundary conditions in the investigation area, which determine the necessary degree of coastal protection at each site, are given. In answering the question, *'which changes regarding these boundary conditions are projected and expected?'*, the need for sustainable adaptations of the islands' coastal protection systems is illustrated. However, it is not only the required protection that depends on these boundary conditions, but also the site conditions for a wide variety of coastal ecosystems, which can be favourable or rather hostile.

3.1 Sandy coasts

Sandy coasts are the interface between land and ocean - the transition zone from the land to the marine environment where morphodynamic effects of the sea meet morphological structures of the mainland and influence each other. Today, in many places these areas of both high ecological as well as (socio-) economic importance are secured and fortified by man-made structures and systems, and coastlines are maintained at great expense. However, there are still sections of sandy coastline that are largely or entirely in their natural state and, despite the absence of anthropogenic coastal protection structures, provide their hinterland with sufficient protection from the forces of the sea.
Sandy coasts are dynamic systems, subjects to constant change. In the course of several tens of thousands of years, changing warm and cold periods as well as sea level fluctuations of over 100 m have led to a variety of coastal forms. Recent events such as the extensive use of the coasts by humans also lead to lasting change of relief norms. Due to continued population growth and migration, the pressure on sandy coasts is likely to increase in the future. In addition to anthropogenic use, the global climate change induced sea-level rise as well as an increase in extreme weather events pose a growing threat that has to be dealt with. Sandy coasts in particular are under severe pressure worldwide. Vousdoukas et al.

(2020) conclude that by the year 2100 almost half of the sandy beaches worldwide could face near extinction.
To protect and preserve these sandy coastlines and the coastal protection they provide, it is required to gain knowledge of the forces and processes that have shaped the relief of today's coastal areas and will continue to do so in the future. The study of these processes is the subject of physical geography, more precisely geomorphology. In the following the processes of geomorphology that underlie the formation of sandy coasts are examined more closely.

3.1.1 Geomorphology of sandy coasts

Geomorphology is the science of the relief of the solid earth and the processes that created it. It investigates how relief forms were created, describes their multitude of forms and finally orders and classifies them systematically.

Processes

Geomorphological forms are the product of endogenous and exogenous processes. Endogenous processes are mainly controlled by the interior of the earth. They are relief-developing and elevating processes that occur on a large scale and over long periods of time.
Exogenous processes describe current processes on the earth's surface that have a relief-reducing effect on geomorphological forms. They cause a finer shaping of the surface forms and are associated with material rearrangements. They include physical, chemical and biological processes that cause the erosion, transport and deposition or weathering of material (Dikau et al., 2019). With the exception of gravity-induced processes, the exogenous forming processes are kept going by the energy supply from the sun (Zepp, 2017).
Impacts on the mainland, which displace material by wind, water and glacial ice, are called aeolian, fluvial and glacial processes. The processes of ocean currents along coasts, wind-induced wave action and tidal sea-level fluctuations, which cause morphological changes in the coastal profiles, are summarised as littoral processes (Zepp, 2017).

Aeolian processes Aeolian processes are geomorphological phenomena caused by the force of wind. Many areas of the earth are characterised by aeolian formation. Wind forces lead to the development of specific surface-reliefs, so-called aeolian forms, which occur mainly in arid regions with little to no vegetation cover. Deserts with sands of small grain size and low soil moisture therefore represent the areas with very high aeolian activity. Aeolian formation, however, also occurs in the sandy coastal regions containing superficial fine sediments but a higher soil moisture (Dikau et al., 2019).
The three main types of aeolian material transport are suspension, saltation and creep. If the shear stress velocity exceeds a threshold value, turbulent eddies can lift sediment particles and transport them as a suspension into the atmosphere, thereby reaching altitudes of up to several kilometres. If the upward component of the shear stress velocity is lower, lifted particles will only move a few centimetres in height, performing a jumping movement, which is called saltation. Particles can no longer be moved through the air

when particle weights exceed certain limits. Thus, coarse sands and gravel move forward rolling, gliding, creeping or in the form of tiny jumps. This transport process is called creep (Presley and Tatarko, 2009).
Aeolian and fluvial processes show certain similarities, since wind and water are both turbulent media. When flowing over a solid surface, forces are transmitted in the interface between medium and material, which allow erosion and subsequent transport of the sediments. However, the density of air is considerably lower (by a factor of about 1000) than the one of water. Therefore, aeolian processes can only transport sediments with relatively small grain size when compared to fluvial processes (Zepp, 2017).

Fluvial processes Fluvial processes are geomorphological phenomena caused by flowing water. They play a significant role, since rivers, streams and rain-induced surface run-off exist in almost all landscapes of the earth. Even in supposedly dry regions such as a desert, fluvial formations, which emerged during past climate phases, can often still be visible (Zepp, 2017).
With solar energy as its driver, the global water cycle, i.e. the exchange and circulation of global water reservoirs, is the decisive force behind fluvial formation. Above the oceans evaporation outweighs precipitation, whereas on the mainland precipitation exceeds evaporation. As a result, rain run-off is usually transported back into the oceans through surface run-off. Although this surface run-off and the run-off in near-surface soil layers only accounts for a small part of the total water resources of the earth, it is crucial for the formation of the earth's relief, as rivers are among the most effective geomorphological systems. It is estimated that 85 to 90 % of today's sedimentary inputs from the mainland to the oceans occur through fluvial systems. In doing so, they produce characteristic fluvial forms such as valleys (Dikau et al., 2019).
In accordance with aeolian transport, fluvial material transport can be subdivided into the transport types solution freight, suspension freight and bed freight. Solution freight describes substances dissolved in water that originate from chemical weathering processes. Depending on the characteristics of the catchment area, the solution freight can have an extremely variable composition. The suspension consists of solid particles of the silt and clay grain size fraction, which are small and light enough to be kept in suspension by the turbulence. Most of the suspension freight is transported near the channel bed. In the bed freight medium to coarse-grained sized particles are transported in fluvial systems, preferably at the river bed by rolling, hopping and sliding processes (Dikau et al., 2019).
Depending on the flow conditions, sand can be transported as bed load or, if prevailing currents are strong enough, even enter the suspension state (Church, 2006).

Littoral processes Littoral processes are closely linked to fluvial and aeolian processes. They are physical processes in the transition zone between the land and the marine environment, which originate from the movement of seawater by waves and currents causing erosion, transportation or accumulation of material. Thus, littoral processes are shaping and reshaping coastlines. The two main drivers behind these processes are wave action and coastal currents (Dikau et al., 2019).

Waves are created when the wind is interacting with the water surface, generating friction which leads to the deflection of water particles. Even without the influence of wind, large individual waves can occur due to volcanic eruptions in the sea or submarine landslides triggered by earthquakes. These so-called Tsunamis, seismically induced single waves, reach enormous heights of up to over 30 m and very high speeds over deep water (Kelletat, 1999).

The wind generated surface waves will be considered in the following. Triggered by the interaction between the wind and the water surface, the water particles perform circular movements, so-called orbital movements, which rapidly decrease with increasing water depth. Wave characteristics, such as wave period, wave height and wave length do not only depend on the strength of the wind but also on the duration of wind exposure and the fetch length. Due to the orbital movement of water particles, the propagation of the wave in deep water is not associated with a net mass transfer. Only when waves approach the coast, and make contact with the seabed at shallower water depths, they transform. The orbital movements flatten until they are completely transformed into horizontal movements, i.e. the oscillation wave transforms into a so-called shallow water or translation wave. The transformation of the wave is also associated with a shortening of the wave length and an increase in wave height, thus a steepening of the wave body. This effect is called shoaling. When a limit steepness is reached, the wave breaks and the water falls forward from the crest of the wave into the wave trough. In the course of this process, large quantities of material can be mobilised.

Breaking waves can have both accumulating and erosive effects. On the one hand, they transport sediments to the shore. Sand and gravel are thrown onto the beach and only partially removed by the reflux. The sediments with larger grain diameters remain onshore and can thus form a beach ridge of several decimetres up to a few metres height. On the other hand, e.g. during major storm events with large wave heights, erosive processes are predominant (Kelletat, 1999). A breaking wave in which the entire amount of energy has been transformed into forward motion, can exert extremely high pressures onto the shore. Through the air, that is trapped between the wave face and the attacked surface and therefore compressed, short-term pressures of over 600 kPa can be generated (Bloom, 1991). These shock pressure values have been recorded against steep seawalls and give an idea of the extreme forces that can be generated. Pressure values against natural sandy coasts are lower but still of significant size and can have extremely erosive effect. Finkl (2004) states that the dissipation of incident wave energy is the most important process which is affecting sandy coasts.

Near-coastal currents represent another type of water movement that influences the coastal formation. Since they are caused by waves, currents along coasts differ from large-scale ocean currents, tidal currents or wind-induced currents. They are divided into currents with an orientation in parallel to the coast and those with an orientation almost orthogonal to the coast.

The latter are the so-called rip currents which arise when waves hit the coast at a right angle and the pent-up water flows back seawards through the surf zone at regular intervals in narrow, strong back currents. These rip currents can reach lengths of 60 to 750 m and flow velocities of up to 1 m/s (Dikau et al., 2019).

Currents with a parallel orientation to the coast are usually caused by waves that hit the coastline at an angle. The waves break at the surf line and the parallel near-coastal currents establish in the surf zone. Those currents can transport large quantities of sediment over long distances and are therefore of great importance for the geomorphological formation of coasts (Zepp, 2017).

Tides represent another crucial geomorphological formation process on coasts. Tides are periodic changes in water levels that can reach amplitudes of up to many metres and last for several hours. Ebb and flood are caused by gravitational and centrifugal forces of the earth and the gravitational forces of the moon and the sun. Due to its shorter distance from the earth, the moon's influence is predominant. In addition to centrifugal and gravitational forces, other factors influencing the tides include obstructions to the inflow of water from rivers and seas into the coastal zone due to high tidal ranges or seasonal winds as well as atmospheric pressure differences (Dikau et al., 2019).
The tides are of such importance for the geomorphological formation of the coasts because they create time-varying wave impact zones due to rising and falling water levels. The tidal stage is the determining factor regarding where other near-shore processes affect the coastline and for how long they interact with coastal landforms (Finkl, 2004). Furthermore, the tidal process is the central control variable for the development of the relief forms of the sea floors and coasts of the world's shallow oceans. At the coasts, the inflowing and outflowing water masses transport sediments and thereby contribute significantly to the development and preservation of the so-called tidal coasts (Dikau et al., 2019).
In coastal areas of major tidal fluctuations, i.e. with a tidal range of more than one metre, there is a wide fringe on flat coasts, which is alternately covered with salt water for many hours a day and then falls dry again for many hours. Due to the shallow water depth, the surf effect is much less effective here than the inflow and outflow of water masses with a short phase of current standstill at the highest water level at the capsize point. These conditions lead to the formation of a special landscape, the mudflats (Zepp, 2017).

Classification

Since the beginnings of the 19th century until today, many different kinds of classifications have been developed and applied to coasts in attempts to characterise dominant features in terms of

- physical or biological properties,
- the shape or form of the land surface,
- the movement of sea-level and land relative to each other,
- the modes of evolution,
- geographic occurrence,
- materials, or
- modifying effects of various processes.

Classification systems range from very broad approaches, such as the simple distinction between open and deltaic coasts at a first stage (Ranasinghe, 2016), to systems with a specific focus, like e.g. the beach morphodynamic classification scheme by Masselink and A. D. Short (1993). For an overview and a discussion of different coastal classification systems see e.g. Valentin (1972) or Finkl (2004).
According to Finkl (2004), most of the existing classifications are specialised rather than comprehensive, since they focus on one or two of the groups, summarising the categories of phenomena that are studied, which he identified as

- processes,
- materials,
- forms,
- age or stage of development,
- and environments.

One example, which primarily focuses on processes (mainly eustatic sea-level rise) and is widely accepted in the field (Dikau et al., 2019; Kelletat, 1999; Zepp, 2017), is the coastal classification approach by Valentin (1952) (see figure A.1 in appendix A). In this classification of coastal forms according to their genesis, it must be borne in mind that not only current geomorphological processes shape the coasts. With the rapid rise in sea level after the last ice age, many reliefs were flooded which were once characterised by other initial geomorphological processes such as fluvial or glacial formations, but are now subject to littoral processes.
Valentin (1952) distinguishes between advanced coasts, which are further subdivided into emerged and build-up coasts, and retreated coasts, which can be divided into submerged and destroyed coasts. Thus, the key factor is the movement of sea level relative to the land and vice versa. Sea-level rise and/or subsidence of the land surface cause the shoreline to advance (transgression) and land to submerge (ingression). On the contrary, a decline in sea-level and/or rising land surfaces cause a retreating shoreline and an emergence of land (regression). Due to the worldwide rise in sea-levels after the last ice age (see 3.2.2), transgression respectively ingression coasts are the most common as well as the most diverse, as various forms of morphological activity have been flooded by the seas (Zepp, 2017).

Finkl (2004) tried to develop a more comprehensive coastal classification system for the whole coastal fringe, a swash zone of 5 to 10 km width across the shoreline. He proposed a bottom-up approach which moves from specific features or forms to increasingly comprehensive categories, integrating many properties that were already included in other classification systems. The major categories in Finkl's classification approach, by which the coastline can be categorised, are

- lithologically controlled morphostructures,

- chronometrically determined morphostructures,
- geodynamic-climatomorphogenic process zones,
- relief types (morphoregions),
- morphogenetic relief features,
- and relief elements and genetically homogeneous surfaces.

Zonation

The boundary layer between land and ocean, the littoral zone, includes the lighted area of the sea that is close to the shore and extends onto the adjacent beach. While the zonation here is mainly driven by water availability (i.e. inundation time), other factors such as wave exposure, light availability, salinity or water temperature also have an influence (Cefalì et al., 2016). Sandy coasts can be subdivided into the epilittoral, supralittoral, eulittoral and sublittoral zones. The epilittoral is located above the waterline in the area of the bank ridges, beach and dunes. It represents the zone free of water influence. The supralittoral or splash zone lies seaward of the epilittoral but still above the high tide line, thus outside the tidal range. This zone is only briefly flooded or splashed during storms and storm surge events. The supralittoral is followed by the eulittoral, also referred to as the intertidal zone. It lies between the high and low tide lines and is essentially shaped by the tides. The tidal flats, for example, form part of the eulittoral zone. The last zone is the sublittoral, which begins seaward of the low tide line where the shelf is continuously covered with water (Küster, 2015; Lalli and Parsons, 2012). All these zones represent different valuable habitats for the existing flora and fauna.

3.1.2 Distribution and current development

Sandy shorelines can be found nearly all around the world. Depending on the type of assessment and the definition of boundaries, regarding what is classified as sandy and what is not, different estimations for the share of sandy coastlines of the overall coastline worldwide can be found in literature, ranging between 20 % (e.g. Finkl (2004)) and 40 % (e.g. Ranasinghe (2016)).
Hagenaars et al. (2018) developed a long-term but local-scale satellite image analysis on shoreline development based on publicly available satellite images. Luijendijk et al. (2018) further developed this method and applied it on a global scale to identify sandy coasts and assess their development over the study period of 32 years (1984 to 2016) with a data accuracy of half a pixel (i.e. 15 m for Landsat imagery with 30 m resolution and a revisit time of 16 years, which the study is primarily based on). They determined that 31 % of the world's ice-free shoreline is sandy. In Europe 22 % of the shoreline can be classified as sandy coast. Figure 3.1 displays the global distribution of sandy coasts. A clear relation with latitude and thus with climate can be recognised. The occurrence of sandy coasts is higher in the subtropics and lower mid-latitudes, while less common in the tropics around

the Equator, where as a result of abundant rainfall and high temperatures muddy coasts and mangroves are common.

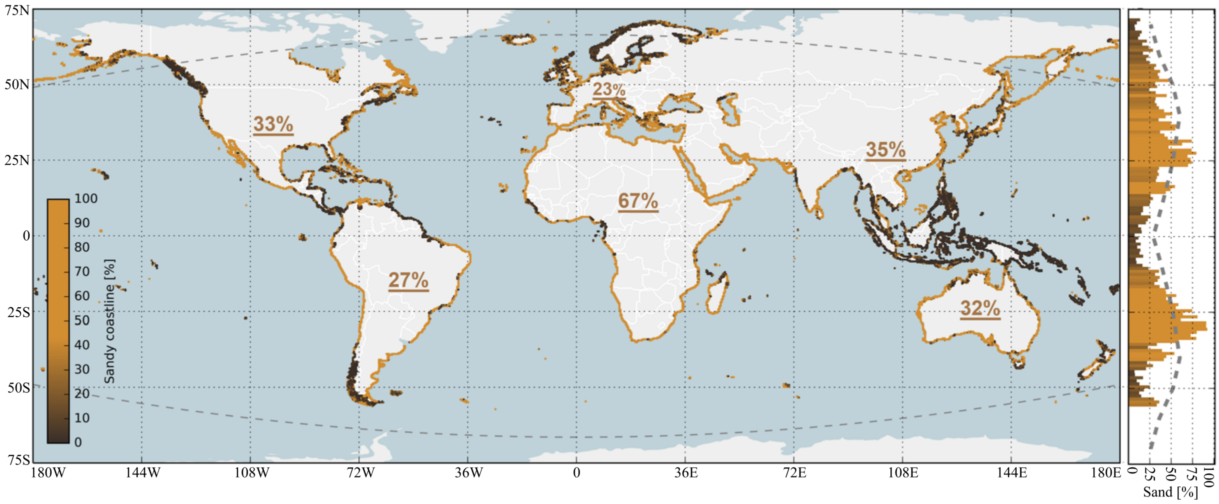

Figure 3.1: Global distribution of sandy coasts. Coloured dots represent the local percentage of sandy shoreline, yellow meaning sand and brown non-sand. The Side-plot displays the relative occurrence per degree and latitude. The given numbers on the continents indicate the percentage of sandy coasts averaged per continent. From Luijendijk et al. (2018), revised for PhD.

Regarding the development of the sandy coasts over the study period, Luijendijk et al. (2018) showed that 24 % of the world's sandy shorelines suffer from chronic erosion exceeding a rate of 0.5 m/yr, while 27 % undergo accretion (including artificial developments and land reclamations, e.g. in China or the UAE). When focussing solely on nature protected areas, the comparatively high percentage of 37 % of all protected sandy coasts is eroding at a rate larger than 0.5 m/yr and 32 % are accreting.

3.2 Investigation area

Parts of this section have already been published in Jordan et al. (2023).

The two German islands of Amrum and Föhr in the eastern coastal region of the North Sea represent sandy islands and serve as the investigation area that is examined in the course of this work.

3.2.1 Introduction

The North Sea is part of the Atlantic Ocean, a marginal sea whose coasts are exposed to the waves and the tides of the open sea. Located in north-western Europe as depicted in figure 3.2 the North Sea is bordered by the island of Great Britain to the west, and the English Channel to the south-west. In the south the mainland coasts of France, Belgium, the Netherlands and Germany follow. The eastern border runs along the German state of Schleswig-Holstein, Denmark, the Skagerrak and Norway's south coast. The northern border along the funnel-shaped opening to the Norwegian Sea runs roughly from the coast of northern Scotland via the Shetland Islands to the Norwegian fjord coast at the height of Ålesund.

Figure 3.2: North Sea basin and bordering countries (base map: `https://de.wikipedia.org/wiki/Datei:North_Sea_map-en.png`).

The water surface of the North Sea is about 575,000 km^2. As a shelf sea, the North Sea largely lies on the European continental shelf. In the southern North Sea there are hardly any locations where the water depth exceeds 50 metres (Küster, 2015). The mean depth however is 80 metres and the maximum depth in the Norwegian Trench reaches up to 800 metres (Sündermann and Pohlmann, 2011).

The bight, stretching from the northern Netherlands along the German coasts of Lower Saxony and Schleswig-Holstein up to the south-western tip of Denmark, is called the German Bight (see figure 3.3). The Wadden Sea extends in front of the entire German Bight. It can be divided into four parts - the Central Wadden Sea or Heligoland Bight at the mouth of the rivers Elbe, Weser and Eider as well as the West Frisian, East Frisian, and North Frisian Wadden Sea. The islands of Amrum and Föhr, belonging to the North Frisian Islands, are located in the North Frisian Wadden Sea in front of the west coast of the German federal state of Schleswig-Holstein (see figure 3.3).

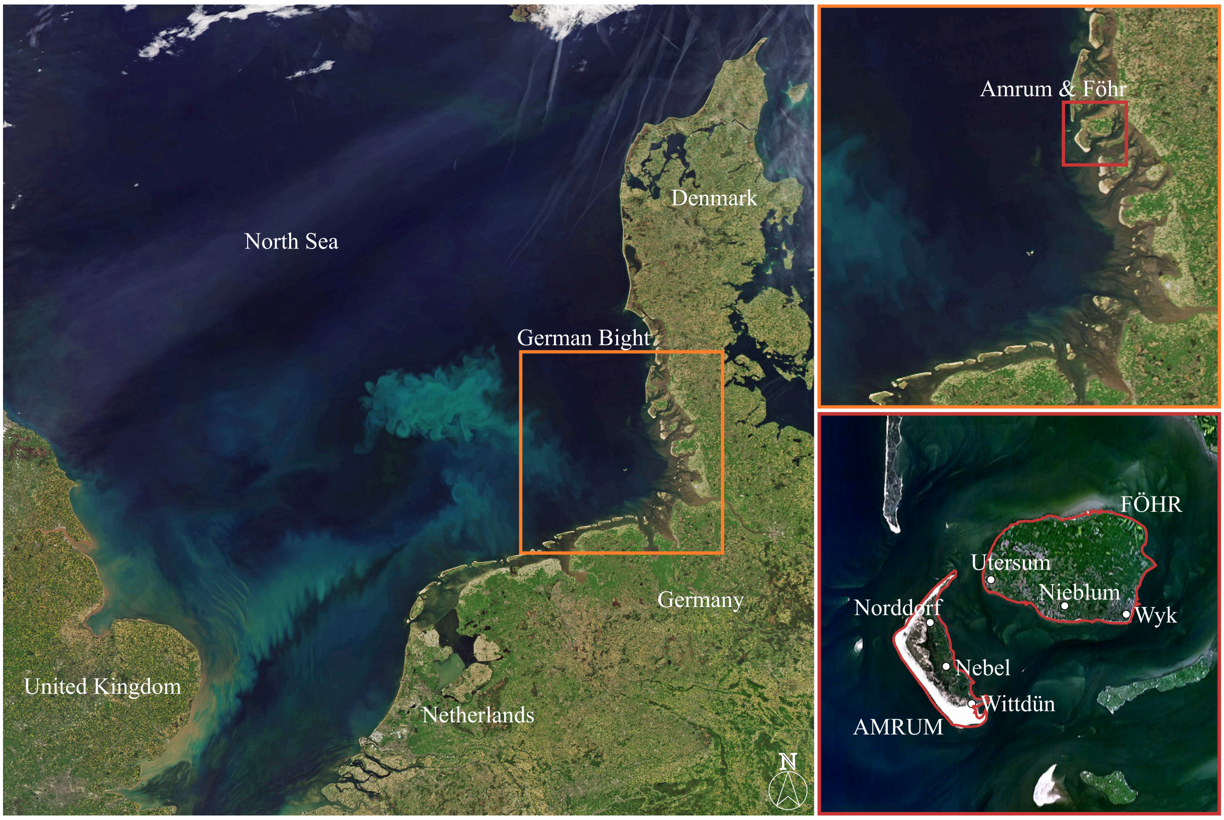

Figure 3.3: Satellite image of the North Sea (NASA Visible Earth, 2018) on the left, the German Bight (NASA Visible Earth, 2018) on the top right and the North Frisian Islands of Amrum and Föhr on the bottom right (NASA, 2020); previously published in Jordan et al. (2023).

3.2.2 Geological formation of the area

Geologically speaking, the formation of the North Sea, as the entire north European region, is shaped by past ice ages and glacial deposits. In the course of the geological development, the area of the north central European shelf sea decreased more and more from ice age to

ice age. Again and again, new debris material was deposited at its edges, causing the area to shrink further (Küster, 2015).
At the peak of the last glaciation, the Vistulian Ice Age about 45,000 years ago, the polar caps alone stored up to 75,000 km^3 of water, causing the sea level to be 100 metres lower than today (Stock et al., 2012). The extent of the North Sea which we see today is a result of the developments after the last ice age. The still dry area of the North Sea Basin, a comparatively flat pleistocene land surface, was flooded by the water released from the ice (Stadelmann, 2008).
Gradually, bogs and forest bordering the coastline were flooded and in the process covered with sediments. These establishes transgression contacts between peat and sediments can be dated back and their height can be determined through radiocarbon determination or pollen analysis, providing the fixed points for the curve of the historic sea level rise in the North Sea Basin. While around 12,000 B.C. the Norwegian Trench was still marking the border between land and sea, around 9,600 B.C. the North Sea already filled most of the northern part of the basin. In the postglacial climate the ice was melting quickly causing a corresponding rise in sea level - between 7,000 and 5,000 B.C. on average 1.25 m per century. Expanding further the North Sea had reached the apron of today's coastline at around 6,000 B.C. (cf. figure A.2 in appendix A). Then, sea level rise decreased significantly and was no longer continuous but from around 3,000 B.C. onward was subjected to fluctuations with altering transgression and regression periods. The average sea level rise per century between 5,000 and 1,000 B.C. was 0.14 m (Behre, 2008).
After the initially rapid rise in sea level, it declined to such an extent that it allowed the relocation of sediments in the area of today's Wadden Sea so that the first wadden areas developed (MELUR, 2015). The origin of the Wadden Sea can hence be dated back some 4,000 years ago, when the rate of sedimentation exceeded sea level rise. Consequently, the formation of the Wadden Sea and the marshland belt began which was triggered through the deposition of finest sediments as well as organic material (Stadelmann, 2008).

Finally, the North Frisian islands of Amrum and Föhr were formed as relics of numerous moderate and some severe storm surges in the Middle Ages.
In the North Frisian region the high moraine cores which later belonged to Sylt, Amrum and Föhr prevented the discharge of inland water into the sea, thus facilitating the development of extensive woodlands or carrs, which eventually transformed into moors and then, by clay depositions above them, into marshlands. Extensive peat cutting, which was later on performed by coastal inhabitants, weakened the marshlands to such an extent that severe storm surges which broke through the outer belt, slowly ripped the landscape apart. (Stadelmann, 2008)
As depicted in figure 3.4, the two storm surges of 1362 and 1634 - the first and the second 'Grote Mandränke' - marked special recesses and caused disastrous land losses which could not be compensated for. Thus, these single disastrous events, in combination with a mass of light and medium storm surges that have occurred over the centuries (Rheinheimer, 2003), ultimately formed the North Frisian Holms and Islands, among them Amrum and Föhr (Thorenz, 2014). The last severe storm surge in 1634 completed the series of major land losses in the Wadden Sea, although other storm tides followed but did not have comparative impacts on the landscape.

Figure 3.4: Changes in the German North Sea coastline through the major storm surges. Coastline before 1362 (left), before 1634 (middle) and around 1800 (right). Modified from Gade and Kohlus (2015).

3.2.3 Prevailing landscape

The islands Amrum and Föhr are embedded in the surrounding landscape of the North Frisian Wadden Sea. Wadden regions or intertidal mudflats can be found all around the world and on almost all continents (cf. Stock et al. (2012)). However, the Wadden Sea - stretching from Den Helder in the Netherlands over a length of 450 km and with a medium width of 7 to 10 km until Esbjerg in Denmark (Stock et al., 2012) - is the largest coherent system of intertidal sand and mudflats in the world and thus listed as UNESCO World Heritage since 2009 because of its outstanding ecological and geological value (Reise et al., 2010).

Characteristics of the Wadden Sea are the dynamics, the worldwide interconnection with other habitats via migratory animal species, and the high biomass productivity (Stock et al., 2012). The mudflats in the North Sea range among the most productive ecosystems in the world in terms of biomass production, comparable with the rain forests of the tropics or coral reefs (Küster, 2015). It is estimated that the Wadden Sea provides habitats for up to 10,000 species of unicellular organisms, plants, fungi and animals (e.g. MELUR (2015) or Hofstede et al. (2019)). All the links of a food web are present in the Wadden Sea, from the producers to the top consumers. This includes unicellular diatoms, bacteria, fungi and higher plants as well as crustaceans, worms, mussels, snails and fish up to seabirds and waders as well as seals and porpoises (Stock et al., 2012). The Wadden Sea is also of increasing importance for the removal of pollutants from the environment, which are introduced into the system via the air and rivers. It serves as a holocene sediment sink, integrating pollutants into the sediment depositions on a long-term basis (MELUR, 2015). Furthermore, the Wadden Sea is of great significance for the coastal protection of the islands and the mainland coast, as it transforms a large part of the energy acting on the coast. Besides its function as a protective habitat, the Wadden Sea also provides the livelihood of many people, such as coastal fishermen or employees in ferry companies or the tourism sector (Hofstede et al., 2019).

Amrum

Amrum, depicted in figure 3.5, is located in the south of Sylt and in the south-west of Föhr, with the west coast facing the open North Sea and the east coast facing the Wadden Sea and the islands and mainland in and behind it. The island is about 14 km long and measures about 4 km at its widest point, resulting in an area of 20 km^2 without and 30 km^2 including the Kniepsand (Amt Föhr-Amrum, 2020). Amrum's coastline is approximately 39 km long.

Figure 3.5: Satellite image of Amrum (modified from base map: `https://cloud.maptiler.com/maps/hybrid/`).

The glacial core of the island has four ridges running from north-west to south-east. Above the moraine core or moraine area of Amrum, which ranks among the highest land ridges in North Frisia (Müller and Fischer, 1937a), there are five different terrain zones from west to east.

- The Kniepsand with its extensive recreational beach,
- the Amrum dunes, which reach heights of up to over 30 m,
- the heathland, which has been gradually reforested with pine trees since the late 19th century slowing down a further penetration of the sand towards the east,
- agriculturally used areas, which were formerly sand-covered heathland, and finally

- the marsh zone, which has formed in the natural bights of the east coast of the island.

The boundaries between the different terrain zones are subject to an incessant change, which can be traced back to both natural as well as anthropogenic influences. Another distinctive coastal feature of Amrum are the two spits, that have formed over the past decades thanks to the constant sand supply by the Kniepsand on both the southern and the northern tips if the island, south of Wittdün and at the Amrum-Odde in the north (Müller and Fischer, 1937a; Stadelmann, 2008; LKN.SH, 2017).

Föhr

Föhr, depicted in figure 3.6, is located between the mainland of Schleswig-Holstein in the east, the island of Sylt in its north-west, and Amrum in its south-west, which, in combination, shelter Föhr from most of the direct influences of the open North Sea. The island is about 12.5 km long and measures about 8.5 km at its widest point, resulting in an area of 82 km^2 (Amt Föhr-Amrum, 2020). The coastline of Föhr is approximately 36 km long.

Figure 3.6: Satellite image of Föhr (modified from base map: `https://cloud.maptiler.com/maps/hybrid/`).

In the surface form of its glacial core, Föhr largely corresponds to the neighbouring Amrum, as it has parallel running valleys between the different ridges. But in comparison to Amrum, Föhr is dominated by agriculturally used areas and cultivated land across almost the whole island. The surface of Föhr consists of about two-fifths of old moraine and three-fifths of marshland. The edge of the moraine area in the south against the marshland in the north is bordered by a series of villages that succeed each other from Wyk via Midlum and Nieblum to Utersum. Two distinctive coastal features of Föhr can be found in the north as well as in the south of the island. In the north, in front of the sea dike, salt marshes have established over a length of around 5 km and with a maximum width of approximately 500 m. In the island's south, in the vicinity of the village of Witsum, there is an original, naturally developed landscape along the small creek Godel, from its spring to its outlet into the North Sea (Müller and Fischer, 1937b; LKN.SH, 2019).

3.2.4 Society and economy

Social History of the North Frisian Wadden Sea Landscape Against the background of the natural history, the socio-historical perspective on coastal protection in North Frisia is to a considerable content based on the dictum 'God created the sea, the Frisians the coast'. This motto refers to those who have fought against the waters coming from the sea, created and maintained the shifting coastline as it exists today and who were and are in charge of coastal protection. Furthermore, and as Allemeyer (2006) and Jakubowski-Tiessen (1992) have shown, diking and coastal protection should always be conceived a part and parcel of a wider social and - sometimes - historical context in which certain social, political, scientific or even religious aspects play a vital role. Dikes were means to tame the sometimes uncontrollable character of the sea while they also offered the possibility to change or partly control the living conditions of those settling in the marshes (Panten, 1992; Steensen, 2020). Furthermore, dikes became and still are a dividing line between the wild and uncultivated sea or nature 'out there' beyond the dike and the cultivated land landward of the dike (Knottnerus, 2021). But they are more, they are regulating devices that contribute to forming and structuring social systems as their maintenance requires a certain degree of social organisation, coherence and institutionalisation which regulated and still organise parts of everyday life in North Frisia (Knottnerus, 1992; Knottnerus, 1996).
In the 18th century, fear of the sea and its storm surges in North Frisia led to an innovation boost during which techniques of building dikes were considerably improved (cf. figure 4.1). A standardisation based on empirical observations and measured data was developed. This progress was accompanied by the development of social security systems which indicate a change in regional cohesion on the one hand and a shift in the prevailing mentality on the other hand: religious interpretations of disasters as willed by god were in a way superseded by preventative human actions taming the consequences of such events (Allemeyer, 2006). Nonetheless, both rationales stand side by side and characterise this transitional period.
Historically seen, these developments led to mottos such as the aforementioned 'God created the sea, the Frisians the coast' or the image of the 'free Frisian' which also refers amongst others to the constant fight of the local population with and against the 'Blanke Hans' (Rieken, 2005; Rheinheimer, 2003). Research revealing the regional and local sense of place or *'Heimat'* (cf. Ratter and Sobiech (2011), Ratter and Gee (2012), Ratter and Philipp (2015), Döring and Ratter (2015), Döring and Ratter (2018), and Döring and Ratter (2021)) shows that even nowadays a deep relationship between the coastal landscape

and its inhabitants, specified in terms of the aforementioned mottos and images, exists.

Today, the region of North Frisia copes with demographic change, a declining agricultural sector and a practically no-longer-existing shipping and fishing industry. The wind energy sector, however, represents a promising area for safeguarding jobs while the whole region economically relies on tourism. Furthermore, aspects of climate change and coastal protection represent current challenges to be managed in the near future as the land behind the dikes often lies below sea-level (Reise, 2015; Hofstede, 2019b). This has been outlined in the governmental strategy for coastal protection (MELUND, 2022) that assesses the state of the art of dikes and develops adaptation measures to be taken for a safe future on the mainland and the islands. Comparable aspects have also been addressed in the so-called Strategy for the Wadden Sea 2100 (MELUR, 2015) representing a cooperative effort to manage and protect the North Frisian Wadden Sea Coast with the national park from possible impacts of climate change (Hofstede and Stock, 2018). For the islands specifically, different reports have been published that assess and aim at improving the current state of the art of protection and adaptation measures against climatic change (e.g. Gemeinde Helgoland (2013) and MELUR (2014)). All these activities are locally negotiated, administratively supported and politically endorsed as outlined in the Climate Protection Concept North Frisia (O. Wagner et al., 2011).
In summary, the district of North Frisia, including the islands, represents a coastal area which was and is deeply marked by its history of diking and storm surges. It displays many characteristics and problems typical for coastal regions and currently prepares to engage and cope on various social, administrative and technical levels with the anticipated risks of an impending climate change.

Municipalities on the islands 2,263 people live on Amrum and are divided between the three municipalities of the island as shown in table 3.1. The oldest still existing settlements are Süddorf and Norddorf, first mentioned in 1464. Nebel, today the largest of the three municipalities, was founded in the beginnings of the 16^{th} century. In the centre of the village there is the church of St. Clemens, which was constructed around 1200 long before the village was founded. Wittdün in the south-east, today's gateway to the island, is the youngest of the three municipalities and was founded in 1890, when a pier and the first hotel were built on the site.

Table 3.1: Municipalities on the island of Amrum and their respective area (Amt Föhr-Amrum, 2020) and population (Statistisches Amt für Hamburg und Schleswig-Holstein, 2020b).

Municipality	Districts	Area [km^2]	Location	Population
Nebel	Süddorf, Steenodde	11.96	central	905
Norddorf auf Amrum	-	5.80	north	570
Wittdün auf Amrum	-	2.61	south-east	788

Föhr, the larger of the two islands, is home to 8,230 people, which are divided between the

11 municipalities as shown in table 3.2. Most of the villages are situated on the edge of the moraine area against the northern marshlands, starting with Wyk in the east followed by Wrixum, Oevenum, Midlum, Alkersum, Nieblum, Borgsum, Witsum and then Utersum on the island's west coast. Some of the still existing settlements date back to the 14th (Utersum) and 15th (Borgsum and Midlum) century. First mentioned in the mid-17th century, Wyk auf Föhr today is the most populous municipality on the island and the only one with town ordinances and privileges, which were obtained in 1910. With the foundation of the seaside resort in Wyk in 1819 the tourism and the heyday of the city began.

Table 3.2: Municipalities on the island of Föhr and their respective area (Amt Föhr-Amrum, 2020) and population (Statistisches Amt für Hamburg und Schleswig-Holstein, 2020b).

Municipality	**Districts**	**Area [km^2]**	**Location**	**Population**
Alkersum	-	9.13	central	391
Borgsum	-	5.47	south	439
Dunsum	Klein-Dunsum, Groß-Dunsum	2.68	west	65
Midlum	-	8.03	central	427
Nieblum	Goting, Bredland, Greveling	7.94	south	569
Oevenum	-	10.53	central	473
Oldsum	Oldsum, Klintum, Toftum	13.12	west	505
Süderende	-	2.61	west	188
Utersum	Hedehusum	5.43	west	398
Witsum	-	1.60	south-west	48
Wrixum	-	7.79	south-east	608
Wyk auf Föhr	-	7.98	south-east	4,222

Economic situation Tourism is by far the main economic sector on Amrum as well as on Föhr. The number of guests and overnight stays has remained at a consistently high level for years. Most recently, before the Covid-19 crisis, the number of arrivals on Amrum in 2019 was over 100,000 and overnight stays almost 860,000. On Föhr nearly 185,000 arrivals and 1,430,000 overnight stays were accounted for in 2019. While on Amrum overnight stays are split between the three municipalities (42 % in Norddorf, 35 % in Nebel, 23 % in Wittdün), 89 % of overnight stays on Föhr are accounted for in the municipalities of Wyk (66 %), Nieblum (13 %) and Utersum (10 %). The remaining 11 % is distributed among the other 8 municipalities (Statistisches Amt für Hamburg und Schleswig-Holstein, 2020a).

Both islands have port facilities. On Amrum the port of Wittdün is used for freight and ferry transport, whereas the port of Steenodde is only used for freight transport. The harbour of Wyk on Föhr is also used for freight and ferry traffic and in addition serves as a fishing harbour and marina for recreational purposes. In all ports the number of ship arrivals tends to decrease slightly. Annual cargo handling is subject to strong fluctuations and no clear long-term trend can be identified (LKN.SH, 2017; LKN.SH, 2019).

The concept of *Heimat* *Heimat*, a specifically German term to which 'homeland' is the closest English approximation, is strongly defined by spatial, social and emotional components. The term encompasses the natural environment, the land- and seascape as well as the social context and the rootedness of the people in question (Ratter and Gee, 2012). Along the west coast of Schleswig-Holstein, in the area of North Frisia and especially on islands like Amrum and Föhr the identification with *Heimat* is strong among residents. The surrounding coastal landscape and the Wadden Sea play a decisive role in the residents' concept of *Heimat*, since people feel a strong connectedness to the natural environment (Ratter and Gee, 2012; Ratter and Sobiech, 2011). As Ratter and Gee (2012) found out in a representative survey conducted among the residents of the west coast of Schleswig-Holstein, the most prominent element perceived as a natural resource by the locals are the Wadden Sea and beaches in the area. Regarding threats to the region, one third named storm surges or climate change as the most prominent one, thus preserving the nature and the landscape of the region also means preserving *Heimat*. 30 % of the local respondents from the survey want to preserve the prevalent nature for future generations, which concludes to the high importance of coastal as well as environmental and resource protection as perceived by the residents.
This sense of *Heimat* is a positive prerequisite for sustainable development strategies regarding future coastal protection (Ratter and Sobiech, 2011). Residents strongly care about the area and are willing to be involved in its preservation. This can and should be used to engage in a joint development of adaptation strategies in order to create sustainable coastal protection solutions for the future, serving protective, environmental as well as social needs.

Heritage site and National Park The cross-border, trilateral Wadden Sea extends from Den Helder in the Netherlands to Esbjerg in Denmark over an area of about 14,000 km^2, making it the world's largest continuous tidal flat area (MELUR, 2015). Starting in 1987, the responsible ministers of the three states have met at regular intervals to advance the protection of the Wadden Sea and develop a trilateral Wadden Sea Plan, in which common environmental goals are set. Since 2009, 11,500 km^2 of this area have been designated a UNESCO World Heritage Site (cf. figure A.3 in appendix A).
In the German part of the Wadden Sea, in addition to the World Heritage Status, the three Wadden Sea National Parks were established. In 1972 the book 'Nationalpark Wattenmeer' by Wolfgang Erz triggered the much-discussed idea, which resulted in a first but unsuccessful draft law for a national park in the North Frisian Wadden Sea presented by the Schleswig-Holstein Ministry of Agriculture in 1973. At the end of 1984 the state government presented a new draft law which, despite a divided response from nature conservation associations and the population, resulted in the establishment of the first Wadden Sea National Park in Schleswig-Holstein on October 1, 1985 - almost 12 years after discussions on the topic had begun. The first national park was soon followed by the establishment of the national parks in the Wadden Sea area of Lower Saxony in 1986 and Hamburg in 1990 (Stock et al., 2012).

Despite the initial difficulties and many conflicts over the national parks, especially in Schleswig-Holstein, the national park has now reached the population and especially the inhabitants of the region. The latest 'SÖM Watt' report (Gätje, 2019), which is based on regular representative surveys among the residents of the regions bordering the national park, concludes that the acceptance of the national park remains high and has ranged between 77 and 93 % since 2002. In the last survey (2018) 85 % of the residents claimed to be proud or to think it important having a national park on their doorstep while only 3 % had a negative opinion of the national park. The protective measures, such as bans on entry, are also rated as 'well acceptable' by over three-quarters of the residents. The visible success of protection measures, the personal, close relationship with nature, and the natural environment as a popular recreational area were cited as reasons for a positive development in opinion towards the national park (Gätje, 2019).
The motto of the Wadden Sea National Parks is to 'let nature be nature'. Thus, the guiding principle of the three states and their federal states, which have committed themselves to the protection of the Wadden Sea, is to achieve an ecosystem that is as natural and self-sustaining as possible, and in which natural processes can run undisturbed (Fröhlich and Rösner, 2015). According to the former Ministry of Energy, Agriculture, Environment and Rural Areas of Schleswig-Holstein (MELUR, 2015), those responsible in the region are acting in line with agreed, long-term development goals, which are

- to maintain the protective function of the Wadden Sea to ensure the safety of the islands and the mainland coast,
- to preserve the islands and holms as essential structures and cultural areas of the Wadden Sea,
- to restore or maintain a favourable conservation status by ensuring the characteristic dynamic development possibilities of habitats,
- to preserve the ecological functions,
- and to achieve a sustainable development beyond the year 2100, ensuring protection and quality of life for the people in accordance with the protection goals.

3.3 Predominant and predicted boundary conditions

Analysing the status quo and discussing possible and plausible future adaptation needs and options, the predominant as well as the predicted boundary conditions in the investigation area need to be taken into consideration. On the one hand, the protection required depends on the boundary conditions prevailing in the investigation area. On the other hand, the boundary conditions also determine the occurrence and thriving of various coastal ecosystems, as they are either supportive or detrimental to their formation.
Regarding the current climate on Amrum and Föhr, measurements from the closest weather station of the *Deutscher Wetterdienst* (German Weather Service) in List on the North Frisian island of Sylt are consulted here. The data from this weather station can be considered representative for the investigation area. Based on measurement values from 1961 to

1990 the mean annual temperature is 8.4 °C, with August being the warmest (mean daily maxima of 19.1 °C to mean daily minima of 16.2 °C) and February the coldest (mean daily maxima of 2.6 °C to mean daily minima of - 1.0 °C) months. The annual mean water temperature, based on measurements from 1988 to 1995, is 10.0 °C. Mean water temperatures are highest in July and August (18.1 °C) and lowest in February (3.3 °C) (DWD, 2021).

The description of climate change as a *'global issue with local impacts'* by Döring and Ratter (2018) is especially true for coastal areas, as the coast is directly subjected to the influences of climate and therefore also to climatic change (Storch et al., 2021). Areas already stressed by human activity and natural extreme events are now further threatened by climate change (EPA, 2017), the impact of which may in turn be exacerbated by human intervention (Storch et al., 2021). Coastal environments are, amongst others, sensitive to changes in air and water temperature, the sea level as well as the frequency and intensity of storms (EPA, 2017). Therefore, climate change - or better yet its effect on the relevant boundary conditions in the investigation area - is of major significance when it comes to the future of coastal protection, adaptation options and the role of coastal ecosystems in this context, i.e. the opportunities they offer or their limitations.

If not mentioned otherwise, the projections of future developments that are discussed in the following for the different boundary conditions are based on the scenarios and pathways defined by the IPCC in the regularly updated Assessment Reports (AR) (IPCC, 2014a; IPCC, 2019; IPCC, 2021a). Per definition by the IPCC (2019) *'Scenarios are a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships'* and *'Pathways refer to the temporal evolution of natural and/or human systems towards a future state'*.

Throughout the years, the IPCC refined and developed the applied and referred to scenarios and pathways. Whereas in reports older than AR5 the SRES-scenarios (Special Report on Emission Scenarios) where applied (IPCC, 2019), the AR5 introduced the so-called Shared Socioeconomic Pathways (SSPs) and the Representative Concentration Pathways (RCPs) in 2014 (IPCC, 2014b). The RCPs *'are a set of time series of plausible future concentrations of greenhouse gases, aerosols and chemically active gases, as well as land use changes'* (IPCC, 2019), whereby RCP2.6 describes a stringent mitigation scenario, RCP4.5 and RCP6.0 cover intermediate scenarios and RCP8.5 describes a very high green house gas emission scenario (IPCC, 2014b). The number given in each scenario title refers to the approximate level of radiative forcing in 2100 relative to 1750 in [W m^{-2}] (IPCC, 2014b; IPCC, 2021b), equal to the change in net radiative flux at the tropopause (IPCC, 2014c). Complementing the RCPs, the SSPs *'describe five alternative socioeconomic futures comprising: sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fuelled development (SSP5)'* (IPCC, 2019).

In the current AR6 five so-called SSPx-y scenarios are introduced, which represent a combination of the former SSPs and RCPs. Thereby, 'SSPx' refers to the aforementioned SSPs 1 to 5 and 'y' to the level of radiative forcing similar to the RCPs. Whereas the AR5's RCPs refer to a baseline period from 1986 to 2005 the baseline period for the SSPx-y scenarios is updated to 1995 to 2014 (IPCC, 2021b). According to IPCC (2021b),

- **SSP1-1.9** implies net zero CO_2 emissions by 2050,
- **SSP1-2.6** implies net zero CO_2 emissions in the second half of the century,
- **SSP2-4.5** slightly deviates from a ‘no-additional-climate-policy’ scenario,
- **SSP3-7.0** is a medium to high reference ‘no-additional-climate-policy’ scenario, and
- **SSP5-8.5** represents a high reference ‘no-additional-climate-policy’ scenario.

In comparison to the former RCPs, where the often applied RCP8.5 represented a worst case rather than a business-as-usual scenario among the no-climate-policies outcomes, the newly introduced scenarios allow for a more detailed and decided consideration of the no-climate-policies scenarios. SSP3-7.0 , which can be ranked between RCP6.0 and RCP8.5, is a middle-of-the-road scenario, whereas SSP5-8.5, comparable to RCP8.5, represents the worst case (Carbon Brief Ltd., 2021).
To enable the comparison of projections which are based on different IPCC scenarios and referred to in the following sections, table 3.3 gives an overview of the current SSPx-y (AR6) and the closest RCP (AR5 and SROCC) and SRES (older than AR5) scenarios from former assessment reports.

Table 3.3: SSPx-y scenarios, closest RCP scenarios and SRES scenarios closest to the assigned RCPs.

SSPx-y	**Closest RCP** (IPCC, 2021a)	**Closest SRES** (IPCC, 2019)
SSP1-1.9	none	none
SSP1-2.6	RCP2.6	none
SSP2-4.5	RCP4.5 (RCP6.0 till 2050)	B1 (A1B till 2050)
SSP3-7.0	between RCP6.0 and RCP8.5	between A1B and A2
SSP5-8.5	RCP8.5	A2

Climate change causes air and water temperatures around the globe to increase throughout the century and further beyond, no matter which scenarios are considered. Subsequently, these changes in water and air temperature cause changes in the boundary conditions examined in the following sections.

For the investigation area considered here, the responsible Schleswig-Holstein Ministry presented the *Strategy for the Wadden Sea 2100* in 2015 (MELUR, 2015), a strategy paper for the adaptation of the Wadden Sea region to climate change-induced alterations of the coastal area. In this strategy paper a moderate and an enhanced scenario are considered for projections of future developments. The moderate scenario ´M’ based on RCP4.5 implies a global reduction in greenhouse gas emissions and predicts changes in air and water temperature of + 1.4 °C till 2050 and + 1.8 °C till 2100. The RCP8.5-based enhanced scenario ´G', which presumes continuing high greenhouse gas emissions, predicts changes in air and water temperature of + 1.8 °C till 2050 and + 3.7 °C till 2100.

Projections of the mean annual temperature change [°C] in the long term (2081-2100) relative to the AR6 baseline period of 1995 to 2014 for the Northern Europe Region (NEU) from the IPCC Interactive Atlas (J. M. Gutiérrez et al., 2021), which was published within the framework of the AR6, are depicted in figures A.4 (based on SSP3-7.0) and A.5 (based on SSP5-8.5) in appendix A. Regarding the SSP3-7.0 scenario, the mean temperature change predicted by the IPCC for the end of the century accounts to about + 4 °C, with a median value of + 3.5 °C for the long-term period between 2081 and 2100 (J. M. Gutiérrez et al., 2021). For the SSP5-8.5 scenario this projected value amounts to just over + 5 °C, with a median value of + 4.4 °C for the same period (J. M. Gutiérrez et al., 2021). Thus, for the directly comparable worst case scenarios, AR6 projections are significantly higher (> 1.3 °C) than those considered by MELUR (2015).

The projections of the mean annual sea surface temperature change [°C] in the long term (2081-2100) relative to the AR6 baseline period of 1995 to 2014 for the Northern Europe Region (NEU) are can also be found in appendix A, represented in figure A.6 for the SSP3-7.0 scenario and in figure A.7 for the SSP5-8.5 scenario respectively.

Regarding the SSP3-7.0 scenario, the IPCC's mean sea surface temperature change prediction amounts to approximately + 3 °C, with a median value of + 2.6 °C for the long-term period between 2081 and 2100 (J. M. Gutiérrez et al., 2021). For the SSP5-8.5 scenario this projected value amounts to almost + 4 °C, with a median value of + 3.3 °C for the same period (J. M. Gutiérrez et al., 2021). Comparing the worst case scenarios considered by MELUR (2015) and in the AR6, projections of the mean sea surface temperature change by 2100 are within close range.

3.3.1 Wind regime

Prevailing wind conditions are a major factor in determining sea state conditions and the severity of storm surges. Therefore, it is important to take a closer look at the wind conditions in the investigation area - more precisely, the measured wind speeds and the relative frequency distribution of the measured wind directions. For this purpose, values from the wind measuring stations Hooge and List (locations, see figure A.8 in appendix A), operated by DWD, are analysed.

The values are available in a temporal resolution of one hour and show the maximum values at wind directions from south-southwest to west-northwest. The peak value at Hooge station was recorded on 28th October 2013 during hurricane Christian with 31.7 m/s from 240° (west-southwestern direction). At List station, the peak value was recorded during hurricane Anatol on 3rd December, 1999 and amounts to 34.7 m/s from 280° (western to west-northwestern direction).

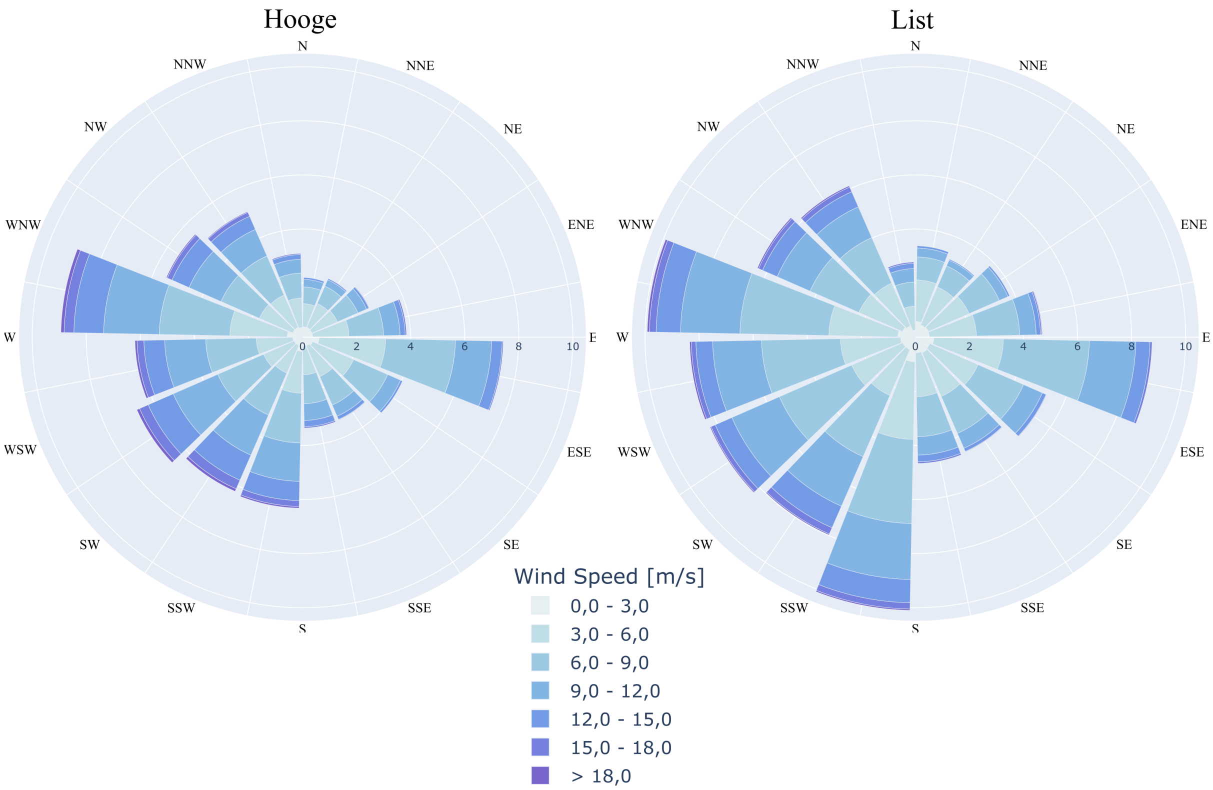

Figure 3.7: Relative frequencies of the daily measurement data of the wind measuring station Hooge (left) for the period 01.01.1969 to 31.12.2020 and of the wind measuring station List (right) for the period 01.01.1950 to 31.21.2020; data provided by DWD; radial axis displays the frequency [%], angular axis indicates the wind direction, colour scheme indicates respective wind speeds [m/s] according to the legend.

Figure 3.7 shows the relative frequencies of wind directions and corresponding wind speeds from hourly measurements. The displayed data was recorded between 1969 to 2020 (Hooge), and 1950 to 2020 (List) respectively. Whereas wind speeds between 0.0 and 6.0 m/s are distributed equally across all directions at Hooge station, higher wind speeds above 15.0 m/s mainly occur from south-southwestern to north-northwestern directions. At List station, lower wind speeds between 0.0 and 6.0 m/s as well as medium wind speeds from 6.0 to 9.0 m/s are also distributed quite equally and occur from all directions. Higher wind speeds from 9.0 to 18.0 m/s also tend to be from westerly directions, comparable to Hooge.

Looking into the future, according to IPCC (2019), wind patterns will be affected by a warming climate, thus wind waves as well. But the results of the changes are not unambiguous. Varies runs of different GCMs predict either an increase or a decrease in extreme wind speeds for the North Sea, ranging from - 1.5 m/s to + 1.5 m/s (Quante and Colijn, 2016), i.e. wind extremes over the North Sea are not necessarily expected to increase (Sündermann and Pohlmann, 2011). The frequency of extreme winds is projected to increase (Sündermann and Pohlmann, 2011). This applies in particular to wind from westerly directions (Quante and Colijn, 2016). Furthermore, the predominant wind directions in the investigation area could shift from south-westerly to north-westerly directions (Sündermann and Pohlmann, 2011). A change in direction can alter the impact of the wind on the generation of waves, even if the speed does not change. A longer fetch, the length over which the wind blows and affects the sea, equals a longer 'working length' for the wind. If the direction changes to north-west, waves could possibly travel in from the Norwegian Sea or the Atlantic and run towards the North Frisian coast.

3.3.2 Sea state

The sea state is another important boundary condition to be considered, since ocean waves, in combination with sea level rise, are regarded as one of the main drivers of coastal hazards (Bonaduce et al., 2019). For example, small waves can cause chronic erosion or large storm waves can have abrupt effects on the coastal landscape (Gedan et al., 2011). The sea state is composed of the superposition of wind waves and the swell. Wind waves are short-crested, irregular waves, which receive direct momentum from wind (Bonaduce et al., 2019). Decisive for their characteristics and development are the wind duration and the fetch. Swell or swell waves are mature, regular waves with longer wave length, which can propagate far across the ocean outside the fetch (Bonaduce et al., 2019). For coastal protection and also for the study of coastal ecosystems, the transformation of the sea state when entering the shallower waters of the coastal zone is of particular interest. By grounding of the waves, the so-called shallow water effects of refraction, shoaling and wave breaking transform the sea state. Natural obstacles or established coastal ecosystems as well as anthropogenic coastal protection transform the sea state by means of diffraction, reflection, transmission and wave breaking.

In the Wadden Sea, the sea state is influenced by the interaction between the topography, local winds and water depth (MELUR, 2015). Maximum wave heights are limited by water depths and new sea states can also develop in the sheltered shadows of islands. Therefore, storm waves are often of local origin and strongly correlate with the prevalent water depth (Hofstede, 2019b). The LKN operates the three measuring buoys Westerland (in 13 m water depth), Süderaue (in 11 m water depth) and Süderhever (in 10 m water depth) - all type directional waverider - in the vicinity of the investigation area around Amrum and Föhr in the North Frisian Wadden Sea (locations, see figure A.9 in appendix A). The operation of the fourth buoy named Rütergat was abandoned in 2013. Rütergat data is therefore not included in the following analysis.

Figure 3.8 shows the relative frequencies of the directions of sea state and the associated significant wave heights for the measurement buoys Westerland, Süderhever and Süderaue. The data shown cover periods between 2012 and 2021 for Westerland, 2008 to 2021 for Süderhever, and 2010 to 2021 for Süderaue.

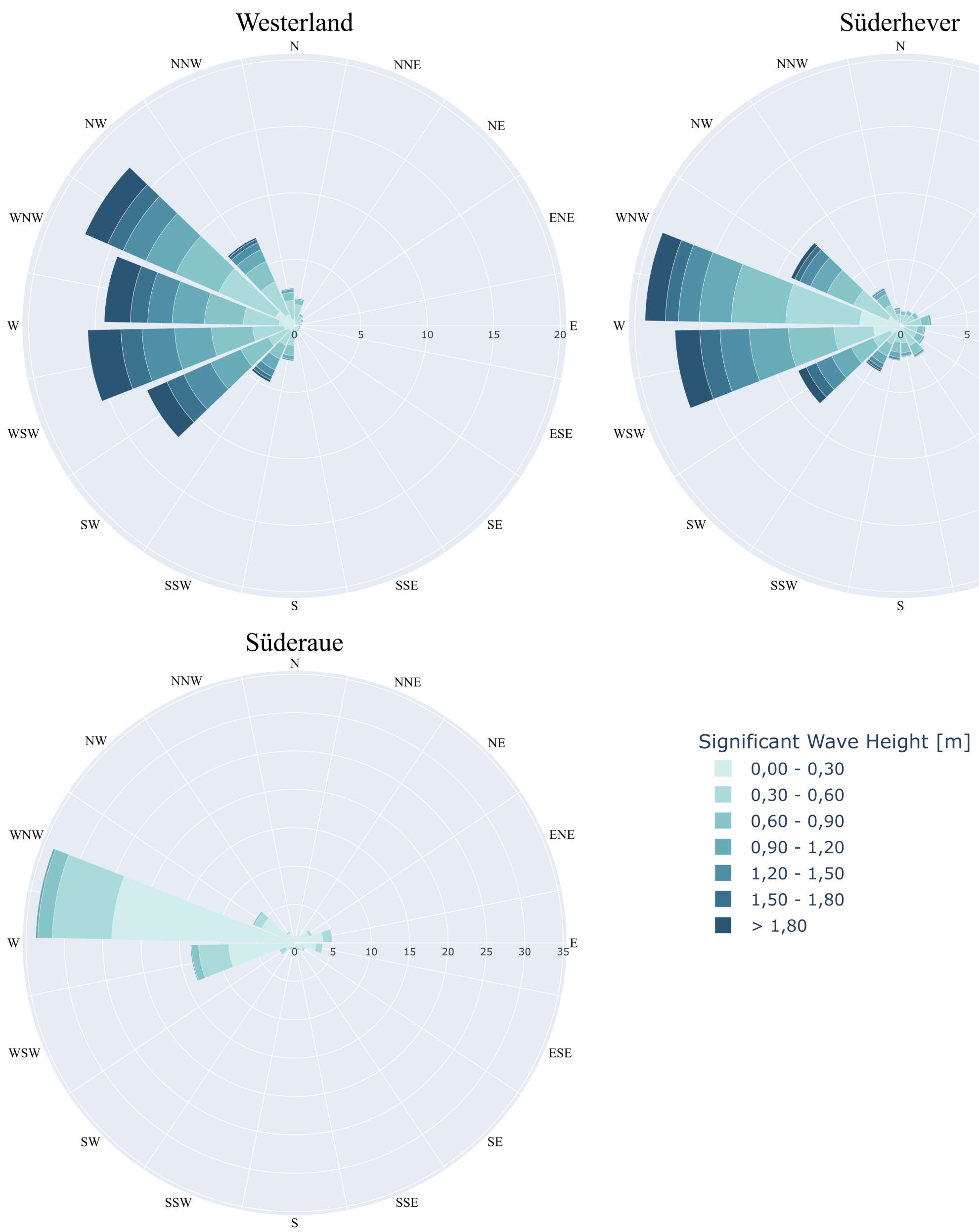

Figure 3.8: Relative frequencies of the 10-minute measurement values of the sea state measuring boys type directional waverider Westerland (top left) for the period 23.07.2012 to 31.12.2021, Süderhever (top right) for the period 21.11.2008 to 31.21.2021, and Süderaue (bottom left) for the period 29.07.2010 to 31.12.2021; data provided by LKN.SH; radial axis displays the frequency [%], angular axis indicates the direction of sea state, colour scheme indicates respective significant wave heights [m] according to the legend.

Westerly directions of sea state are dominant at all the buoys considered. The buoys Westerland and Süderhever are located in the open North Frisian Wadden Sea. Here it can be seen that the sea state from westerly directions can spread unimpeded - between

southwest and northwest at Westerland and west-southwest and west-northwest at Süderhever. The measuring buoy Süderaue, on the other hand, is located in the tidal channel that inspired its name. The bathymetry at this location therefore has a significant influence on the distribution of the sea state, as can be seen in figure 3.8. The main direction of the sea state here clearly corresponds to the course of the tidal channel, which runs from west to west-northwest towards the buoy. Since the location of this measuring buoy can be described as much more sheltered than the Westerland and Süderhever buoys, the significant wave heights measured here are also in a lower range of up to one metre.
The previously described changes in wind directions and changing currents show to what extend the sea state and the direction of sea state are affected by climate change and will develop in the future. In general, severe as well as mean wave heights are projected to have increased by 2100 (Quante and Colijn, 2016). According to Burcharth et al. (2014), significant wave heights in the North Sea will increase by 2 % until 2050 and up to 5 % until 2100.

3.3.3 Water-levels

In terms of coastal protection, the water level is a decisive factor for the required level of protection and at the same time also crucial for the occurrence and thriving of various coastal ecosystems. The water level can be influenced by short- and long-term factors. Various processes can influence water levels locally and globally on different time scales. According to Dangendorf (2015), these processes and the respective time scales include

- tides (hours to decades),
- wind stress (hours to decades),
- ocean circulation and density changes (months to centuries),
- vertical land movement (decades to centuries),
- terrestrial water storage (years to centuries), and
- ice melting (decades to centuries).

Historically, the sea level in the North Sea area was much lower and rose to the current level in the course of the last millennia, as described above in subsection 3.2.2. Over the past century, the average relative sea level rise in the investigated area on the Schleswig-Holstein North Sea coast was 2.2 mm/a between 1937 and 2008 (Jensen et al., 2011; MELUR, 2015). For the more recent past, a significantly higher trend of 4.1 mm/a was determined on average for the Schleswig-Holstein North Sea coast between 1971 and 2008 (Jensen et al., 2011).
In respect of wave climate, the German North Sea coast can be considered as tide dominated (Niemeyer et al., 1996). Thus, the North Sea's dynamics are largely influenced by the astronomical tides (Sündermann and Pohlmann, 2011). Tidal stages are crucial with regard to the exposure of the sandy shore. They determine the location where nearshore processes act on the coast (Finkl, 2004), i.e. where erosion occurs or waves hit

the shoreline. Based on the definition by Davies (1964), the German North Sea coast can be classified as either high meso- or low macro-tidal (Niemeyer et al., 1996; Passeri et al., 2015), depending on the exact location. The Mean High Water (MHW) on the west coast of Schleswig-Holstein rose by 3.8 mm/a or a total of 0.26 m between 1940 and 2007 (MELUR, 2015). Overall, it can be observed that the relative MHW on the German North Sea coast rose from 1950 to 2015 while the relative Mean Low Water (MLW) changed only slightly. As a result, the mean tidal range increased by up to 10 % during this period (DKK and KDM, 2019), and at some measuring stations, such as Wyk on the island of Föhr, the tidal range increased by more than 11 % between 1958 and 2014 (Jänicke et al., 2021).
Tide gauges have existed and have delivered continuous water level measurements on the islands of Amrum and Föhr since 1936 at Wittdün (Amrum) and 1941 at Wyk (Föhr) respectively (LKN.SH, 2017; LKN.SH, 2019). The different tidal parameters for the tide gauges Wittdün and Wyk as well as historic high water levels are listed in table 3.4. The mean high water (MHW) at the Wittdün gauge (between 2001 - 2010) is PN + 6.27 m, whereas PN or PNP at this tide gauge is the equivalent to NHN+5m. The corresponding mean low water (MLW) is PN + 3.66 m, resulting in a mean range of tide (MN) of 2.61 m. At the Wyk gauge the MHW for the same period accounts to PN + 6.36 m and the MLW to PN + 3.54 m. This results in a MN value of 2.82 m at Wyk.

Table 3.4: Tidal parameters - 1996 to 2005 after LKN.SH (2017), 2001 to 2010 after MELUR (2015) - and historic high water levels (MELUND, 2022; MELUR, 2015) for the tide gauges at Wittdün on Amrum and Wyk on Föhr; MHW = mean high water, MLW = mean low water, MN = mean range of tide, MTL = mean tide level.

	Wittdün		**Wyk**	
	1996 - 2005	2001 - 2010	1996 - 2005	2001 - 2010
MHW	PN + 625 cm	PN + 627 cm	PN + 634 cm	PN + 636 cm
MLW	PN + 362 cm	PN + 366 cm	PN + 351 cm	PN + 354 cm
MN	263 cm	261 cm	283 cm	282 cm
MTL	PN + 494 cm	PN + 497 cm	PN + 493 cm	PN + 495 cm
16./17.02.1962	PN + 914 cm		PN + 931 cm	
03.01.1976	PN + 905 cm		PN + 938 cm	
24.11.1981	PN + 908 cm		PN + 952 cm	
26.01.1990	PN + 879 cm		PN + 936 cm	
28.01.1994	PN + 877 cm		PN + 889 cm	
06.12.2013	PN + 871 cm		PN + 888 cm	

Changes in tides can have multiple reasons. According to Haigh et al. (2020), regional and global mechanisms that change the tides, can be driven by tectonics, shoreline position, sea ice coverage, seabed roughness, ocean stratification and internal tides, non-linear interactions, radiational forcing as well as water depth. The latter being the main driver behind short-term changes in tides.

Sea level rise There is consensus among experts and institutions worldwide that with SLR the risk of flooding and flood related disasters will increase in numerous regions around the globe (see e.g. Arns et al. (2015), Hinkel et al. (2014), IPCC (2019), IPCC (2021b), Passeri et al. (2015), Temmerman et al. (2013), and Vousdoukas et al. (2020)). Effects of SLR that can be witnessed immediately are increased flooding, submergence of low-lying landscapes as well as salt water intrusion into coastal surface waters. Long-term effects, on the other hand, will be the erosion of shorelines and salt water intrusion into the ground water (Passeri et al., 2015).
Causes for the global mean sea level rise (GMSLR) are manifold, but the IPCC (2019) states with *'high confidence'* that anthropogenic forcing is the dominant cause. Global warming, on the one hand, leads to the thermal steric expansion of the oceans (DKK and KDM, 2019; Grinsted et al., 2015). Due to this thermal expansion, sea levels will even rise if the ocean mass would remain constant (IPCC, 2019). Major uncertainties regarding the thermal expansion in the deep sea still lead to wider ranges in GMSLR projections (Reise, 2015). On the other hand, global warming leads to the loss of land-based ice mass (Grinsted et al., 2015). The sum of glacier and ice sheet melting is projected to pose the major contribution to GMSLR in the future (Hinkel et al., 2014; IPCC, 2019) and to be the cause for its acceleration (DKK and KDM, 2019). Comparing, for example, the periods from 1997 to 2006 and from 2007 to 2016 according to DKK and KDM (2019), the loss of land-based ice mass doubled in Greenland and tripled in Antarctica. For future SLR the Antarctic ice sheet still bears a main uncertainty (Hinkel et al., 2014; Reise, 2015) - for northern Europe the fate of Antarctica poses the dominant uncertainty (Grinsted et al., 2015). Vertical land movement is one of the non-anthropogenic forcing behind SLR (IPCC, 2019). This process is also of relevance in the southern North Sea. As a result of the missing weight of former land ice (from the last ice age), Scandinavia is rising while vertical crust movements in the German Bight are negative and therefore correlate with SLR (DKK and KDM, 2019; Quante and Colijn, 2016).
A stabilisation of the sea level at some point is of course possible but not probable (Mengel et al., 2018). Even if the global rise in temperatures can be slowed or the trend actually reversed, sea levels will continue to rise throughout this century and for the centuries to come, due to the slow response times of processes such as thermal expansion or glacial melting (IPCC, 2019; IPCC, 2021b; Mengel et al., 2018). Thus, SLR-driven physical impacts will also manifest themselves as long-term impacts (Ranasinghe, 2016).

As stated by the IPCC with *'high confidence'*, the global mean sea level rose faster in the last century than in any other century before over the last three millennia - in fact GMSLR amounted to 0.20 m from 1901 to 2018 (Fox-Kemper et al., 2021). GMSLR is accelerating as measurements from tide gauges around the world show (cf. IPCC (2019) and IPCC (2021b)). Nerem et al. (2018) determined a climate change driven acceleration of GMSLR of 0.084 mm/yr^2 and a probability of the acceleration being zero of less than 1 %. According to IPCC projections from the SROCC (IPCC, 2019) with a correction regarding the baseline period, GMSLR under the RCP8.5 scenario accounts to 0.81 m by 2100 relative to 1995 - 2014 (Fox-Kemper et al., 2021). After AR6 of the IPCC (2021b), it is likely that GMSLR by 2100 lies between 0.63 and 1.01 m under the SSP5-8.5 scenario (very high greenhouse gas emission scenario) and between 0.98 and 1.88 m by 2150. Extremes such as a GMSLR of 2 m by 2100 are considered unlikely, but cannot be ruled out completely due to the uncertainties concerning the future of Greenland's and Antarctica's ice sheets (IPCC, 2021b).

Sea level rise, of course, is not globally uniform but regionally variable within a range of ± 30 % around the global mean value (IPCC, 2019). The reasons are varying influences of land ice loss, variations in ocean warming and ocean circulation, vertical land movements (as stated above) or local human activity. The projections of the sea level rise [m] in the long term (2081-2100) relative to the AR6 baseline period of 1995 to 2014 for the Northern Europe Region (NEU) from the IPCC Interactive Atlas (J. M. Gutiérrez et al., 2021), which was published within the framework of the AR6, are depicted in figures A.10 (based on SSP3-7.0) and A.11 (based on SSP5-8.5) in appendix A. Regarding the SSP3-7.0 scenario, the SLR predicted by the IPCC for the end of the century accounts to about + 0.48 m, with a median value of + 0.4 m for the long-term period between 2081 and 2100 (J. M. Gutiérrez et al., 2021). For the SSP5-8.5 scenario this projected value amounts to approximately + 0.57 m with a median value of + 0.5 m for the same period (J. M. Gutiérrez et al., 2021).
Looking more closely at the investigation area, DKK and KDM (2019) state that the absolute sea level change on the German coast is close to the global average. Regional sea level projections by Grinsted et al. (2015) predict a median 21st century rise of 0.8 m near London and Hamburg, being located a little further inland from the North Sea coast at two of the major estuaries. Based on past developments and an accelerated SLR in the Wadden Sea area (cf. Becherer et al. (2018), MELUR (2015), and WWF Deutschland (2018)), Becherer et al. (2018) consider a strong acceleration in SLR in the 21st century as *'highly probable'*.
Two possible responses to SLR and the changes that come along with it are mitigation on a global level, and adaptation on a regional or local level. The Wadden Sea, within which the investigation area is located - or better said some of its ecosystems such as the mudflats and even more the salt marshes - bear a certain adaptation potential of their own. Through the accretion of sediments they can grow in height and keep up with a moderately rising sea level (Fröhlich and Rösner, 2015; MELUR, 2015). However, a constant sediment supply and huge amounts of sediments are needed for the whole Wadden Sea to compensate for SLR (Hofstede et al., 2019), and the accelerated SLR poses an additional threat, as vertical accretion fails to keep pace at a certain threshold (Kirwan and Temmerman, 2009; MELUR, 2015).

3.3.4 Morphodynamics

Morphodynamics describe the development of bed structures through accretive and erosive processes, i.e. accumulation and erosion. In coastal areas morphodynamics are highly complex and dependent on various different factors such as flooding frequency and height, sediment concentration in the water, prevailing winds, currents and the intensity of storms, or even the presence of vegetation (Wöffler, 2016). Figure 3.9 depicts a digital terrain model of the investigation area around the two islands from 2016. The base map was created in the EasyGSH project based on a 10 m grid. Typical geomorphological features like the islands' moraine cores, tidal flats, tidal creeks, gats as well as the man-made dikes are highlighted.

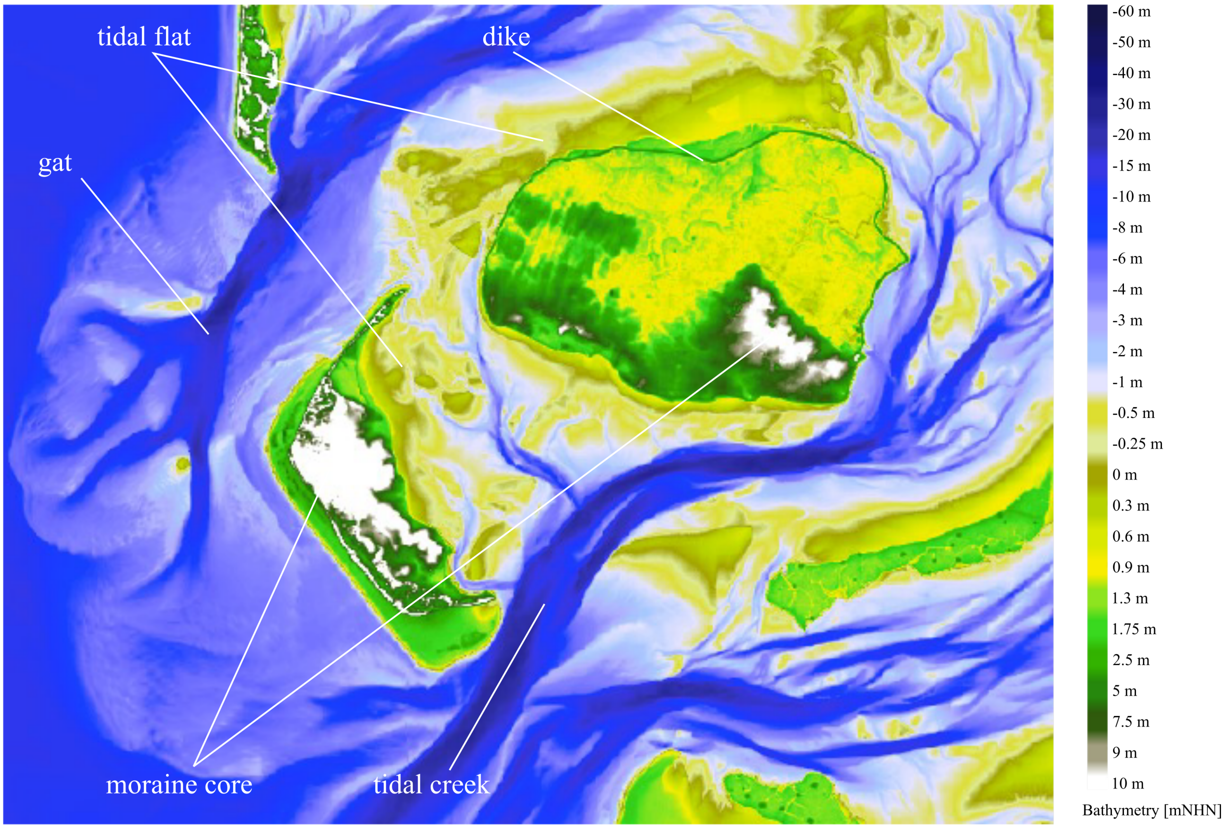

Figure 3.9: Digital terrain model of the investigation area around the islands of Amrum and Föhr with exemplary designation of the main geomorphological features; detail of the digital terrain model of the German Bight from the EasyGSH project (base map: `https://mdi-dienste.baw.de/terria/`).

Regarding the current morphodynamics in the investigation area, the west coast of Amrum - the Kniepsand - is highly dynamic. In their study on the state of the world's beaches Luijendijk et al. (2018) rank Amrum as one of the erosive sandy beach hot spots of the world. According to MELUR (2015), between 1948 and 2008, rates of recession of several metres per year on the NHN +1 m line were observed on Amrum's outer coast in the west. Due to the strong interaction of morphodynamic processes and developments with many other processes in the investigation area, sea level rise plays a decisive role for the future development of morphodynamics in the entire Wadden Sea and the investigation area. The question is, whether coastal areas can increase in elevation through sediment accumulation and keep up with SLR, or whether areas that still regularly dry out today will be permanently flooded in the future. The previously described increase in tidal range, which can already be observed today, is also highly relevant for the transport capacity of sediments and thus for the development of morphology (DKK and KDM, 2019). In order to be able to make qualitative statements about the adaptability of specific beach ecosystems or salt marsh ecosystems in the foreland of the islands, or specific areas where such ecosystems can be established, site-specific studies on sediment accumulation and its spatial variability are needed.

3.3.5 Storm surges

The term storm surge does not refer to a single high water level, but always to an entire event - a certain period of time with high occurring water levels (Petersen and Rohde, 1991). In terms of natural disasters, storm surges represent the most serious threat in the North Sea region (Sündermann and Pohlmann, 2011). According to Ratter and Gee (2012), this threat is still perceived as such by the coastal residents in the Wadden Sea region today.

The various factors that influence the formation and development of storm surges are tides, external surges, coastal bathymetry and meteorological variables such as wind direction and wind speed (Gedan et al., 2011; Gönnert, 2003; Wöffler, 2016). With regard to the influence of wind direction and speed, the fetch plays the decisive role. In the investigation area, this is greatest when the wind blows from the north-west. Then an impulse can be carried into the water body over the entire distance from the Arctic Ocean to the North Sea. The meteorological effects are mainly influenced by the properties of the low-pressure areas that cause them, i.e. the pressure differences and trajectories of the intense low-pressure systems. According to Petersen and Rohde (1991), based on the trajectories, there are three types of intense low-pressure systems passing and thus affecting the North Sea area:

- **Jutland type**: The trajectories of the Jutland type run from west to east, from central England across the North Sea and finally between 55 and 57 degrees latitudes across Jutland. These fast-moving lows cause strong storms for a short time.
- **Scandinavia type**: Scandinavian-type low-pressure systems move south-east from Greenland and Iceland and cross Scandinavia between 60 and 65 degrees latitude. It often happens that these lows settle, producing very long-lasting north-westerly storms for the entire German North Sea coast.
- **Skagerrak type**: The Skagerrak-type lows run between the trajectories of the two aforementioned. They usually move from west-north-west to east-south-east.

Storm surges can be classified either on the basis of mean annual exceedance numbers of certain water levels after DIN 4049-3 or on the basis of water level exceeding the MHW according to BSH (2021). Both systems divide into (minor) storm surges, severe storm surges and very severe storm surges. The boundary values for each of the three classes are given in table 3.5.

In the past as well as today, storm surges were perceived as a normal, natural phenomenon in the investigation area as well as, of course, along the entire North Sea coast, but at the same time often constituting special incisions of local or regional significance (Rheinheimer, 2003). In contrast to today, the severity of a storm surge used to be assessed not by

Table 3.5: Boundary values for the classification of storm surges in the German North Sea by (i) mean annual exceedance numbers after DIN 4049-3 and (ii) water levels exceeding the MHW (BSH, 2021).

DIN 4049-3	**BSH (2021)**
Minor Storm Surge	**Storm Surge**
10 to 0.5	1.5 to 2.5 m above MHW
Severe Storm Surge	
0.5 to 0.05	2.5 to 3.5 m above MHW
Very Severe Storm Surge	
< 0.05	> 3.5 m above MHW

the maximum water level that occurred but by the damage caused (Rheinheimer, 2003). Storm surges and the associated damage were one of the most important drivers of coastal protection measures for centuries. In some locations damage occurred only rarely, making individual consequences and measures necessary, while other locations were particularly exposed to the forces of the North Sea storm surges. In the examined investigation area, for example, large waves develop in the Norderaue inlet, hitting the south coast of Föhr, which therefore has been prone to erosion for decades or even centuries (Ehlers, 1988). Tables 3.6 and 3.7 give a selection of well documented past storm surge damages and effects on Amrum and Föhr respectively.

Table 3.6: Damages and events that occurred during and/or due to past storm surges on Amrum based on Müller and Fischer (1937a) and Stadelmann (2008); Locations: S Kniepsand = southern Kniepsand.

Year	**Location**	**Damage or Event**
1825	Risum	Dune breach in February
1914/1915	Wittdün	Severe damages to the sea wall in winter
1926/1927	*not specified*	Storm surge damages
1937	Wittdün	Severe damages at the sea wall in October
1954	Odde	Dune breach in January
1962	Norddorf	Dike breach at Norddorfer Marsch
1962	Nebel	Damage to several houses
1962	Wittdün	Dike breach at Wittdüner Marsch
1973	Wittdün	Damages at the northern sea wall in autumn
1976	Nebel	Damage to several houses
1976	Dunes & S Kniepsand	Breach of the sand dam
1981	Dunes & S Kniepsand	Breach of the sand dam
1994	Wittdün	Severe damages at the DRK revetment in January

Historically, periods of greater storm intensity have occurred before, for example during the so-called little ice age, which began between the 14^{th} and 16^{th} century and lasted until about 1850 (Rheinheimer, 2003). Looking into the future, taking into account various projections and reports, the question arises whether the North Sea region might be facing such a period again.

According to Quante and Colijn (2016), changes in ESL can be either driven by changes in particular atmospheric conditions or by sea level changes averaged over time, since these simply change the baseline onto which extremes such as storm surges are added. The latter has been the predominant factor over the past 150 years (Quante and Colijn, 2016). Future projections also predict rising sea levels for the NSR. Thus, higher loads on natural features as well as built structures (Hofstede et al., 2019) due to higher storm surges, but not necessarily new or higher extremes (Sündermann and Pohlmann, 2011). Regarding changes in storm surge water levels in addition to mean sea level rise (MSLR), thus driven by other atmospheric factors, ESLs statistically increase with rising CO_2 emissions (Lang, 2020). Arns et al. (2015) predict a rise in storm surge water levels in the shallow Wadden Sea areas of up to 15 cm, which might be attributable to a shift in prevailing wind directions (Lang, 2020; Sündermann and Pohlmann, 2011) or a strengthened north Atlantic storm belt (Lang, 2020).

Globally, MSLR will lead to an increase in the frequency of ESL events (IPCC, 2019), storms will also occur more frequently in the North Sea (Calafat et al., 2022; Sündermann and Pohlmann, 2011). Technically speaking, the frequency distribution of storm surges is predicted to shift to a higher base level, thus storm surges of given heights will shift to a shorter return interval (Arns et al., 2015). For example, a 100-year event of today will be much more common by 2100 - under all considered RCPs (IPCC, 2019). In global context, the IPCC (2021b) states with *'high confidence'* that 100-year ESL events will occur annually at over half of all examined tide gauge locations by 2100. More specifically, regarding the investigation area around Amrum and Föhr, ESLs are expected to increase over a wide range of return periods along the west coasts of Denmark and the Federal State of Schleswig-Holstein (Lang, 2020).

Table 3.7: Damages and events that occurred during and/or due to past storm surges on Föhr based on Müller and Fischer (1937b) and Stadelmann (2008); Locations: W Dike = western Dike, N Dike = northern Dike, NE Dike = north-eastern Dike.

Year	**Location**	**Damage or Event**
1717/1720	W, N, NE Dikes, Näshörn & Wyk	Destruction of the dikes
1791	W & N Dike	Damages at the dikes
1796	Näshörn	Foreland near Kuham breaks off
1824	W, N, NE Dikes, Näshörn & Wyk	Damages at the dikes in autumn
1825	W Dike	Several ground failure; dike partly washed away
1825	NE Dike, Näshörn & Wyk	Several dike breaches
1833	NE Dike, Näshörn & Wyk	Severe damages at the dikes
1833/1834	W & N Dike	Several damages in spring, autumn and winter
1895	W & N Dike	Severe damages at the dikes in December
1909	Wyk	Destruction of the wall at Boldixumer Südstrand
1917	Wyk	Severe damages, especially off Boldixum
1923	Wyk	Partly destroyed concrete cover in front of Oldenhörn in August
1928	Wyk	Severe damages at the Wyk sea wall in October
1936	NE Dike, Näshörn & Wyk	Damages at the dikes in October
1953/1963	Goting Cliff	Bank erosion by 20 m
1954	Greveling	Washout in the Greveling dike
1962	W & N Dike	Damages at not yet reinforced dikes
1962	Greveling	Dike breach at Greveling dike
1967	Greveling	Further storm surge damage at Greveling dike
1976	Clinic Utersum	Damage to the clinic revetment in January
1984	Clinic Utersum & Goting Cliff	Breach of the beach bank at Godelniegerung
1987	Greveling	Scouring and revetment collapse in autumn
1990	Clinic Utersum	Damages in front of the clinic in January
1990	Nieblum	Damages at Nieblum beach in January

3.4 Summary and interim conclusion

Sandy mainland coastlines and islands occur around the globe. Since they are often densely populated, most sandy coasts require coastal protection measures to enable coastal

dwellers' safe livelihoods right by the sea. The two North Frisian islands of Amrum and Föhr, situated in the German Bight in the North Sea, are typical examples of sandy islands in this investigation area.
Coastal protection has always been needed to ensure safe living and commerce on the islands. Whereas in the century before last agriculture and especially fishing played an important economic role, nowadays tourism is the most important source of income for most islanders. Due to the booming tourism, many more people than just the inhabitants stay on the islands during the season. They all want to feel safe in the face of the North Sea and at the same time increase the pressure on the existing coastal ecosystems and the coastal protection measures and structures.

The relevant boundary conditions like the sea level or storm surge frequencies, with which these coastal ecosystems interact and according to which the coastal protection measures are designed to withstand, are already changing globally as well as locally in the investigation area. Due to climate change, these alterations are projected to increase in the future. Hence, the current coastal protection requires adaptation, and the changing boundary conditions act as a door opener, stimulating a political as well as societal discussion about technically possible and sensible future coastal protection.

IPCC (2019) states that changes in ESLs are small until 2050, thus there is time left to plan and adapt. With a focus on sea level rise - but conceptually transferable to the other changing boundary conditions as well - van den Hurk et al. (2022) defined four major SLR adaptation challenges, namely decision-making under uncertainty, a society-wide definition of adaptation objectives, conflict management with regard to acceptable risks for locals and the responsible authorities, and the integration of adaptation to SLR with other societal goals and planning processes.
To figure out how these challenges can be dealt with in coastal protection, the evolution of coastal protection holds important clues. Analysing how similar challenges were dealt with in the past, how adaptation to changes worked in the past, can help to plan for future adaptations. Furthermore, awareness and knowledge of how coastal protection has been and is perceived by relevant actors in the past and present can help to develop sustainable solutions for future challenges.
Both aspects, the evolution of coastal protection in the investigation area as well as actors' perspectives on the matter, are further analysed in the following chapter.

4 Coastal protection in the investigation area

Parts of this chapter have already been published in Jordan et al. (2023).

Coastal protection has always been a discipline whose rationale was and still is characterised by a constant process of change, re-evaluation and evolution. When people first settled on the North Sea coast in the German Bight (cf. Brandt (1992)), they were ostensibly exposed to the dangers of storm surges from the North Sea without any protection (Knottnerus, 2005). To be able to sustain a living under these harsh conditions they needed to adapt to the coastal environment (Bijker, 1996). From the construction of simple earthen mounds to create protected sites for settlements, to ever-growing dwelling mounds, dams and finally dikes, they developed measures – nowadays called coastal protection – to protect their lives as well as their goods and chattels from the floods (see figure 4.1). For a long time, coastal protection has been a reactive process – single protective structures such as mounds or dikes were constructed, strengthened and heightened after having proven to provide insufficient safety (Küster, 2015). It was not until the 11th or 12th century that collaborative measures of coastal protection began to take hold and spread (Bijker, 1996), although individual sections were still to be maintained and secured by the local residents.

In this chapter, the evolution of coastal protection on Amrum and Föhr is presented, which leads to a description of the status quo and current or upcoming challenges. To keep islanders and their properties safe from flooding, coastal protection on Amrum and Föhr has been executed and developed since hundreds of years - always adapting to the changing boundary conditions. To put the current status quo and the islanders' strong connectedness with the coast and coastal protection into context, the evolution of coastal protection works and structures on Amrum and Föhr is analysed from the early beginnings until today.

If one looks more closely at the history of coastal protection in the NSR, it becomes apparent that dikes have been just one - though prominent - measure to protect the coast while other ways of doing coastal protection, such as the protection and development of dunes (e.g. Müller and Fischer (1937a), Sørensen et al. (1996), and Reise and MacLean (2018)), the creation of salt marshes in the dike foreland (e.g. Müller and Fischer (1937b) and Vriend (2014)) or working with sand in the coastal foreshore or on the beach (e.g. Niemeyer et al. (1996) and Wiegel and Saville Jr. (1996)), existed as well. All these measures have been applied and executed in part for decades or even centuries as a supplement to so-called 'hard' coastal protection which indicates that the so-called path dependency

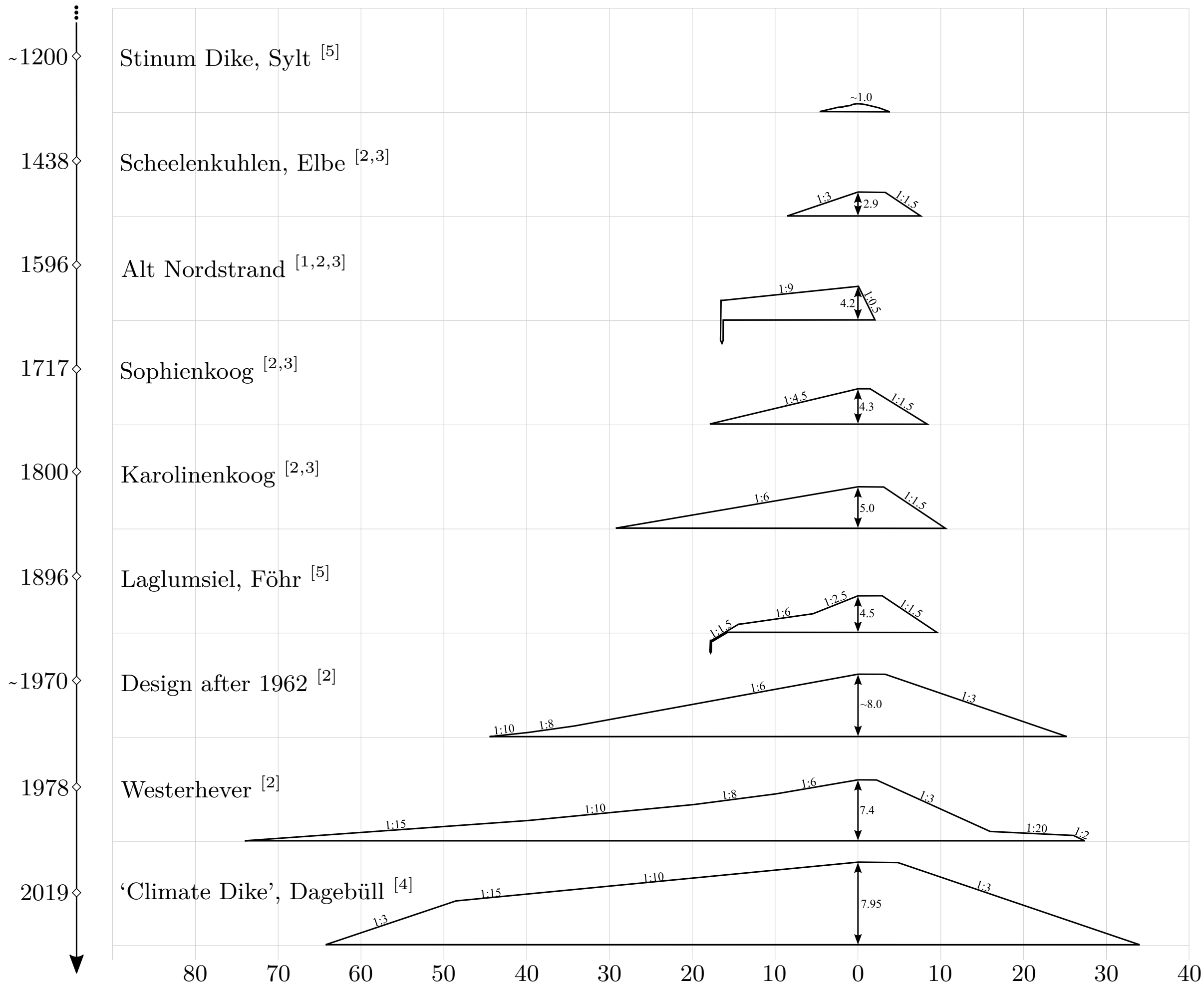

Figure 4.1: Development of dike design and construction – dike cross sections from the 13th century until today for different locations along the North Sea coast of Schleswig-Holstein. Scale of dike width below in metres; References: [1] Hofstede (2019a), [2] Kramer (1989), [3] Kramer (1992), [4] LKN.SH (2016), [5] Scherenberg (1992); previously published in Jordan et al. (2023).

of diking as the only measure for coastal protection does not exist.

Within the scope of this chapter the interplay, as illustrated above, is analysed from a place-based and socially oriented perspective because coastal protection basically is a local endeavour protecting local communities. A descriptive literature review on the development of coastal protection on the two islands will provide a diachronic insight into the various and sometimes shifting concepts and developments of coastal protection. These insights will be contrasted with a synchronic snapshot about the assessment of protective measures, as well as their current and anticipated future development with regard to the possible feasibility and implementation of NbS, gained from stakeholder interviews and systematised with the help of the theory of social representations. These insights will assist in answering the following three interconnected research questions:

- Is the history of protecting the islands against the sea characterised by a rigid and confronting rationale, or can a more dynamic rationale be disclosed that displays a more experimental evolution of coastal protection?

- In what way and to what extent is the prevailing rationale of coastal protection anchored in the minds of the people, and what role do past experiences and memories play in the present?
- What role can the analysis undertaken here play in the context of future coastal adaptation with regard to NbS?

4.1 Evolution of coastal protection on Amrum and Föhr

In the following, the evolution of coastal protection will be described for both islands from the poorly documented beginnings in the 15^{th} century until the end of the 20^{th} century, marking the beginnings of the preparations for the current status quo with the so-called *'Generalplan Küstenschutz - integriertes Küstenschutzmanagement in Schleswig-Holstein'* (MELUR, 2012; MELUND, 2022), the new General Plan for Coastal Protection. In order to provide a concise overview over the abundance of measures implemented per century and location, the most relevant events, documented projects and measures relating to coastal protection have been divided into the categories (cf. figures 4.4 and 4.7)

- storm surge with consequences,
- administration and decrees,
- grey measures (hard structures, e.g. dikes and sea walls),
- green measures (soft measures, e.g. nourishments and plantings),
- and hybrid measures (hard structures using or supporting natural processes, e.g. groynes).

Storm surges display key events and experiences, which can mark the the beginnings of new eras in coastal protection. Through damages to existing coastal defences, storm surges represent a directly visible influence that help to drive development and are therefore included in the following compilation. However, major man-made infrastructure developments in the respective region may also influence the dynamics of currents or sedimentary processes. Therefore, they are also of importance for coastal protection and its evolution and shall be mentioned here briefly. Harbour constructions, which took place on Amrum in the 20^{th} century (Stadelmann, 2008) and even began on Föhr in the early 18^{th} century (Müller and Fischer, 1937b), can influence the local sedimentation and erosion processes. Harbour construction measures that also serve protective purposes such as seawalls or groynes, are included in the following. Other developments that could also influence the conditions on Amrum and Föhr are large-scale coastal protection projects in the region, like the sand nourishments on Sylt which have been carried out regularly since 1972 (Führböter and Dette, 1992; Staudt et al., 2021), or major infrastructure projects like the construction of the *Hindenburgdamm* in 1927, connecting the neighbouring island

of Sylt with the mainland and thus interrupting the tidal current in the northern North Frisian Wadden Sea area. In addition, large-scale land reclamation in the region, which continued well into the 20th century, can affect conditions on the islands. So-called *Köge* (polder) were originally built to gain arable land, e.g. the *Gotteskoog* as one of the biggest and earliest in 1566 (Meier, 2011). During the 20th century, smaller areas like the *Tümlauer Koog* (1935) or the *Norderheverkoog* (1936) were reclaimed from the sea in order to build new settlements. More recent projects such as the *Hauke-Haien-Koog* (1960) or the *Beltringharder Koog* (1987) primarily served coastal protection or water management purposes (Kunz and Panten, 1999; Stadelmann, 2008). As a last influential factor, the development of tideways is to be mentioned. The tideways around the islands - *Norderaue*, *Süderaue* or the *Amrum Tief* - are constantly changing, whether through natural processes or anthropogenic interventions. These can include single events like the sand extraction in the Norderaue for nourishments on Föhr between 1975 and 1982, whereupon the tideway experienced more erosion and shifted to the north (LKN.SH, 2019), or constant maintenance works in the tideways to guarantee a tide-independent shipping traffic.
As stated at the outset, in contrast to the damages caused by a storm surge, the influences of these man-made infrastructure developments cannot be attributed as clearly to changes on the islands and are not located directly on the islands but in the wider surroundings or the region. As the following analysis is limited to the measures implemented directly on the islands, the developments or events briefly described above are neglected hereafter.

4.1.1 Amrum

The history of documented works on coastal protection on the island of Amrum dates back to the end of the 17th century when the era of passive and active dune management began. Several decrees and regulations regarding the protection of the dunes were issued in the 18th century (cf. Figure 4.4). At the time, the reason for this measure consisted not primarily in doing coastal protection, but was rather motivated by the inhibition of windblown sand to protect the farmland and settlements to the east of the dunes. Hence, the importance and the influence of the natural habitats present on the island were recognised early on and certain measures to shape these natural environments were taken-up to push nature and natural processes towards a desired outcome for the islanders. As a result of the land division as introduced in 1800, dune protection work was placed under authority supervision, marking the beginning of the institutionalisation of coastal protection works. From the beginning of the 19th century, stalks were actively planted repeatedly to prevent the island from sanding up. Furthermore, between 1887 and 1898, afforestation of the heath areas between the dunes and meadows began in order to further contain the drifting of sand onto the eastern side of the island (Müller and Fischer, 1937a). The storm surge in February 1825 caused a dune breach near Risum in the north-west of the island, henceforth known as *Risumlücke* (Figure 4.2 - Risum Gap). After first attempts of naturally redeveloping the dunes through enhanced sand deposition caused by stalk plantings and wooden sand-trapping fences between 1865 and 1869, the authorities in charge decided to soften the impacts from the sea on the younger foredunes. Furthermore, between 1894 and 1899, several stone groynes and wooden groynes, which were the first of this kind on Amrum, were built to protect the Risumlücke (Müller and Fischer, 1937a).

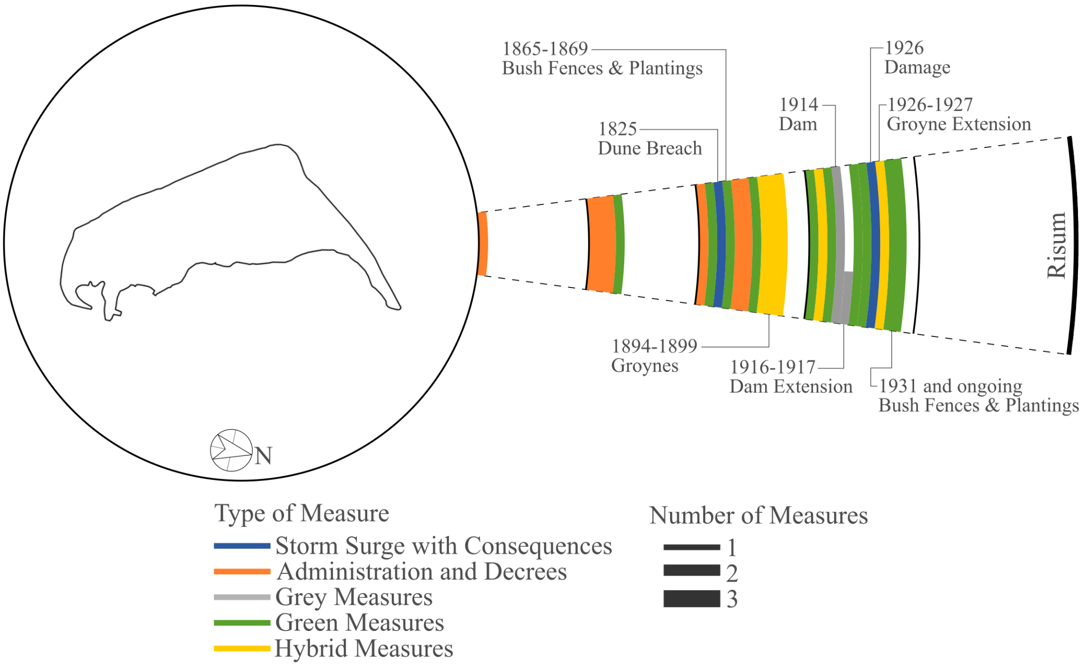

Figure 4.2: Evolution of the coastal protection at Risum (enlarged detail from figure 4.4, section rotated in clockwise direction for display purposes, north arrow below the shape of the island indicates cardinal directions). Display of the most important coastal protection related measures and events documented in Müller and Fischer (1937a) and Stadelmann (2008). Measures or events mentioned in the text are marked in the figure giving the year and a keyword. Previously published in Jordan et al. (2023), revised for PhD.

In the 20th century dune conservation and maintenance remained of great importance, and stalk planting as well as the afforestation of heath areas were continued with interruptions by two world wars. The first half of the 20th century also marks the beginning of grey or hard coastal protection measures such as dams, sea walls or dikes. In 1914, both a dam in the Risumlücke (see Figure 4.2) and a sea wall off Wittdün (see Figure 4.3) were built, since previous efforts did not result in the desired long-term protection. Grey measures such as the Risum dam did not replace green techniques and approaches from before, but were rather constructed to work and function together. The overall approach to tackle coastal protection issues was thus very much problem-oriented, pragmatic, and relied on combinations of proven and new techniques and ideas (Müller and Fischer, 1937a).
The seawall at Wittdün was continuously extended and strengthened in the years following its construction in 1914, partly after having been severely damaged by several storm surges. A foot protection was added and increased fortification was created by groynes in front of the sea wall. After the storm surge in October 1936, the seawall had to be restored again and a revetment of asphalt was added for additional protection and weighting at the foot of the wall (Müller and Fischer, 1937a). Besides the developments in Wittdün and Risum, diking was introduced on Amrum in the first half of the 20th century. After

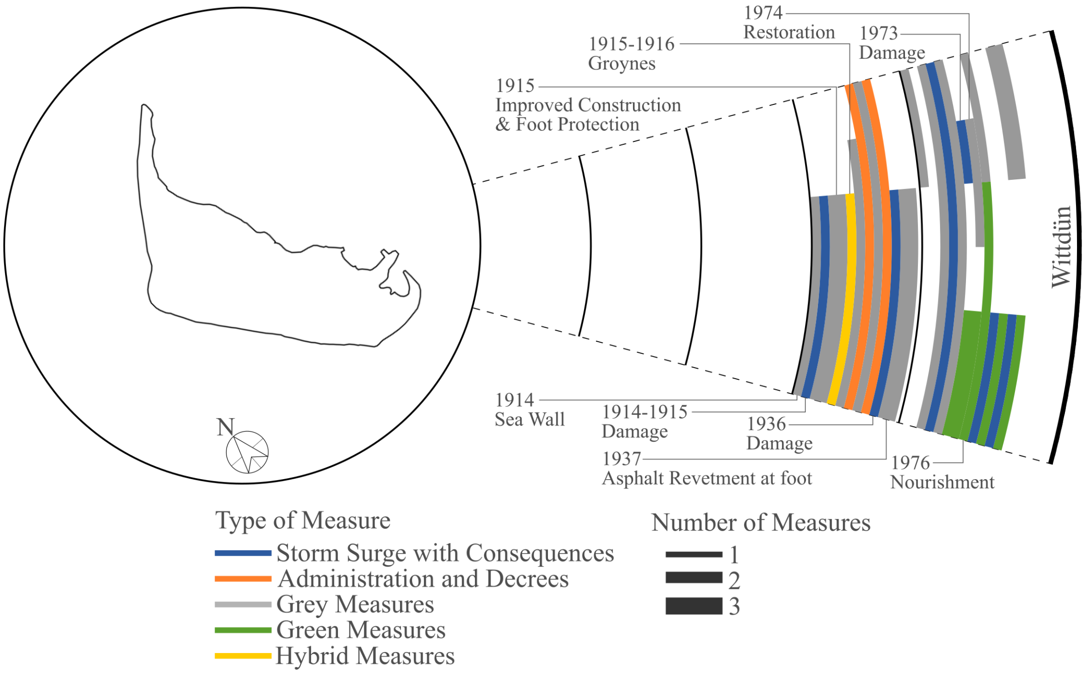

Figure 4.3: Evolution of the coastal protection at Wittdün (enlarged detail from figure 4.4, section rotated in anti-clockwise direction for display purposes, north arrow below the shape of the island indicates cardinal directions). Display of the most important coastal protection related measures and events documented in Müller and Fischer (1937a) and Stadelmann (2008). Measures or events mentioned in the text are marked in the figure giving the year and a keyword. Previously published in Jordan et al. (2023), revised for PhD.

completion in 1934 and 1935 respectively, first official dike inspections were held in the *Norddorfer Marsch* (marshland between Norddorf and the dunes at Amrum Odde) in 1935 and the *Wittdüner Marsch* (marshland between Wittdün and Steenodde) in 1936 (Müller and Fischer, 1937a).

In the second half of the 20^{th} century the construction of grey, hard coastal protection continued to progress. At the same time, however, working with sand using natural distribution processes was beginning to get some recognition. In dune management, the focus of maintenance work was primarily on the areas at the northern and southern end of the Kniepsand. Hence, there was never only one concept or rationale of coastal protection, but always a variety if not explicit diversity of approaches best-suited for respective locations. The authorities responsible, as one can see, always kept on learning more about the natural environment and how to interact with it, developing coastal protection accordingly, using hybrid measures, and combining grey and green coastal protection.

The severe storm surge in 1962, which accounted overall for massive damages and claimed many lives on the mainland, caused a dike breach over a length of 300 m at Norddorfer Marsch and a smaller breach over 75 m at Wittdüner Marsch. Both dikes were repaired and, in case of the dike at Norddorfer Marsch, improved and strengthened in the same year. After renovations to the sea wall as a consequence of a storm surge damage in the

autumn of 1973, a sand nourishment was carried out for the first time to further protect the wall after the 1976 storm surge (Stadelmann, 2008). Again, a new approach was followed and tried out, combining proven and new techniques in order to advance coastal protection.
The evolution of coastal protection, different strategies, structures, concepts and regulations on Amrum in interaction with damaging flood events over the past centuries as described above, are summarised and depicted in figure 4.4.

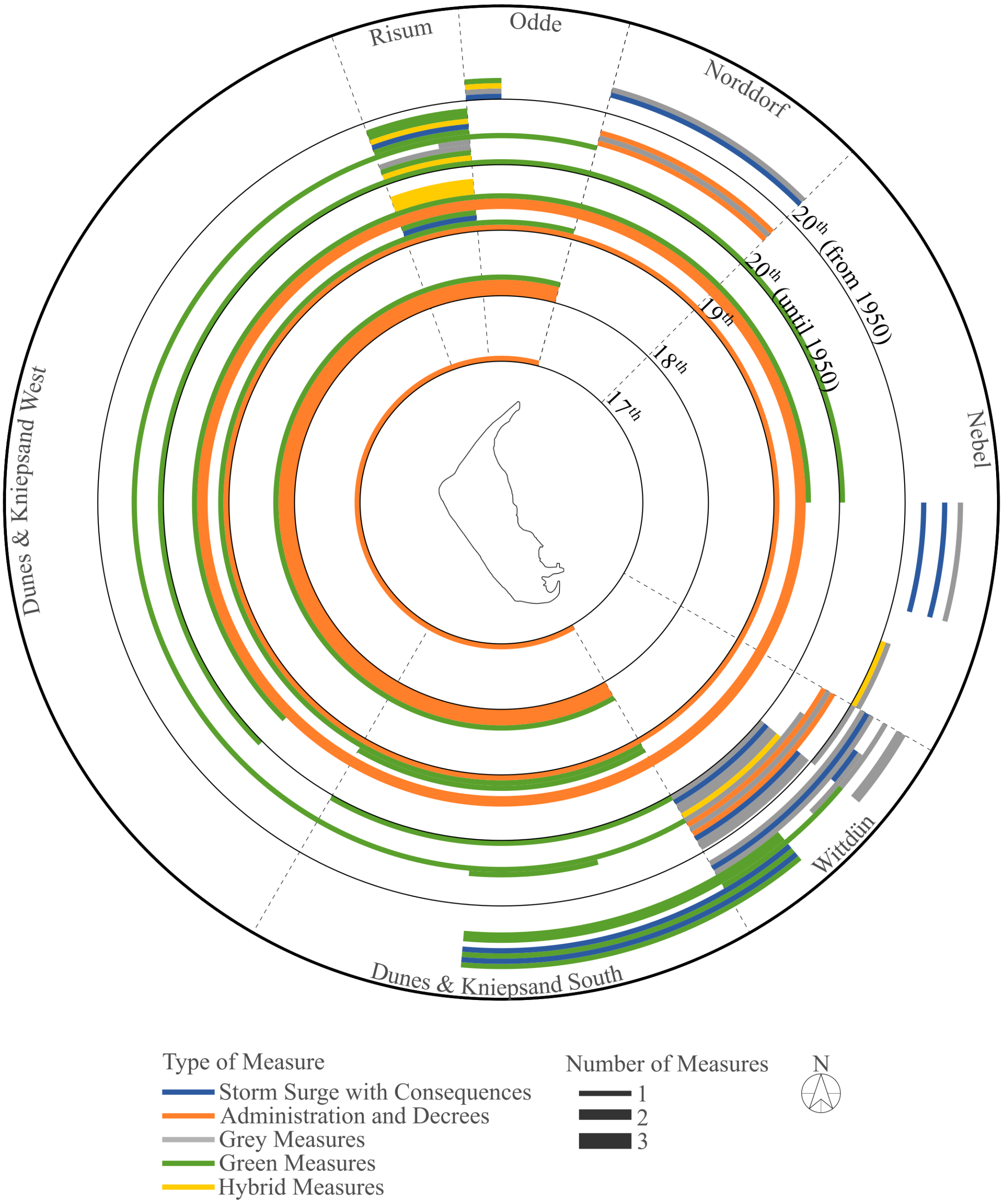

Figure 4.4: Evolution of the coastal protection on the island of Amrum. Display of the most important coastal protection related measures and events documented in Müller and Fischer (1937a) and Stadelmann (2008) (cf. appendix B.1). Each of the light grey rings represents a century; from inside to outside, the 17th, 18th, 19th, 20th (first half) and 20th (second half) century. Measures and events are divided into five categories (see legend) and displayed as coloured ring segments according to their respective century and location. The thickness of the ring segments indicates the combined number of entries of the same category at this location (see legend). The sequence of the ring segments (inside to outside) represents the chronological sequence in this century for each location in a simplified way. Previously published in Jordan et al. (2023), revised for PhD.

4.1.2 Föhr

The evolution of coastal protection on Föhr is closely linked to its institutional history. Until 1864 the island was administratively separated into an eastern and western part with the border splitting it almost in half and running from north to south through the village of Nieblum. The separation influenced the various developments in *Osterlandföhr*, which belonged to the duchy of Schleswig, and *Westerlandföhr*, which was part of the Kingdom of Denmark.

In contrast to the situation on Amrum, the inhabitants of Föhr had no dune as a natural barrier against the sea and, therefore, could not purely rely on and work with natural forces for protecting the island against the incoming sea. So, man-made technical coastal protection was much earlier of importance than on the neighbouring island. In the 15th century, to whence solid documentation of coastal protection on Föhr dates back, houses in the eastern and western marsh of Föhr were built on dwelling mounds. Only a few areas were secured by so-called summer dikes, built by the farmers to protect their lands from minor floods during the summer months. By the end of the century in 1492, the first documented, coherent dike was completed. For the most part, however, the usual kind of coastal protection consisted in a summer dike. The first known decree regarding dike maintenance on the whole island was not issued until 1658, illustrating that progress in dike construction and maintenance was initially rather slow. A series of several storm surges in 1717, 1718 and 1720 largely destroyed the existing dike on Föhr. Only after the reconstructions and restorations that were executed in the aftermath of these events - speaking in today's terms – the first real sea dike on the island was completed. The first half of the 18th century also marks the beginning of the varying development between the eastern and the western part of the island. In Westerlandföhr, the dike design was further improved as it can be seen by the evolution at the western dike (Figure 4.5). Starting in 1738, a stone revetment was constructed on the outer slope of the western dike for further protection and dike strengthening. And again, after damages of another storm surge in Westerlandföhr in 1791, the dikes in the west and north-west were restored and heightened to better resist future storm events (Müller and Fischer, 1937b).

While planting of beach grass to secure sand depositions and counteract erosion was executed along Föhr's southern coast, the protective focus in the 19th century in terms of diking was still very much on the western, northern and eastern coast. Thus, green and grey measures also co-existed on Föhr at the same time, but their areas of application were still spatially separated from each other in the beginning. New dike regulations were issued by the respective authorities in 1803 (east) and 1805 (west), putting the works on the dikes under communal supervision and thereby institutionalising coastal protection tasks around the same time as on neighbouring Amrum. The severe storm surge of February 1825 is to be mentioned here as the first of a series of storm surges that caused considerable damage to both the dikes in Westerlandföhr as well as Osterlandföhr. At the western dike, the storm surge produced several ground failures and a breach between Utersum and Dunsum, which was closed within the same year (see Figure 4.5). In addition to the dike, two groynes made of stone and kelp were installed at the northern and southern end of the western dike in 1863, which were further heightened and extended in 1865 and supplemented by constructions of additional brushwood groynes in 1866. Here, the dike

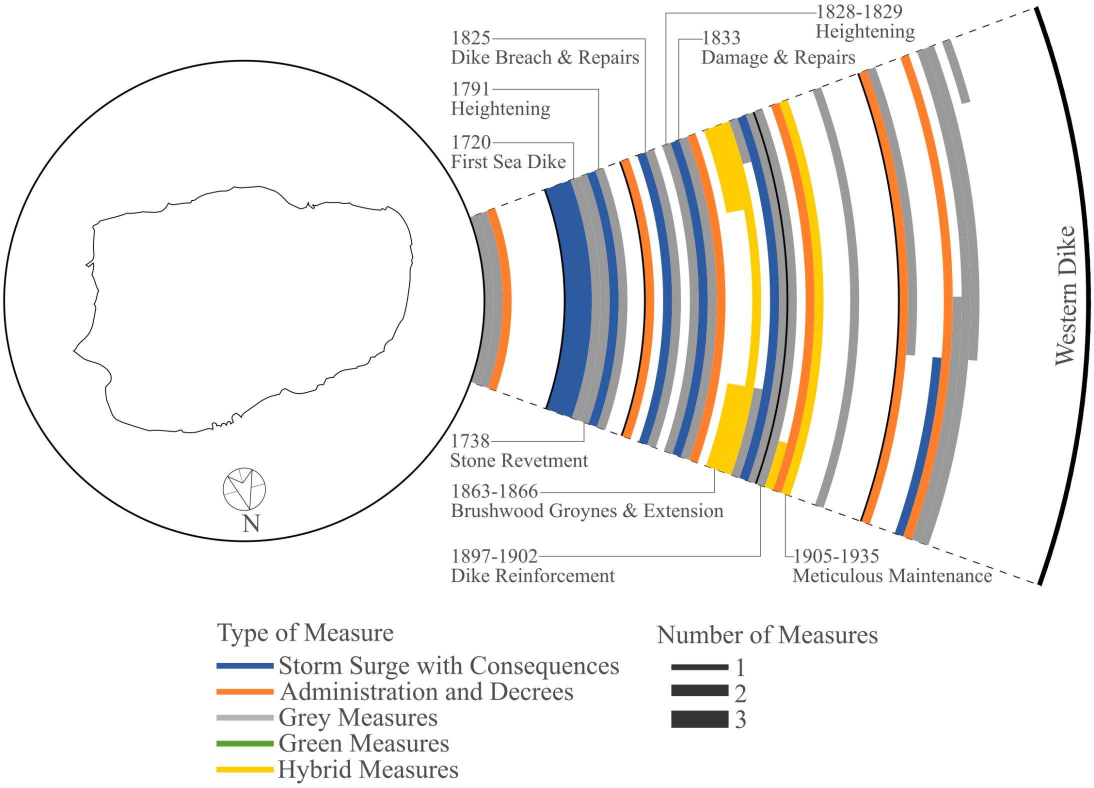

Figure 4.5: Evolution of the coastal protection at the western dike (enlarged detail from figure 4.7, section rotated in clockwise direction for display purposes, north arrow below the shape of the island indicates cardinal directions). Display of the most important coastal protection related measures and events documented in Müller and Fischer (1937b) and Stadelmann (2008). Measures or events mentioned in the text are marked in the figure giving the year and a keyword. Previously published in Jordan et al. (2023), revised for PhD.

was combined with other green or hybrid measures to advance its protective function and to safeguard the dike structure itself, by influencing the natural coastal processes around it (Müller and Fischer, 1937b).

Figure 4.6 shows an enlarged view of the evolution of coastal protection at Näshörn, around the easternmost tip of Föhr, and poses an example for the developments in Osterlandföhr. The storm surge in 1825 caused seven breaches and other severe damages along the whole dike from Wyk over Näshörn until the end of the north-eastern Dike as indicated in Figure 4.7. As emergency measures, the locations posing the biggest threats were dammed up with piles and layers of earth and straw in the weeks after the event. By the mid-19th century foreshore areas were already recognised as additional protection for the adjacent dike and the inhabited and cultivated marsh behind it. Because large parts of the previously existing foreland around the Näshörn tip were lost at the end of the previous century, officials tried to secure the remainder by the construction of angled brushwood groynes in 1838 and the following years. Despite these efforts, the storms of the winter between 1847 and 1848 caused the foreshore and the mudflats off Näshörn to disappear almost completely. The little remaining foreshore areas at Näshörn and the still existing ones off Kuham to the south were maintained and improved in the following years from 1853 to 1861. Among other things, these improving adaptations were made through the construction of drainage ditches and in the case of Kuham the installation of new brushwood groynes (Müller and Fischer, 1937b). This example highlights the versatility of the concept of diking and the dynamic adaptations and possible combinations with other measures that have always been applied in response to natural processes and changes in coastal environments. Coastal protection properties of the foreland were already well known, appreciated and used. Without the foreland, dikes had to be strengthened. With the foreland, dikes were safe and well-functioning.

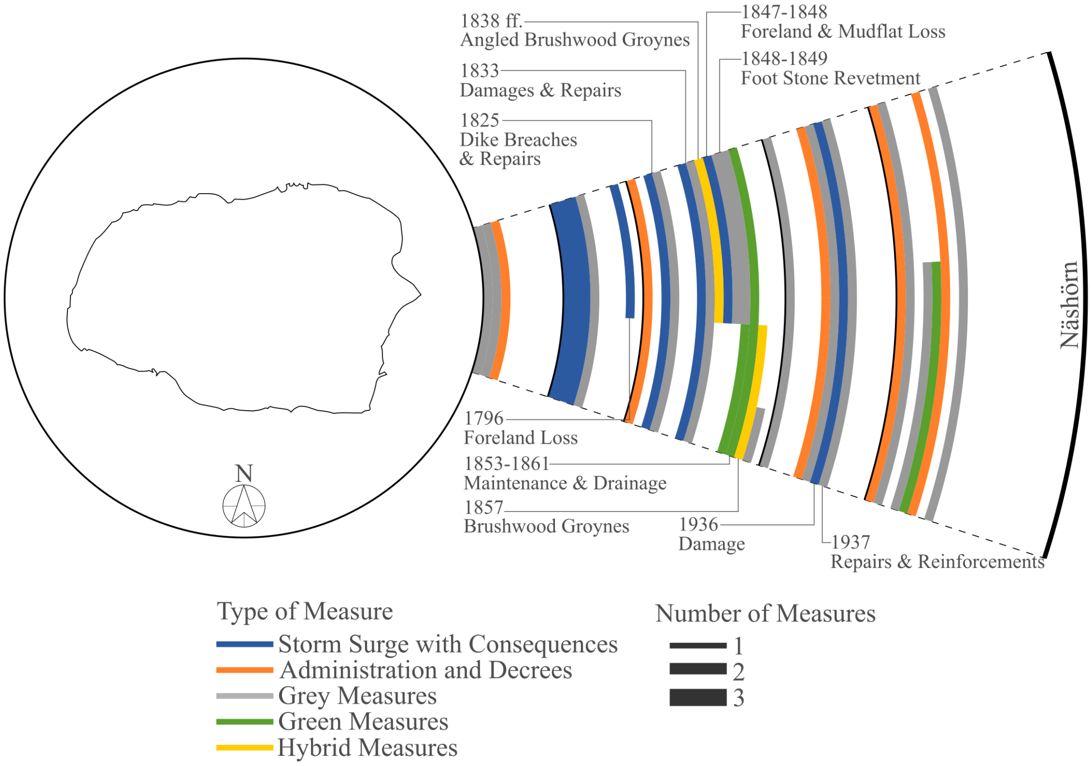

Figure 4.6: Evolution of the coastal protection at Näshörn (enlarged detail from figure 4.7, north arrow below the shape of the island indicates cardinal directions). Display of the most important coastal protection related measures and events documented in Müller and Fischer (1937b) and Stadelmann (2008). Measures or events mentioned in the text are marked in the figure giving the year and a keyword. Previously published in Jordan et al. (2023), revised for PhD.

In the first half of the 20th century, dikes and adjacent structures were strengthened further and suitable maintenance was promoted by the enactment of new dike regulations in 1900 (Westerlandföhr) and 1923 (Osterlandföhr). Besides, the construction of the sea wall at the city of Wyk began and opened a new chapter for the protection along the southern coast of the island (see Figure 4.7). The first sea wall at Wyk was constructed in 1904 as a 280 m long concrete wall at the beach. Similar to the developments in dike construction in the previous century, progress at the sea wall can be characterised as reactive. Several

storm surge damages in the years of 1909, 1917, 1923 and 1928 at different locations of the sea wall instigated a constant advancement and improvement of the construction (Müller and Fischer, 1937b).
In the second half of the 20th century, after the first joint plan to secure the entire Föhr sea dike was issued in 1951, work began in various steps from 1953 onwards. The severe storm surge of 1962, however, ensured that a new extension programme was launched before the reinforcements were completed. Authorities decided to reinforce all dikes again and to upgrade them with a sand core, a flat outer slope, an inner berm and dike defence paths. The work for this began within the same year and continued for the next decades (Stadelmann, 2008). The loose association of communities interested in the protection of the island's south coast established in 1952, which ultimately led to the foundation of the South Coast Association (*'Zweckverband Südküste Föhr'*) in 1969, representing the kick-off for the intensive efforts to preserve Föhr's southern coastline (Stadelmann, 2008).
A change in the coastal protection strategy from grey to green measures can be observed on locations like the Clinic Utersum or Nieblum in the years following the first ever sand nourishment on Föhr in 1963, which was executed between Wyk harbour and Oldenhörn with a volume of 180,000 m^3 of sand. After restoring the previously extended revetment off the Clinic as a reaction to storm surge damages in 1976, a sand nourishment was executed and two rubble stone groynes were constructed in 1977 to secure the coastline. The nourishment was renewed twice in the following decades, once in 1982 and once in 1990 in response to storm surge damages dating from January of the same year. A similar development took place off Nieblum. Following the construction of a boulder groyne to secure the beach, the first sand nourishment on Nieblum beach was executed in 1975 with a volume of 290,000 m^3 of sand. As with the Clinic, the nourishment at Nieblum beach was replenished in 1982 and renewed after the storm surge in 1990 (Stadelmann, 2008). While authorities stuck to the system of diking in the north of the island, coastal protection on the south coast was more open to change and experiments. As described above, even after severe damages through storm surges, authorities did not deviate from Föhr's dikes but rather made them higher and stronger. In the south of Föhr, coastal protection evolved more dynamically and proved to be open to change and going new ways, as the deployment of sand nourishments instead of revetment or dike construction indicates.
The development of coastal defence on Föhr is summarised and depicted in Figure 4.7.

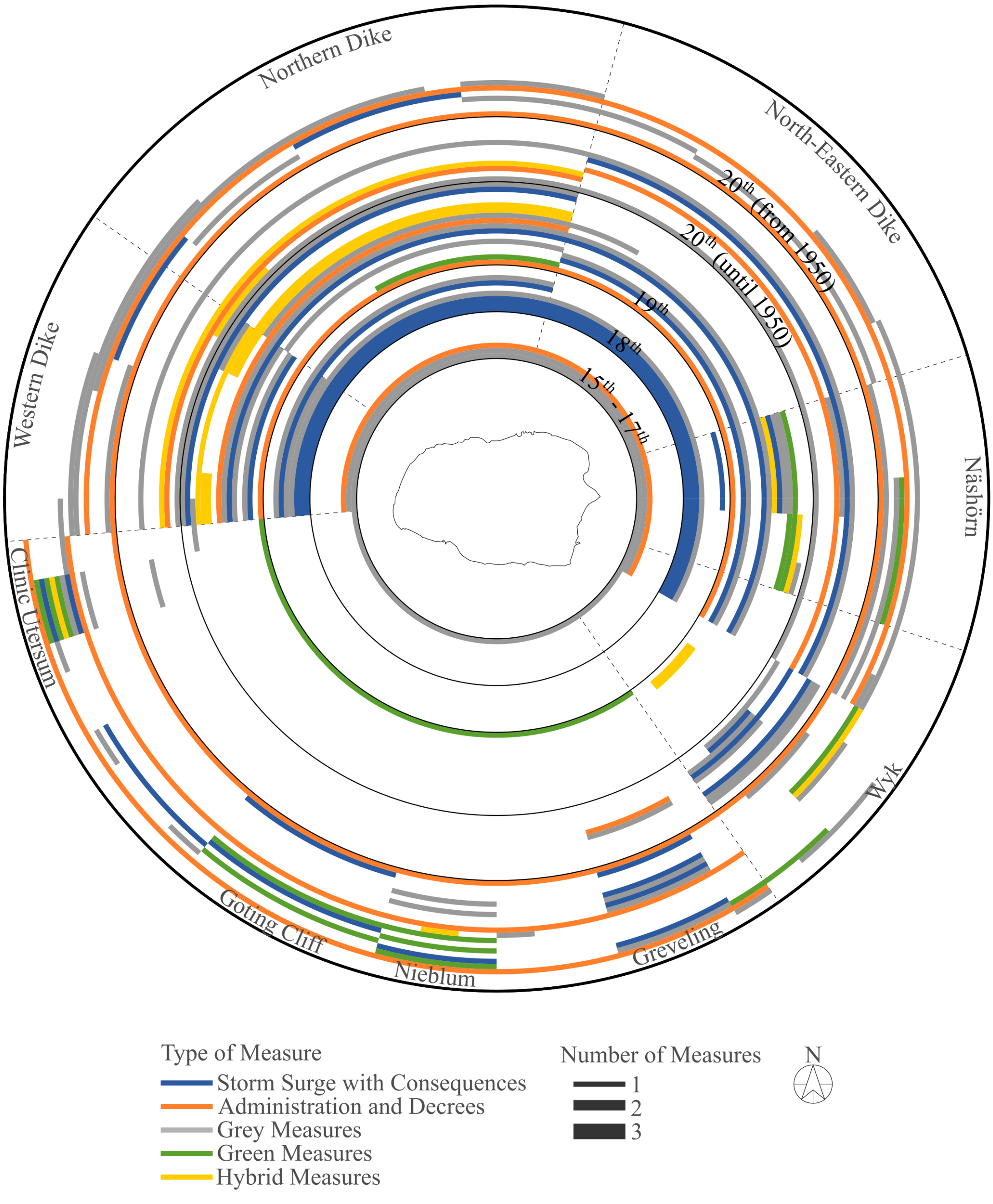

Figure 4.7: Evolution of the coastal protection on the island of Föhr. Display of the most important coastal protection related measures and events documented in Müller and Fischer (1937b) and Stadelmann (2008)(cf. appendix B.2). Each of the light grey rings represents a century; from inside to outside, the 15th till 17th, 18th, 19th, 20th (first half) and 20th (second half) century. Measures and events are divided into five categories (see legend) and displayed as coloured ring segments according to their respective century and location. The thickness of the ring segments indicates the combined number of entries of the same category at this location (see legend). The sequence of the ring segments (inside to outside) represents the chronological sequence in this century for each location in a simplified way. Previously published in Jordan et al. (2023), revised for PhD.

4.1.3 Comparison of the evolution

Recognition of the importance of the natural ecosystems for the preservation of the island has a history on Amrum that had its beginnings in a time when the technical possibilities for coastal protection were naturally still limited. However, it continues to this day that islanders could and still can rely on natural protection such as the wide dune belt and the Kniepsand beach. Multiple combinations of grey and green measures were implemented, experimented with and further developed - a problem-oriented and pragmatic way of dealing with coastal protection was relied on, which did not rigidly follow a straight developmental path but interacted dynamically with the changes experienced. On Föhr, due to differing environmental preconditions in comparison to Amrum, diking was more important throughout the development of Föhr's coastal protection. Nevertheless, other measures were applied as well and advanced coastal protection on the island. In a reactive and problem-oriented manner, dike construction evolved as a major part of Föhr's protection strategy - but not as the exclusive one. Combinations of grey and green measures were tested and implemented and, driven by storm events and changing boundary conditions, innovations in diking and more nature-based concepts dynamically advanced the island's coastal protection over the course of the past centuries.

4.2 Status quo

As a consequence of the storm surge in 1962, the first special plan for the general planning of coastal protection throughout Schleswig-Holstein, which was published in 1963 and updated twice in the following decades in 1977 and 1986, stipulated the reinforcement of the existing dikes and laid the foundation for a uniform strategy and coastal protection concept for the entire federal state. In 2001 a new general plan for coastal protection was issued by the federal state ministry, based on the principles of integrated coastal zone management (MELUR, 2012; MELUND, 2022)). In addition to coastal protection that had been built and evolved by 2000, the new construction programme, that went hand in hand with this plan, marks the starting point for the realisation of the coastal protection systems. These represent the current status quo. The core of the new plan was a dike reinforcement programme including a so-called 'climate buffer' of 0.5 m for the expected anthropogenic sea level rise. In the following, the status quo of coastal protection on Amrum and Föhr is summarised. According to the definitions for grey, green and hybrid coastal protection measures given above (see section 4.1), the currently prevailing measures on Amrum and Föhr are displayed.

4.2.1 Amrum

Around the northernmost tip at Amrum Odde dunes are the prevailing habitat, and these dunes are secured by sand trapping bush fences (see figure 4.8, left). Moving clockwise to the eastern side, brushwood groynes are installed in front of the dunes to accrete sediment (see figure 4.8, middle). These fields of brushwood groynes continue further along the coast where an asphalt overflow dike is constructed in front of the Norddorfer Marsh. This combination is then followed by a combination of a stone revetment with adjacent fields of brushwood groynes. As can be seen in figure 4.10, coastal protection is lacking in the following section on the east coast. Subsequently, only some of Nebel's houses are protected by an embankment. The coastal section at Steenodder Cliff just before Wittdün is secured by regular sand nourishments.

Figure 4.8: Bush fences in front of the dunes to accrete sand at Amrum Odde (left; previously published in Jordan et al. (2023)), fields of brushwood groynes and developed foreland along the dike Norddorfer Marsch (middle) and sea wall with stone revetment at Wittdün (right).

Similar to the Norddorfer Marsch, the Wittdüner Marsch is protected by an overflow dike, followed by sea walls with additional revetments, which are protecting the actual city of Wittdün (see figure 4.8, right). In the south of the city the longitudinal coastal protection works merge into the adjacent dunes (see figure 4.9, left). Several groynes are installed there to counteract erosion and secure the coastline.

Behind Wittdün in the south-east, the extensive dune area of Amrum begins to extend northwards along the west coast of the island (see figure 4.9, middle). In addition, from the south of the island to the north-west just before Risum, the wide Kniepsand extends in front of the dunes, nourishing and protecting them (see figure 4.9, right). The prevailing currents cause it to shift northwards along the island. Up to the easternmost tip it is therefore in decline, while it continues to grow north of this point. The formerly constructed asphalt dikes around Risum still exist in their original form but are nowadays completely covered by dunes, maintaining the dune chain intact along the entire west coast in its current state.

Figure 4.9: Longitudinal coastal protection work south of Wittdün with groynes (left), vast dune area near Norddorf (middle; previously published in Jordan et al. (2023)) and young foredunes forming on the edge of the Kniepsand to the dunes in the south (right).

The status quo of Amrum's coastal protection is depicted in figure 4.10 in a categorised manner, displaying the variety of applied measures and concepts in Amrum's coastal protection.

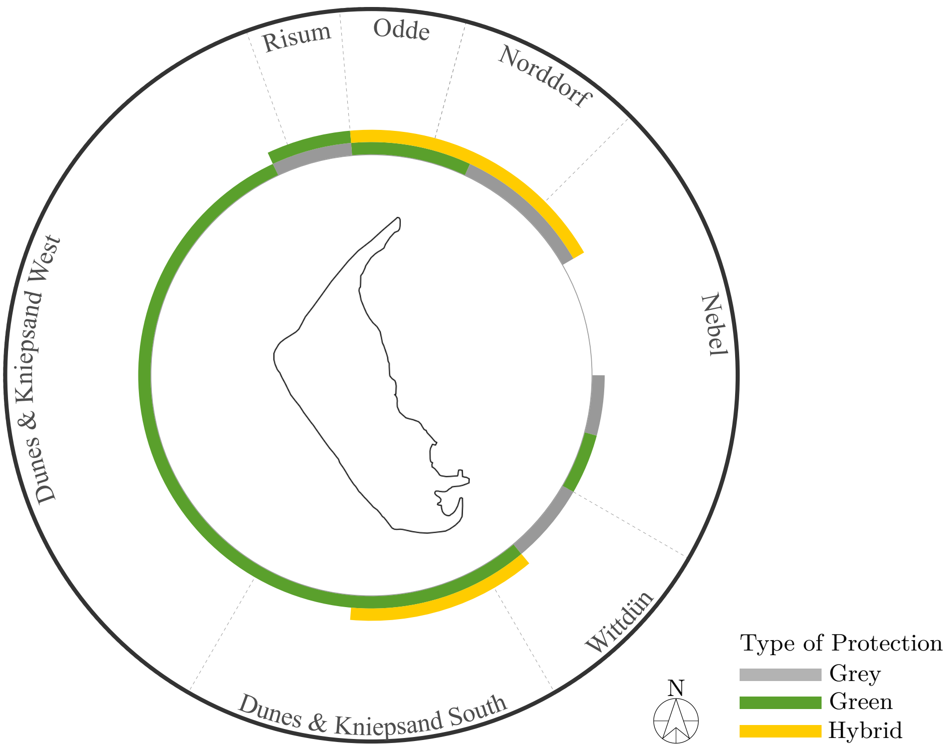

Figure 4.10: Status quo of the coastal protection on the island of Amrum. Display of the currently prevailing coastal protection measures as inspected on site and as documented in LKN.SH (2017). Measures are divided into three categories (see legend) and shown as coloured ring segments in the figure according to their respective location on Amrum. Previously published in Jordan et al. (2023).

4.2.2 Föhr

The entire Marsh area of Föhr is protected by the dike, which stretches from Utersum in the West along the north coast of the island to Wyk harbour in the south-east. The dike profile varies along the whole construction. Designs differ mainly in the gradient of the outer slope, the design at the bottom of the outer slope and additional features such as roughness strips (e.g. figure 4.11, left).

Starting in the west, the coastline between Utersum and Dunsum is additionally secured by several groynes constructed in the North Sea in front of the dike (see figure 4.11, middle). Moving clockwise in figure 4.13, a large foreland area stretches out in front of the sea dike from the north-western corner of the island to the north-east with its maximum extension in the north. Fields of brushwood groynes in the north-east are constructed to accrete more sediment and help build up more foreland areas in front of the dike (see figure 4.11, right). These measures are continued until the easternmost tip of Föhr at Näshörn.

Figure 4.11: Sea dike with a partly asphalt-covered outer slope including a roughness strip in the north-west (left), sea dike with adjacent groynes between Dunsum and Utersum (middle) and fields of brushwood groynes in the north-east of Föhr with already developed foreland in the back (right; previously published in Jordan et al. (2023)).

After the harbour dike, the city of Wyk is protected by sea walls (see figure 4.12, left) in combination with revetments for erosion protection. Furthermore, several groynes are constructed at the eastern beach and the southern beach is nourished regularly. A rubble stone revetment is connecting the city area, which is protected by sea walls, to the area around Greveling where an asphalt overflow dike is constructed behind the beach (see figure 4.12, middle).

Figure 4.12: Sea wall with an opening and sliding gate in the centre of Wyk (left), connecting section of the rubble stone revetment to the Greveling dike (middle) and regularly nourished beach off Nieblum (right).

Continuing on from the area around Wyk and Greveling, coastal protection on the south coast of Föhr is in part very small-scale, localised, and lacks a holistic concept. While the section adjoining Greveling lacks coastal protection, the coast of Nieblum is protected by the old dike and regular nourishments (see figure 4.12, right). These have also contributed to the dike being covered by sand over the years, which is why nowadays it more or less resembles a dune. The rest of the southern coast is either protected by further sand nourishments, as in the area in front of Goting and at the south-western tip of Föhr off the Clinic Utersum, or by a beach ridge. Around the mouth of the Godel, the coast is secured by additional riprap and groynes are constructed at the beach in front of the Clinic Utersum. Additionally, three single embankments are constructed further inland to protect individual houses and farms in Hedehusum, Witsum and Goting.

The status quo of Föhr's coastal protection is depicted in figure 4.13 in a categorised manner. Although on Föhr diking was very present in the past and still is of major importance today, it becomes clear that this is not the only form of coastal protection applied on the island today.

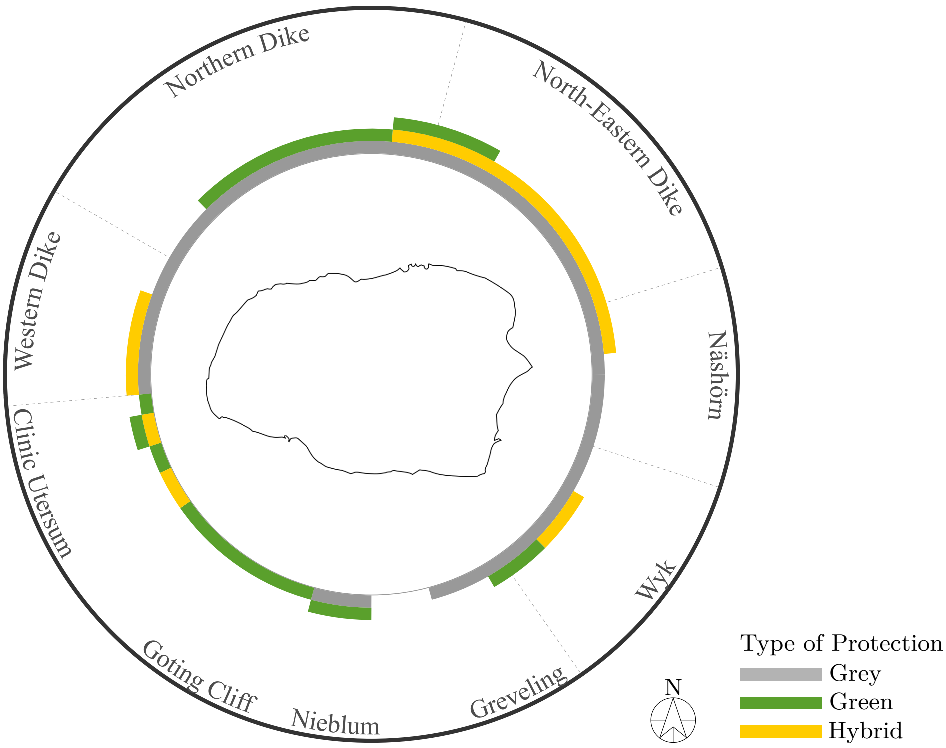

Figure 4.13: Status quo of the coastal protection on the island of Föhr. Display of the currently prevailing coastal protection measures as inspected on site and as documented in LKN.SH (2019). Measures are divided into three categories (see legend) and shown as coloured ring segments in the figure according to their respective location on Föhr. Previously published in Jordan et al. (2023).

4.3 Actors' perspectives on historical, present and future dynamics

4.3.1 Theory of social representations

To analyse the varying rationales of coastal protection, the theory of social representations (SRs) first formulated by Serge Moscovici (Moscovici, 1961; Moscovici, 1988; Moscovici, 2000) was used, as it provides an interdisciplinary applicable and methodologically viable way for studying and analysing how those involved in the context of coastal protection produce diverging or converging representations of it and discuss, negotiate and contest underlying issues and values. Moscovici defined SRs as

> *'[...] a system of values, ideas and practices with a twofold function: first, to establish an order which will enable individuals to orientate themselves in their material and social world and to master it; and secondly, to enable communication to take place among members of a community by providing them with a code for social exchange and a code for naming and classifying unambiguously the various aspects of their world and their individual group history.' (Moscovici, 1973)*

Generally, the advantage of the theory of SRs conceptually consists in the fact that it helps to specify and study a variety of communicative mechanisms and social processes which assist in forming commonly shared or contested representations of a certain issue. This can, for example, be seen in the present case as living in the district of North Frisia is characterised by the fact that coastal dwellers are more or less directly engaged in current issues of coastal protection. The motto 'God created the sea, the Frisians the coast' – as already indicated in section 3.2 - reflects a self-attributed identity, forms a relation to the coastal landscape and subcutaneous values bound up with it that contribute to developing meaning systems which enable or hinder communication among those involved in the issue of coastal protection.
However, one has to be aware that SRs do not develop out of the blue as their emergence requires a sufficiently relevant issue for a community or social group to initiate negotiation, debate or even a conflicting discourse. The example discussed in this work of changing the rationale of coastal protection in the probable direction of NbS is such a case. It was gradually introduced during various research projects (e.g. MELUND (2021) and Fröhlich and Rösner (2015)) and publications (e.g. Reise (2015)) in the recent years and created a critical assessment among the group of the interview partners. Importantly though, the present communication about the implementation of NbS is now and again rendered against the SR of past ways of doing coastal protection which displays a *'peculiar power and clarity of [social] representations [...] with which [...] the reality of today [is assessed] through that of yesterday'* (Moscovici, 1984). This so-called process of cultivating an issue or topic, as based on a backward reasoning, can be seen in the fact that references to the history of diking on the North Frisian islands pervade the interviews conducted and contribute to setting a conceptual background against which the current issue of NbS is assessed: the long-lasting ways of doing coastal protection is often depicted as the right and apparently successful way while a change of doing it in terms of NbS is in many cases experienced as challenging or even difficult within the current social, scientific, political and institutional rationale. Additionally, this process could be characterised by mechanisms of anchoring which contribute to making the new or unfamiliar known by integrating it into a pre-existing structure of SRs. Thematic anchors provide a big or overarching picture, for example between nature and culture via the use of antinomies such as the opposition between coastal and nature protection, and transfer them further on into constitutive paradigms such as 'the fight against the water' or 'providing space for water and nature'. These processes of anchoring are complemented by the mechanism of objectification which makes the unknown graspable by transforming something abstract

into something concrete. Here, a new or abstract phenomenon such as climate change is rendered concrete by linking it to perceivable meteorological events or by using scientific results developing a network of experiences and knowledge(s) many people can relate to. This *'network of ideas [is] [...] more or less loosely tied together'* (Moscovici, 2000) by metaphors, images, facts, values, assessments as it unfolds when new ways of doing coastal protection enter the discursive arena.

In summary, one can say that individuals achieve SRs not exclusively by thinking, contemplating or personal experience, but also by actively taking part in societal discourses and social conflicts. *'Social representations play an important epistemological [and pragmatic] role in communication'* (W. Wagner, 2012) forming collective meaning systems that corroborate or differ from traditional views on and acting about certain issues.

4.3.2 Analysis of actors' perspectives on historical, present and future dynamics in coastal protection

The preceding depiction of the historical development of coastal protection in the study area has shown - contrary to the prevailing public discourses - that coastal protection could be characterised as problem-oriented, pragmatic, dynamic and, in view of the measures taken, hybrid. The socio-historical ways of dealing with coastal protection presented in section 4.1 hence show that it has in fact always been characterised by an inherent dynamic and ways of tinkering. To investigate if and how actors perceive this divergence between commonly shared synchronic narratives and historical developments in the present, 14 interviews with actors from local as well as regional authorities and NGOs were conducted (further 21 interviews were conducted with actors in science and islanders). Analytical emphasis was put on the linguistic structures used as this can assist in revealing how certain issues are perceived, framed and integrated into existing meaning systems to develop social representations about how coastal protection was, is and should be carried out. This will show that coastal protection is not exclusively an engineering issue, but genuinely a social process – an aspect which has often been overlooked to date. Institutions play a major practical and normative role in and for negotiating and implementing coastal protection. In the following, these interviews will be analysed in more detail, as various framings and assessments of coastal protection can already be identified here. The empirical categories revealed and used for the analysis are *Coastal Protection*, *Nature-based Solutions*, *Interface Coastal Protection - Nature Conservation*, and *Future of Coastal Protection*. These have been selected from a larger group of empirical categories emerging from the interviews as they directly relate to the research questions mentioned at the outset of this chapter as well as in section 1.3 – an overview over the whole category set including all sub-categories can be found in appendix D. In the following sections, a detailed analysis of paradigmatic examples taken from these four categories will be provided. The guiding questions permeating the sections are *what was*, *what currently is* and *what will be happening in coastal protection?*

Coastal protection

Coastal Protection permeated the reflections of all interviews. In most of the cases, the process of reflection starts with depicting a sometimes vivid image of the past, e.g.

> *'You see, they still fortified the dike by hand. (...) they still tried to protect the dike with long rye straw, to hold it (...).'*

> *'Yeah, well, I mean, dikes have been built here on the North Sea coast for thousands of years. I would say that this has proven itself.'*

Both references craft a past and generic image of diking as hard manual work which is complemented in the first quote by the aim to secure the dike, and consequently to protect the livelihoods behind it against the forces of the North Sea. This representation uses a socially shared imagery that appears now and again when the issue of coastal protection and diking in North Frisia is raised. It is often complemented by a thematic anchoring that reveals processes of objectification based on an imagery revolving around the fight against the sea, the forces of the sea, and the struggle humans have to go through to protect their livelihoods behind the dikes. Such a socially constructed and widely shared history about diking reveals a stark contrast to contemporary procedures of diking because these are scientifically driven and business-like engineering processes, often using heavy machinery. This line of thinking is furthermore elaborated upon in the second interview excerpt where the usefulness of the diking rational is temporally outlined. and connects its temporality to the supposedly long-lasting experiences made with diking throughout history. The conclusion *'that this has proven itself'* frames diking as an adequate technique. However, this focus in perspective partly hinders the broadening of the view resulting in the fact that alternative concepts and measures were and currently are seldom considered.
Another important aspect, that is strongly influenced and shaped by the past, is the status and relevance of coastal protection. This more abstract and social aspect is often portrayed in individualised terms referring to personal experiences also using paradigmatic or exceptional events as in the following example:

> *'(...) and from earlier times it was like that, I mean, in 1962 I can still remember it from hearsay, I was four years old (...) and the dike was threatening to break. (...) and that's why coastal protection is essential for me to live on the islands, on the holms, on the mainland.'*

Here, the temporal reference *'from earlier times'* in combination with the individualised memory of the 1962 storm surge – a thematic anchor – provides a frame of reference, that is used to strengthen the relevance of coastal protection.
The aforementioned aspect is insofar important, as if disasters are situated too far in the past, the memory of them and the fears associated with them hold the danger to fade further and further resulting in oblivion. Hence, the topic of coastal protection is slipping out of the individual and common focus in the context of an increasing security and prosperity achieved by a well-executed coastal defence. This process is conceived by some interview partners as being amplified by the increasing institutionalisation of coastal protection and growing social prosperity in recent decades:

> *'So, of course, this is due to a social development of prosperity where you can claim all kinds of things with a big belly and a big salary. You don't take any risks. (...) We have taken more and more responsibility away from the local people as a state. (...) well, so one relies more (...)'*

Here, a rather general picture about society and its relation to coastal protection is developed. The representation of social prosperity, objectified via the negative images of *'a big belly and a big salary'*, and its consequences for coastal protection is reflected upon. Taking away responsibility from local people is assessed as a sign of the times in view of the overall caring state and its authorities in charge. Hence, the *'exemplary care and provision'* of governmental coastal protection poses a reflexive threat to its status for some interview partners. On the one hand, due to its well-functioning, no severe flooding has occurred on the German coast since 1962. Thus, coastal inhabitants feel safe and the former fear of the sea is more and more pushed aside, ignored or even forgotten. This is of course a positive development as long as the general interest in coastal protection and the respect for the forces of nature are not lost at the same time. On the other hand, the institutionalisation and professionalisation of coastal protection entail that coastal dwellers are less and less involved in these processes which lead to alienation, a lack of interest and practically no engagement with the issue. In the past, as we have seen in section 4.1, it was the task of those living behind the dikes to take direct responsibility for the facilities protecting them. Nowadays, the general picture is somehow reversed since institutions like the 'Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein' (LKN; Schleswig-Holstein State Agency for Coastal Protection, National Park and Marine Conservation) are in charge of maintaining the dike line and by doing a good job, they accidentally fuel a lack of interest for issues revolving around coastal protection. However, coastal protection is seen – as expressed in the following quote – as the basis for enabling people to live on the islands and the coast.

> *'To me, coastal protection is the foundation for enabling people to live here in this region.'*

This widely shared representation implicitly includes aspects of coastal protection such as safety, the protection of human life, shoreline protection, or in slightly more engineering terms, the two areas of flood protection and shoreline stabilisation. From the perspective of nature conservation, however, the assessment can be much more negative as coastal protection also comprises the obstruction of nature or the destruction of natural coastal ecosystems through artificial structures and barriers.

> *'From my point of view, it is first of all something where one has the feeling that they are constantly stepping on nature's toes, making it constantly smaller and destroying it.'*

This representation illustrates the impact measures of coastal protection have on the natural environment. By doing so, it challenges the rationale of coastal protection and refers to its continuing obstruction of the natural development - or of nature per se - as well as the destruction of nature. In line with these varying and partly opposing rationales, the process of diversification in coastal protection will certainly continue in the future, in view of new challenges such as climate change. The decisive criterion for future development seems to be sea level rise, as it is expressed in the two following quotes:

> *'If, for example, the issue is now, when we strengthen dikes, "to what level?", then of course we take that into account there, that the sea level rises (...)'*

> *'So basically, in the long term, sea level is ... determines how the coast develops, not the storm surge.'*

Across all responsible authorities and NGOs involved, sea level rise is perceived as the main criterion when it comes to the future design of coastal protection. This representation includes necessary efforts that are regarded as economically and socially sound and will shape the future of the coast in general. How these unavoidable challenges, that come with sea level rise, are to be met, is assessed differently among the interview partners. Some of those responsible are aware of the enormous future change and various consequences on the technical, institutional and social level, while others do not see it as a reason or even a necessity to rethink or change the established ways of executing coastal protection.

> *'Nevertheless, for us that does not mean that we would, let's say, make changes to the way we do coastal protection.'*

Based on a representation that implicitly uses the path dependence of historical experience, the current practice of protecting the coast and its underlying path dependency is legitimated and sustained for the time being. As long as it does not prove to be unsuitable, there is no reason for change, regardless of the demands upon coastal protection as described above. Others, however, raise the issue of a need for new perspectives, methods and strategies to meet future challenges on the coast:

> *'(...) there are areas that also have to be processed with completely different, well, perspectives and methods where you have to have completely different strategies.'*

This perspective obviously contrasts with the aforementioned aspects raised. It is grounded in a representation referring to the need of change in perspectives, methods and finally strategies. To objectify this more or less abstract thinking, spatial images such as 'area', 'way' or 'path' characterise this thinking outside the box which is still in the process of conceptual structuration. Hence, in addition to the path-dependency, the engineering-based protection and preservation of the coast, ecological and social concerns seem to gain relevance and should also be taken into account. One concept that enables the combination of these three areas - Water, Nature, People (e.g. Watkin et al. (2019)) - is NbS in coastal protection (c.f. Jordan and Fröhle (2022)).

Nature-based Solutions

In the analysis of actors' views and ideas on NbS, the forces of nature in the coastal zone have always come up in the past as well as in the present. Especially in the past, not all natural processes could be fully understood or were significantly underestimated.

> *'I think that many, well, processes or many things have already shown this, where one has tried to basically lock the coast, but in the end, it has not necessarily worked as intended because the natural processes are simply too strong (...)'*

Thus, working in and with nature in the coastal zone has always been particularly challenging as natural forces were and are sometimes unpredictable. This representation is informed by the rationale of locking the coast on the one hand, while on the other hand processes of tinkering in coastal protection in terms of the trial-and-error principle existed as well. Interestingly though, the aspect and image of locking the coast in terms of dikes was strongly cultivated in the past decades, while the aspect of tinkering was less stressed, although it was common practice. This is astonishing as in many locations in the region of North Frisia and on the islands, it has already been shown in the past that working against nature and natural processes - for example, rigidly fixing the coastline or blocking off entire bays from the sea - is laborious and often futile. Consequently, an understanding of natural processes was needed in order to work with and not against natural forces. This basic idea, which also underlies the current understanding of NbS in coastal protection, has - as described in section 4.1 - already been pursued in the region. The genuine practice of orienting one's work towards natural processes and systems for one's own purpose has already proven to be efficient over the last decades or centuries.

> *'(...) and here, too, I have to say that we have been practising foreshore management since the end of the century before last. So that's nothing new either.'*

Including the foreshore area with e.g. salt marshes into the coastal protection strategy - today framed as a nature-based concept or measure under the umbrella term of NbS - has thus been proven to be useful for a rather long time in a number of cases. The temporal indication *'since the end of the century before last'* emphasises the extended period of time which might have contributed to a habitualisation and the framing of this issue by the interview partners as *'nothing new'*. When considering NbS in coastal protection, it is sometimes disregarded or forgotten among locals and scientists that in many cases these are not completely new measures, ideas and concepts, but often already existing practices which are just bundled under the comparatively new umbrella term of NbS.
In the recent decades, approaches to coastal protection like NbS that differ from the concept of diking were often being met with scepticism and doubt on the local level.

> *'(...), but the reaction on the local level was not in a way that any of the coastal protection officials felt encouraged to pursue this further (...)'*

This scepticism on the side of the local population often led to a lack of courage on the side of the authorities in charge to plan and implement innovative approaches, although

this has already been done unnoticed for a long time. This representation of social scepticism towards other ways of doing coastal protection in terms of already existing NbS approaches resulted in a lack of encouragement, support and trust as well as sometimes fierce pushbacks, which finally resulted in the reaction of authorities to not yet officially pursue new approaches, such as NbS in coastal protection.
However, the forces of nature and their potentials are nowadays much more present among the actors interviewed than they were just a few decades ago.

> *'So nature helps itself, so to speak. Or nature helps man.'*

The representation of nature's self-sustaining processes and their value for humans is increasingly being recognised and epitomises a perspective gathering more and more attention among those involved in coastal protection. Hence, the central point of NbS seems to have just arrived in the field of coastal protection. However, the potential of nature to support itself and humans naturally has certain limits, as exemplified in the following quote:

> *'In other areas we know that nature cannot regulate this at all because there is simply a lack of material. If there is no material, then there is nothing.'*

Human intervention in natural systems can impede natural processes and functions. If, for example, there is a lack of sediment or the supply of plants is too low, i.e. there is a lack of material with which nature can work, then even nature is powerless and the so-called forces of nature reach their limits. Within these limits, where nature contributes to coastal protection or coastal protection actively uses natural processes and systems, acceptance among actors for such nature-based measures has already increased to a certain extent.

> *'On Sylt the situation is very tense because the island is much more strongly attacked by the North Sea (...). On Amrum the dune belt is much wider, so that you can say, okay, it looks quite nice and just let it happen. I find that very appealing about the island of Amrum.'*

Here, the representation of two islands is depicted that is widely shared among all actors involved in the study. While Sylt is objectified as *'strongly attacked by the North Sea'*, Amrum appears not to be as threatened as Sylt. This opposition is, moreover, characterised by the adjective *'tense'* that describes the situation and the atmosphere felt in view of Sylt as compared to Amrum. If the situation is difficult, the acceptance for deviating from established concepts of coastal protection is still limited among locals as well as officials. If, on the other side, the risk of damage and danger to life from storm surges and flooding is low, as is evaluated by the interviewee to be the case on Amrum with its protective dune belt, the acceptance of coastal dwellers and their willingness to think about and test new approaches in coastal protection increase significantly. This could open up opportunities for pilot projects and experimental research.
Despite this partial serenity, as long as projects do not come at the expense of safety, many obstacles remain. In the future, more work is needed to conceptually integrate NbS into the practice of coastal protection, especially into the perception of coastal protection of all actors involved. This aspect is raised in the following quote:

> *'There will be a lot of work to do until the local people and those responsible realise that this is a favourable solution.'*

This representation is shared among many of those involved in coastal protection using the phrase *'a lot of work'* in the temporal as well as in the sense of effort to be performed. The underlying objectification of a way, in which the *'favourable solution'* represents a goal and the current state of the art a starting point, is characteristic for the comparable quotes gathered. Although NbS are said to be financially and conceptually effective and efficient in terms of time, it still has a long way to go before such measures are truly accepted at the local and institutional level.
There is, however, another representation that frames the issue differently. According to these interview partners, standstill cannot be an option in coastal protection when future challenges on the coast, not least due to climate change, need to be handled. A new line of thinking is needed as depicted in the following interview excerpt:

> *'We need to think of the multiple benefits that can then accrue to society as a whole from new ways of doing things. But if that really works is something that needs to be experimented with. So, that's what I really wish for - that we become more open.'*

This representation again uses the image of a 'way' to objectify the need for change. The *'new ways of doing things'* is complemented by the need to experiment and tinker with these possible measures to instigate progress resulting in a though unspecified process of social accretion. However, experimental approaches and new concepts are always abstract and often accompanied by a certain risk. From the side of the authorities, a certain willingness to take such risks and an openness towards nature-based pilots in coastal protection is being signalled.

> *'We would like to develop such pilot projects and then also realise them, so that one can really experience this first hand. According to the principle that you can write down a lot of good ideas, but when you actually realise them, you only become aware of the difficulties that may arise.'*

Here, the question remains, *What is then still holding back the responsible authorities?* Possibly, the fact that it is still questionable among the representatives of the authorities whether such a new way of doing coastal protection can prove itself. The NbS approach is initially perceived from a rather negative perspective. There is no talk about *opportunities*, but rather of *difficulties* and *obstacles* that only become apparent in practical trials and not in theory on paper. As already mentioned, the opposition between the abstract and practical or between engineering practice and science is evident here.
New strategies and concepts, as was shown in this section, need time to develop. They cannot be launched overnight, but should be started in the here and now and consider the socio-historical experiences made. In brief, approaches such as NbS require sensitive planning and participation as nature should be promoted and actors should be part of this process as well. This reconciliation between ways of connecting nature and the social would be the only way to gather support for such sustainable measures in the long run.

Interface coastal protection - nature conservation

Taking a closer look at the interface between coastal protection and nature conservation in the investigation area, it becomes apparent that many conflicts between the people working in the two areas are based on the introduction of the national park. The conflict at that time about the implementation of the national park is an important anchor of memory and in many cases is still divided into two different representations that harden positions between coastal protection and nature conservation.

> *'Well, there are so many issues that weigh on this and... in the past it was said that this has no influence on coastal protection at all. Coastal protection has priority. But because of all the generational changes that have taken place, that was in 1985, I think... well, and then ... they were all against it here in the region. Everyone was against the National Park, 'we don't want it any more', like that. And then it was decided in Kiel, so it was determined by others here in the region.'*

As articulated here, the promised prevalence of coastal protection over the protection of nature has disappeared. This aspect is, furthermore, complemented by various thematic anchors that depict the events that have taken place during the implementation of the national park. Such experiences also play a role in the context of coastal protection and nature conservation in which members of the opposing groups had to gather under the institutional roof of the LKN where coastal protection partly lost its priority to nature conservation:

> *'In the past, it was intended differently when it became the national park, that coastal protection should have priority. But now they say, no, no, let nature be nature, that has priority because we are a national park.'*

Some of the interview partners see the readjustment of authority between coastal protection and the protection of nature as a political breach of promise. Originally communicated priorities seem to have lost their validity and the ironical use of the objectifying motto of the national park – 'let nature be nature' – appears quite often to express the still prevailing resistance in this representation. The aftermath of these old conflicts partially reaches into the present and ensures that common ground is discovered late and cooperation is prevented – even if, as in the following example of preserving tidal flats, a common perspective or even consensus exists.

> *'That is so obvious and so clear, but it is actually because of this conflict situation, which in fact existed 30 years earlier, that it unfortunately took a very long time to come to this rather banal realisation.'*

Even after *30 years*, the relationship between coastal protection and nature conservation is still highly loaded with the above-mentioned mistrust and conflicts, although there are common issues and goals. Hence, underlying conflicts are still at work and emerge whenever sensitive issues are touched upon or require negotiation.

To tackle existing common goals in the present and pursue common issues, both parties need to let go their past representations and experiences to pave the way towards compromise. There is a significant need to make mutual concessions to each other in order to develop cooperative grounds. One prerequisite consists in perceiving the other side as an equal party and to take its contingencies and sensitivities seriously.

> *'Some things were then poured into a compromise where, as nature conservationists, we say that we are simply not at the point where we want to be, especially in areas that are not used. So we are still ... still some way off, but nevertheless it has also brought relevant progress at that time.'*

> *'Then, of course, there is the whole area of nature conservation where everyone is allowed and wants to have a say. (...) So this dogmatic, let nature be nature, is actually kamikaze in our region, especially when we look at climate change.'*

As can be seen in these quotes, nature conservation in particular is still framed by many actors in coastal protection as an obstacle and in some cases not even making practicable or realistic claims. The latter highlights the problem of too many actors being part of decision-making in coastal protection. Some even see nature protection as a considerable danger in itself as it hinders the necessary processes of adaptation needed to protect the region against looming dangers such as sea-level rise. According to this perspective, the dogmatic attitude on the side of nature conservation hinders rather than advances progress and is often underlined by reference to the multitude of documents and guidelines in environmental legislation and various other protection regulations (e.g. National Park, Natura 2000, RAMSAR, FFH). From the point of view of nature conservation, this is one of the reasons why it is difficult to unite on the working level.

Apparently, the institutionalisation of Schleswig-Holstein's coastal protection and the national park authority under one roof did not resolve differences in one fell swoop, but even made them more complicated. Tensions still smoulder under the surface and in the background, while institutional unity has to be demonstrated. What is still lacking is open and honest communication about the possibility to explore important and overarching common issues.

> *'We get along well on that subject because we don't talk to each other, you see?'*

In order to ensure that such mocking statements are a thing of the past, the *Strategy 2100* was developed and was passed by the state parliament in 2015. According to the state government's idea, it should represent the uniting moment to explore and develop synergies between coastal protection and nature conservation.

> *'We created the Wadden Sea Strategy a few years ago, and the goal is simply the same. We both want to preserve the Wadden Sea. We for coastal protection and the nature conservationists for the World Heritage Site, so to speak. And - and here we can often even agree on the measures if we have the same goal.'*

The Strategy 2100 represents an integrative attempt to form a uniting moment, although it is based on very different motivations underlying this initiative. What is decisive here, however, is the question of the respective goals and the overarching target to protect the inhabitants of the region as well as the nature against the impacts of climate change.
The collaboratively developed strategy paper represents thus a first step towards a stronger and more fruitful cooperation in the future, which is recognised as such by both coastal protection and nature conservation. However, the goal has not yet been achieved because, as previously highlighted, there is still a need for an improved culture of discussion and debate to form shared motivations and goals.

> *'It's not as if it's already reached the end here when I say that we - we cooperate more, we deal with each other better. It's like a little plant that has to be nurtured, isn't it?'*

A start has been made, but the established paths and relationships are still very fragile and need to be nurtured to grow and strengthen. As already said, there appears to be the possibility to develop shared goals, motivations and representations in the context of the Strategy 2100 but this is *'a little plant'* to be treated with caution and care to grow.

Future of coastal protection

The future results from the past and is built in the present. Regarding the future of coastal protection and its forthcoming development, one has to take a look into the historic development of coastal protection in the investigation area (c.f. section 4.1) to identify main drivers behind change and development. In the case of coastal protection, these drivers, which are at the same time historic markers for rethinking, renewal and innovation, are usually major storm surge events. The last of which was the storm surge in February 1962.

> *'Well, it's difficult to assess because it has been very event-driven in the past, especially from the storm surge in 1962, after which we actually had a peaceful time.'*

Especially the developments in German coastal protection and on the side of the institutional management in the past decades were initially triggered by this disaster. Due to the lessons learnt by those working in coastal protection, storm surges since then did not have such a disastrous impact and did not claim lives and livelihoods of coastal dwellers. Although, for example, during the storm surge events in January 1976, November 1981, January 1990, January 1994 or December 2013 comparably high or even higher water levels were recorded for the tide gauges at Wittdün on Amrum and Wyk on Föhr (MELUND, 2022; MELUR, 2015), these events did not have such disastrous impacts and therefore do not play such an important role as historic markers in the coastal dwellers' mindset. One might now think, that the future development of coastal protection is unclear, unpredictable, as its main driver has been metaphorically objectified as quite *'peaceful'* in the recent past. However, the new drivers called climate change and its consequences have come into focus and are a major challenge highlighting the need for current adaptation.

> *'If I look at coastal protection as, well, a form of infrastructure that has to be adapted, the requirements for making such adaptations to the infrastructure have become increasingly demanding.'*

This representation highlights the upcoming challenge regarding the adaptation of coastal protection by the responsible authorities. Even without severe storm surges and storms with considerable damage, this challenge is outlined as particularly *'demanding'* calling for more work to be done. Nevertheless, a social consensus is still seen with regard to maintaining the demanding and costly protection of the coasts. There is no social legitimisation for abandoning individual islands or coastal sections as society is still prepared to jointly bear the high costs of coastal protection today and in the future.

> *'I am quite happy to live in a time when we are in a position to raise these funds in order to be able to protect the people in these exposed locations, and thus also ourselves. That should not be disregarded.'*

Reference is made here to the fact that the so-called barrier islands in front of the North Frisian Coast, in combination with the coastal protection on the coast, protect the mainland. This representation outlines that island protection equals coastal protection, as they are (in) the first line of defence against the North Sea. In addition to their purely protective function, the coast and above all the North Sea islands, moreover, have a high economic value, as island tourism generates high tax revenues for the federal state, whereas the islands finance their protection and preservation virtually by themselves.
One of the most prominent measures to adapting existing coastal protection to climate change, that is being pursued in the federal state of Schleswig-Holstein, is the so-called 'climate dike' (cf. Hofstede (2019a) and MELUND (2022)). According to this measure, existing dikes should and will be raised and, above all, widened so that the dike crest becomes wide enough to be raised again in the future by means of a 'cap' to be placed on top. While this approach reacts to the estimated sea level rise and makes coastal protection structures such as dikes more adaptable to changing boundary conditions, it still poses a one-sided approach to the problems coastal dwellers will be facing. Merely concentrating on the aspect of protecting lives and livelihoods, it currently lacks to incorporate ecological and societal concerns and aspects of coastal protection associated with these.

> *'But my position is that a climate dike can only ever be an interim solution. It only postpones, so to speak, truly sustainable adaptation measures to the ever-rising sea due to global warming. Of course, it is right to build such climate dikes, no question about that. But to leave it at that, I don't think that's the right way (...).'*

Here, the climate dike is represented as a matured concept for the current transition phase, but not truly a sustainable adaptation fit for future challenges and changes. Integrative coastal protection, however, can be a sustainable solution as the following quote indicates:

> *'In the end, the decisive question is whether this transformation succeeds, so to speak, that coastal protection also thinks about nature.'*

If this path is followed in the future, and nature conservation as well as societal concerns have to be taken into account, the need for interdisciplinary cooperation will increase significantly and a reflection of the needs of coastal dwellers will become an important part of planning and implementation.

> *'(...) the necessity to work with many actors will become much greater than it already is.'*

In order to bring about such a change in coastal protection practice and, for example, to generate multiple benefits with NbS, many interviewees believe that societal change is still needed.

> *'(...) this requires a fundamental societal change in coastal protection, in the guidelines and also the paradigms in coastal protection, but also in societal acceptance as a whole, in the public (...)'*

> *'We have to become more amphibious, if I may say so casually, in order to cope with the long-term future. In other words, we have to make friends with more water in the coastal region, I can't really imagine it any other way.'*

Here, these representations re-connect to the historical developments as depicted in section 4.1 because a change in the rationale of coastal protection also requires societal change. A new mind-set cannot be achieved overnight because new professional paradigms require social reflection and integration as well as a change in mentality as expressed by becoming *'more amphibious'*. This change needs time and can only take place and succeed by gathering experience with nature-based measures in coastal protection. To *'make friends'* with changing boundary conditions, changing landscapes and changing forms of coastal protection, the responsible authorities need to start experimenting with NbS today, while problems and threats along the coasts are not yet that pressing. To achieve societal change towards or even start a paradigm shift in coastal protection, all relevant actors need to be taken into account and participate in the small-scale processes as previously outlined. The range to be thought about here goes from scientific research to even making coastal protection a social topic to pave the way towards a more nature-based future in the field.

4.4 Selected investigation sites

Two exemplary investigation sites, one on each island, are chosen for further consideration and application of the concepts developed within the scope of this thesis. The selection is based on the 35 interviews conducted for this work and reflects upon locations that are mentioned by the interviewees.

On Amrum, the *'Steenodder Kliff'* and on Föhr, the *'Hedehusumer Geest'* will be looked at more closely. Both locations are chosen, because they are mentioned several times in the interviews by interviewees from different actor groups (7 mentions of Steenodder Kliff by authority, NGO and locals; 5 mentions of Hedehusumer Geest by authorities and locals). At present, both locations are not being protected by major structures, but challenges or problems and, therefore, a need to act are being identified by mainly local actors.

The Steenodder Kliff is located at the east coast of Amrum (see figure 4.14) in coastal area A3 according to the sectoral plan for Amrum (LKN.SH, 2017). It is a low-lying coastal stretch with a very narrow fronting beach and a small cliff in some parts. Adjacent is the hiking and cycling trail that runs parallel to the coast, to which fields and meadows connect inland. In the past, the shoreline here was temporarily protected with sand or shingle fillings.

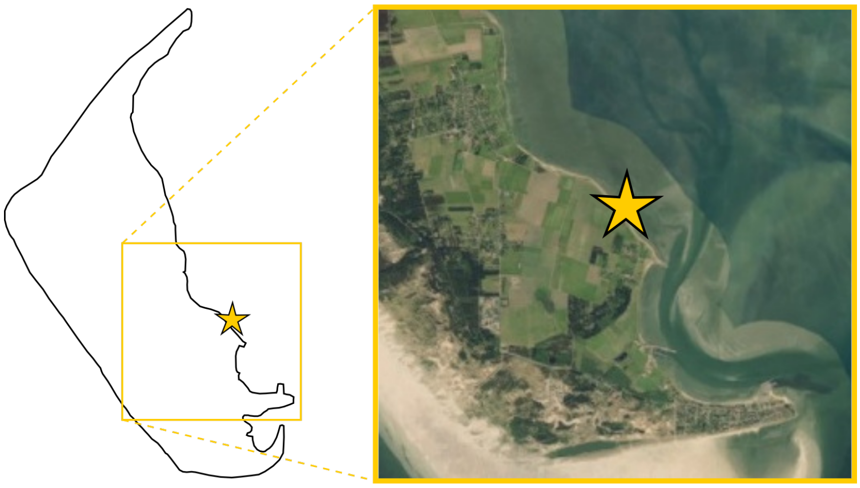

Figure 4.14: Location of the Steenodder Kliff on the east coast of the island of Amrum (modified excerpt from satellite picture on the right from base map: `https://cloud.maptiler.com/maps/hybrid/`).

Figure 4.15: The Steenodder Kliff looking northward with the coast-parallel hiking trail (left, photo taken in October 2022), and looking southward erosion as well as land losses and destruction of the trail after storms in the spring (right, photo taken in May 2022 by L.K. Schwede).

Identified problems here are erosion and land losses, especially during storm events, and the increasingly frequent damage or destruction of the path (see figure 4.15), which is then impassable for a longer period of time and has to be relocated further inland. Possible protection to prevent erosion could be a revetment to secure and fix the coastline or the development of salt marshes in the coastal foreland to serve as a buffer zone during storm events.

The Hedehusumer Geest is located at the south-west coast of Föhr (see figure 4.16) in coastal area A3 according to the sectoral plan for Föhr (LKN.SH, 2019). The existing small beach there shows some initial dune vegetation and foredune development, followed partly by a small cliff or ridge, partly by a narrow belt of lower dunes. In some stretches, agricultural land is located directly adjacent to it.

Figure 4.16: Location of the Hedehusumer Geest on the south-west coast of the island of Föhr (modified excerpt from satellite picture on the right from base map: `https://cloud.maptiler.com/maps/hybrid/`).

Figure 4.17: The Hedehusumer Geest showing land losses at the edge of the farmland (left, photo taken in October 2022), and erosion of the narrow dune belt (right, photo taken in March 2022).

Identified problems and challenges are also erosion and farmland losses during storm events, as can be seen in figure 4.17. To protect the adjacent farmland from being eroded more and more, a dike could be built to separate the hinterland from the sea, or the dune development could be further promoted to form a more natural transition zone between land and sea.

4.5 Summary and interim conclusion

4.5.1 Summary and discussion

The issue of coastal protection is, besides relevant technical craftsmanship, considerably permeated and structured by social processes. The pervious analysis of various synchronic perspectives, visions and assessments of how to carry it out in the present and the future clearly indicate this aspect and reveal problems as well as potentials for further development that do not exclusively require technical improvement, but also social negotiation on institutional, scientific and social levels. Obviously, present events and experiences socially structure the field and are, in part, negotiated against the background of the past. In fact, it became diachronically and synchronically apparent, that coastal protection is a socio-technical practice that is situated at the interface between nature and culture. Here, disagreements and tensions between various groups involved represent a steady process over time that has now and then been overcome, as shown in the historical section 4.1, by constant negotiation and tinkering. Hence, the question whether *'the history of protecting the North Frisian Islands against the sea is characterised by a rigid and confronting rationale or if a dynamic logic can be disclosed that contributes to a more experimental evolution of coastal protection?'* can be answered with a no and a yes. Experimenting with different measures including diking, as displayed in the diachronic as well as in the synchronic section, clearly indicate that both rationales have been used, but on the basis of a dynamic and problem-oriented negotiation of the natural and the social requirements and contexts. This becomes visible on Amrum where never only one concept or rationale of coastal protection existed, but always a variety, if not an explicit diversity of approaches best-suited for respective locations, was chosen. Coastal protection issues were dealt with pragmatically and very much relied on combinations of proven concepts and new techniques. On the island of Föhr, however, the north was characterised by diking and the elevated south of the island possesses a certain degree of so-called natural protection against the sea. Various measures also co-existed on Föhr over the centuries, but their areas of application appear to be spatially separated from each other. Although diking evolved over time as a major part of Föhr's protection strategy, it was not the exclusive one because combinations of grey and green measures were tested and implemented, advancing the island's coastal protection. Similar to Amrum, the impact of external natural events worked as the driver for incremental development and change in coastal protection and assisted in creating the versatility of the concept of diking. However, the analysis of the history of coastal protection on both islands discloses a dynamic rationale which is characterised by a constant and pragmatically oriented experimenting and testing of different concepts and measures.

Contemporary visions of coastal protection exhibit superficial coherence while a closer look – as the interviews show – reveals diverging if not disagreeing perspectives on coastal protection. Answering the question *'In what way and to what extent is the prevailing rationale* *of coastal protection anchored in the minds of the people and what role do past experiences and memories play in the present?'* reveals certain contradictions. On the one hand a set of consolidated representations can be disclosed which are, on the other hand, from time to time challenged or critically deconstructed. Coastal protection, including the concept of the climate dike, is prevailingly assessed as useful, adequate and trustworthy for the time being. Diking and other measures such as stalk plantings in dunes or the construction and maintenance of brushwood groynes to generate foreland coexist. These concepts and techniques are not questioned as they represent well-established and ubiquitous ways of protecting the coast. Following this rationale in the recent past, approaches to coastal protection like NbS, that differ from the concept of diking, were often met with scepticism on the local level and treated by institutional, political, NGOs and local representatives with initial doubt. People in the region as well as the aforementioned representatives seem to have lost sight of the fact that coastal protection has always been and still is a dynamic endeavour while the need and the relevance of coastal protection remain unchallenged. A critical, if not problematic relation nestles in-between coastal and nature protection. This latent conflict goes back to the implementation of the national park in North Frisia where the relevance of protecting nature supposedly superseded coastal protection and since then provokes, as outlined beforehand, irritation among representatives of coastal protection and nature conservation. A culture of non-communication and envy characterises this relation which openly materialises in contexts where members of both parties meet while possibilities for cooperation in projects appear to be a viable way to dissolve this conflict step by step. To summarise, a long-standing image of path dependency exists with regard to diking as an adequate way of protecting the coast while this image is now and then challenged and not corroborated in practice. NbS are met with scepticism among local actors and some institutional representatives while some protective measures already in place appear to be in fact NbS, indicating that they have practically though not conceptually entered the area of coastal protection.

Against this background the second part of the question - *'and what role do past experiences and memories play in the present?'* - seems to be relevant. The diachronic and synchronic analysis of the historical developments together with the synchronically existing representations revealed that without tinkering, experimenting and testing, progress in terms of doing coastal protection differently could not have been achieved. Numerous references in the analysis show how present past experiences are. Vivid narratives about storm surges and the historicised fight against the sea depict a lingering image of threat and fight requiring a controlling containment of the water. This shows its social influence on the perception of coastal protection. The historical contingency of the Frisians, who created an embanked coast while *God created the sea*, characterises the prevailing way of how coastal protection is currently perceived and carried out. However, this consolidated path-dependency is contrasted with a willingness on the side of some interviewees to experiment and work with NbS measures which are currently applied in interdisciplinary projects. Hence, there is a sensitivity of rethinking coastal protection along different lines although this is currently unincisive. As a solution, indicated by some interviewees, small projects currently offer testing grounds not only for providing new or more elaborated technical solutions for coastal protection in terms of NbS, but also to provide places where actors and interested persons can meet, experience and negotiate these measures. It be-

came apparent that the social aspect of such projects should not be underestimated.
Finally, one might ask *'What role can the analysis undertaken here play in the context of future coastal adaptation with regard to NbS?'* Knowledge and learning about and from the past hold the potential to reshape current images and productively reflect existing perspectives. The diachronic and synchronic results clearly indicate that coastal protection also is a genuine social endeavour. Besides technical aspects, questions of engineering and scientific research, the social dimension of coastal protection in its own right has only been revealed in the historical research while there appears a need not only to acknowledge but to practically re-introduce the social dimension into coastal protection. Contemporary analyses addressing the social dimension are scarce and, in many cases, do not engage with the social processes at work in negotiating measures of coastal defence. The qualitative analysis of the different perceptions not only took stock of current perspectives, disputes and their basic structures, it also searched for a way forward to overcome implicit ideologies and mental lock-ins. The underlying perceptions pre-structure any negotiations of coastal protection and impacts on changing the rationale of coastal protection towards NbS. Small projects provide space for thinking and commonly gaining experiences, places to personally meet and interact. To get to know each other, and to cooperatively find a solution for a specific problem is conceived as a way to develop communities of practice that facilitate negotiation, co-construction, and finally testing of measures such as NbS, which can be possible signposts for the future of coastal protection.

4.5.2 Interim conclusion

Climate change and the changing boundary conditions with which coastal protection must ultimately compete as a result have opened the door for discussion about these very signposts (see section 3.3). Coastal protection, which has been performing well up to now, is being confronted with new physical but also societal challenges. The Strategy 2100 (MELUR, 2015) represents a major document for the investigation area and the region of North Frisia as a whole, that is intended to help translate the paradigm shift already emerging in society into coastal protection practice. In this highly engineered world, it is easy to forget that things also used to work differently in the past, as revealed in this chapter. Nature and natural ecosystems are robust by nature. Regarding coastal protection, one only has to find a way to make use of this inherent robustness or resilience again. As an addition to the existing protection, NbS might fit in well to tackle the adaptation challenges ahead (c.f. van den Hurk et al. (2022) and section 3.4). Since NbS inherently bear an integrative moment, they can bring culture and nature together and help overcome competing uses or existing conflicts of interest.
Coastal ecosystems that may serve as NbS in future coastal protection (and are already effectively protecting and benefiting many coastal areas around the world) are analysed in detail in the following chapter, taking into consideration Water, Nature and People, hence protection as well as ecological and societal concerns.

5 Nature-based Solutions on sandy coasts

Parts of this chapter have already been published in Jordan and Fröhle (2022).

As revealed in the analysis in the previous chapter, certain nature-based measures - which would nowadays fall under the umbrella term of NbS - have existed in coastal protection for decades or even centuries and evolved just like traditional, structural coastal protection measures did. Nevertheless, nature-based measures are not yet really established as an equal option in practice or in general perception.
Within the scope of this chapter, the following will be investigated:

- Which natural coastal ecosystems can be used as NbS in coastal protection?
- Where and under which conditions do natural coastal ecosystems thrive?
- Which processes within or provided by these ecosystems protect and stabilise sandy coasts?
- Which further benefits do these ecosystems provide to promote and cover ecological and societal needs?

Thus, the full potential of coastal ecosystems as an addition or adaptation to the existing coastal protection to cope with the challenges caused by climate change will be disclosed. These insights, gained through an extensive literature review, in combination with the analysis of expert interviews pertaining to the potential of NbS in coastal protection will help to provide answers to the following two research questions:

- How is the relevance of NbS for future coastal protection assessed by experts?
- Do coastal ecosystems as NbS in addition to the existing coastal protection offer a chance to bridge the gap between coastal engineering and nature conservation in the land-sea transition zone?

5.1 Terminology

When discussing ‘Nature-based Solutions’ a variety of different definitions and terminologies arise and one can easily get confused by the range of wordings or brandings used in scientific publications as well as in policy documents and recommendations. To structure the concept and to define a clear terminology for this work, the term ‘Nature-based

Solutions' was identified as the main caption for the measures investigated in this work. Regarding the meaning of the individual words of which the term is made up, C. Albert et al. (2019) point out the descriptive part of the first term ('nature-based'), which suggest the essential role of natural or self-regulating ecosystem processes. Secondly, the word 'solution' implies that a predefined challenge should be solved. Hence, the ecosystem processes are evaluated against their contribution to problem-solving.

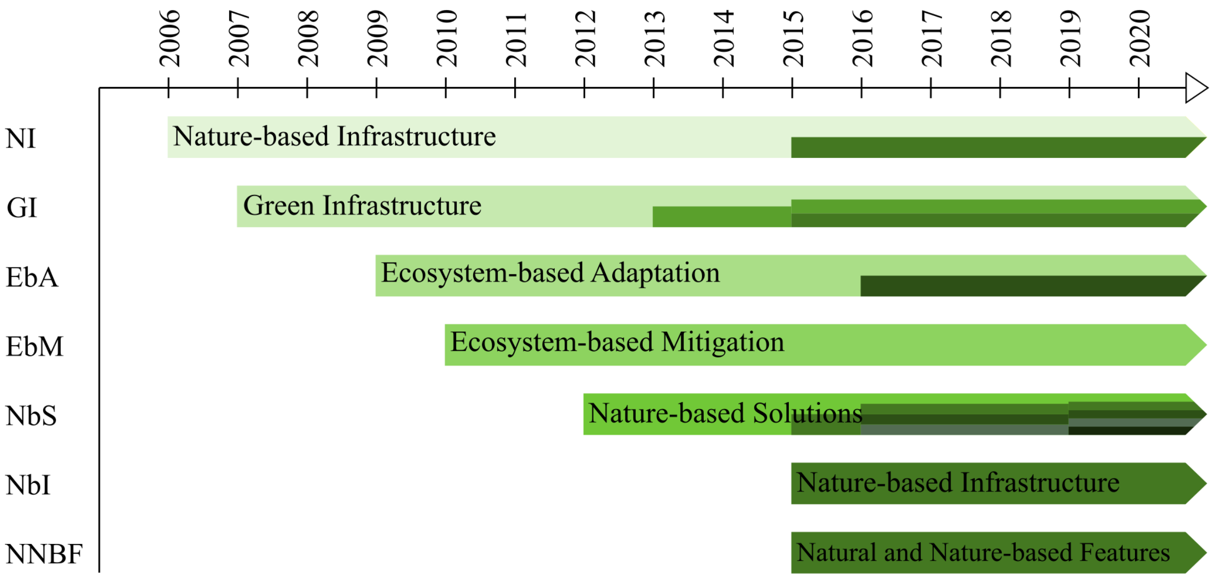

Figure 5.1: Overview of the evolution of the term 'Nature-based Solutions' and associated terms focusing on arising new definitions; new colour-bar indicates the arising of a new or adapted definition of the same term (cf. table A.1 in appendix A). Previously published in Jordan and Fröhle (2022), revised for PhD.

Bearing this in mind, the evolution of the definition of Nature-based Solutions can be investigated. A brief overview of the terms' evolution is depicted in figure 5.1. While terms such as 'Natural Infrastructure' (Benedict and McMahon, 2006), 'Green Infrastructure' (Tzoulas et al., 2007) or 'Ecosystem-based Adaptation and Mitigation' (CBD, 2009; CBD, 2010) arose earlier, today they can be regarded as subsets of NbS. An overview of the key aspects of the different terms associated with and definitions of Nature-based Solutions can be found in table A.1 in appendix A.

A first and widely accepted definition for NbS by IUCN (2012) briefly describes NbS as a concept to actively promote nature for climate mitigation and adaptation purposes. According to the European Commission (2015), NbS *'aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges as well as exploring more novel solutions. Nature-based solutions use the features and complex system processes of nature (...) in order to achieve desired outcomes, such as reduced disaster risk and an environment that improves human well-being and socially inclusive green growth'*. Building on this, the IUCN's definition was

refined, emphasising the multi-benefit character of NbS, which are defined as *'actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits'* (Cohen-Shacham et al., 2016). Lately, C. Albert et al. (2019) included a policy perspective into the definition of NbS, stressing the importance that NbS are *'embedded within viable governance or business models for implementation'*.
The terms 'Nature-based Infrastructure' (Bridges et al., 2015) and 'Natural and Nature-based Feature' (Bridges et al., 2015) can also be regarded as a subset or respectively a mechanism of NbS.
Within the scope of this thesis, Nature-based Solutions are defined as measures that use characteristics and effects of natural features like coastal ecosystems for climate adaptation and to promote nature while simultaneously providing protective, ecological and societal functions or benefits.

With a focus on flood protection and coastal risk reduction various frameworks or concepts exist, that deal with NbS. The common goal is to use natural processes to serve the fields of **Water**, **Nature** and **People** - thus facilitate societal, economic and ecological benefits. The most prominent national and international frameworks are listed below.

- **Building with Nature**, BwN (Netherlands): The BwN concept develops multi-functional solutions through the use of natural processes and ensures that they are *'aligned with the interests of both nature and stakeholder'* (Vriend and van Koningsveld, 2012).

- **Ecological Engineering**: Ecological Engineering is defined as *'the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both'* (Mitsch and Jørgensen, 2003).

- **Engineering With Nature**, EWN (USA): The USACE's concept of EWN is based on the *'intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental and social benefits through collaborative processes'* (USACE, 2012).

- **Living Shorelines** (USA): The Living Shorelines framework pursues several goals such as shoreline stabilisation, ecosystem services provision or interconnections between land and water ecosystems (SAGE, 2015).

- **Soft Engineering**: *'Soft engineering aims to work with nature by manipulating natural systems which can adjust to the energy of the waves and tides to good effect and has the potential for achieving economies whilst minimising the environmental impact of traditional engineering structures'* (Pethick and Burd, 1993).

- **Working with Nature**, WwN (PIANC, worldwide): PIANC's WwN concept is centred around the identification and exploitation of *'win-win solutions which respect nature and are acceptable to both project proponents and environmental stakeholders'* (PIANC, 2011).

5.2 Coastal ecosystems as Nature-based Solutions

In light of the terminology described above as well as the definitions and the various subsets of NbS, natural and semi-natural ecosystems are to be considered the most pristine NbS. As per definition by the Millennium Ecosystem Assessment Board, *'an ecosystem is a dynamic complex of plant, animal, and microorganism communities and the nonliving environment, interacting as a functional unit'*, including humans as an integral part of many ecosystems (Watson and Zakri, 2003). Intact ecosystems naturally provide diverse benefits to humans and nature equally. These benefits, that people obtain from ecosystems, are called ecosystem goods and services (Watson and Zakri, 2003). Hereafter, they are collectively referred to as ecosystem services. Displayed in table 5.1 grouped after their function, these include selected provisioning, regulating, cultural and supporting services, which, as the name suggests, are the basis for the provision of all other ecosystem services. As ecosystems offer a wide range of services, not all can be mentioned and listed here.

Table 5.1: Ecosystem services - functional groupings as supporting, provisioning, regulating and cultural services according to the Millennium Ecosystem Assessment (Watson and Zakri, 2003).

Provisioning Services	**Regulating Services**	**Cultural Services**
Food and fibre	Air quality maintenance	Cultural diversity
Fuel	Climate regulation	Spiritual and religious
Genetic resources	Water regulation	Knowledge systems
Biochemicals	Erosion control	Educational
Ornamental resources	Water purification	Inspiration
Fresh water	Waste treatment	Aesthetic
	Disease regulation	Social relations
	Biological control	Sense of place
	Pollination	Cultural heritage
	Storm protection	Recreational and ecotourism
	Supporting Services	
Soil formation	Nutrient cycling	Primary production

Since the focus of this work is on sandy coasts and their protection and preservation, the most significant coastal ecosystems, that represent possible NbS to coastal threats like storms or erosion, are presented in the following sub-sections.
Regarding the scale of this investigation, featured ecosystems include **wetland** (salt marshes, mangroves and seagrass meadows), **beach** (beaches and dunes), and **reef ecosystems** (coral and shellfish/oyster). Offshore islands and **barrier islands**, that border many sandy shorelines sheltering wetlands, bays and the mainland coast from direct offshore impacts - thus fulfilling an outstanding function for coastal protection - can be considered separate ecosystems themselves (cf. Feagin et al. (2010)). They are, however, to be assigned to a broader scale of investigation, as they are essentially composed of many of the

aforementioned basic coastal ecosystems of finer scale examined below. Therefore, offshore and barrier islands are not studied further within the scope of this thesis or listed as a separate ecosystem. In the following, the different coastal ecosystems are defined and their most prominent characteristics, their formation, natural distribution and existing threats are described. When relevant and suitable, a brief reference is made to the investigation area around the islands of Amrum and Föhr.
Besides flood and storm protection and erosion control, which are considered regulating services according to the Millennium Ecosystem Assessment (Watson and Zakri, 2003), coastal ecosystems provide a number of other important services, which benefit nature and people. These ecosystem services constitute the ecological and societal value of coastal ecosystems. Both coastal protection processes and effects provided by the coastal ecosystems as well as their ecological and societal value are explained in the following. It should be mentioned that the quantification of these processes and benefits is possible, but nevertheless, highly complicated, requires in-depth studies and usually is highly site-specific and difficult to transfer to other locations.

5.2.1 Wetland ecosystems

Wetland ecosystems such as salt marshes, mangroves and seagrass meadows serve as buffers for storms and extreme events while also providing important coastal habitats for a variety of different plant an animal species.

Salt marshes

At the coasts of the seas, the salt marsh zone begins above the line to which the tide rises on average, which is therefore only flooded at irregular intervals. This zone can be characterised as amphibious, i.e. at least occasionally under water, and by a strongly fluctuating salinity. In temperate climates, salt-tolerant herbaceous plants typically colonise such sites, which are then collectively referred to as salt marshes (Zerbe and Wiegleb, 2009). Salt marshes are intertidal ecosystems that form in shallow, low-energy, wave-protected shorelines under continuous sedimentation. They are characterised by a sharp vegetation zonation and rather low species diversity, but a high primary and secondary productivity (Barbier et al., 2011; Rupprecht, 2015). Bio-geomorphic feedback processes between plant growth, water flow and sediment transport and deposition as well as anthropogenic impacts and global change make up the dynamics in salt marsh formation and stability, which enable salt marshes to inhabit these harsh coastal environments (Rupprecht, 2015).

Salt marshes can develop naturally on shallow sandy or muddy coasts where sediments are eroded with each tide and redeposited in areas of low current speed and wave height. Over time, this creates areas along the coast that are flooded less and less frequently. Here, the first pioneer plants can spread such as the glasswort (*Salicornia*) in case of the North Sea Region, which can tolerate very high salinity levels. Young shoots and dead parts of the plants promote sedimentation on the surface. They act like a filter, retaining the sediment on the surface at low tide. This positive feedback accelerates the growth of the area accordingly. With an extensive pioneer population, the land is already high enough to

no longer be flooded with every tide. Now, other plants such as common saltmarsh-grass (*Puccinellia maritima*) can spread, which, for example, additionally stabilises the young salt marsh through its root formation and leaves lying close to the ground. Especially where the first plants grow, debris and sediment are more strongly retained. At the beginning, the vegetation is therefore not yet evenly distributed, but in patches over the entire area (Küster, 2015). Currents tend to concentrate around these patches of salt marsh vegetation, which can lead to the formation of tidal creeks or channels, through which the salt marsh is drained from this point onwards (Best et al., 2018). The salt marsh continues to grow in its further evolution with each flooding and more plant species settle. As the sea-ward edge of the salt marsh is flooded more frequently by the tide, over time it grows faster than the areas further in-land, forming so-called bank ridges (Küster, 2015).
Many salt marshes that can be found along the coasts today are actually not naturally grown ecosystems, but their development was once triggered and promoted by man-made interventions in the coastal landscape. In the south-eastern North Sea Region for example, salt marshes are created with the use of sedimentation fields, brushwood groyne fields, in which low hydrodynamic energy conditions enable sediment deposition. Artificial creeks and channels enhance the drainage of the area and therefore accelerate marsh formation. For decades or even centuries, until the mid-20th century, land reclamation measures were implemented to create arable land for cattle or sheep grazing or mowing (Thorenz, 2014). Thus, the majority of today's salt marshes in the foreland of the dikes in the North Sea Region thrive on sites that in many places could only be developed with human support under the protection of brushwood groynes (Stock et al., 2012). In many man-made marshes, however, artificial drainage systems persist even decades after their abandonment and the well drained conditions are related to shifts in vegetation cover such as the formation of rather homogeneous plant populations, which on the one hand alter the stability of the marsh and on the other hand provide less suitable habitats for breeding birds (Rupprecht, 2015; WWF Deutschland, 2018).

Salt marshes can be found throughout the world in mid-elevation coastal zone in temperate regions, while in the subtropics and tropics mangroves widely occur in similar environments (J. L. Gutiérrez et al., 2011; Nolte et al., 2013; United Nations, 2016). As depicted in figure 5.2, salt marshes can be found on every continent except Antarctica and cover an estimate of 22,000 to 400,000 km^2 worldwide (Mcleod et al., 2011).

> *With regard to the investigation area:* According to Rupprecht (2015), the Wadden Sea area in north-western Europe includes around 400 km^2 of salt marshes, accounting for approximately 20 % of the European salt marshes. In the investigation area, larger salt marsh forelands can be found in the north of Föhr as well as the north-east of Amrum and used to exist around the easternmost tip of Föhr.

The natural composition of vegetation in salt marshes is determined by both abiotic factors as well as biotic processes. Decisive abiotic factors are elevation, salinity, flooding and nutrient availability. Relevant biotic processes are competition and facilitation among flora and fauna (Rupprecht, 2015). Salt marshes are semi-terrestrial habitats. Trees cannot

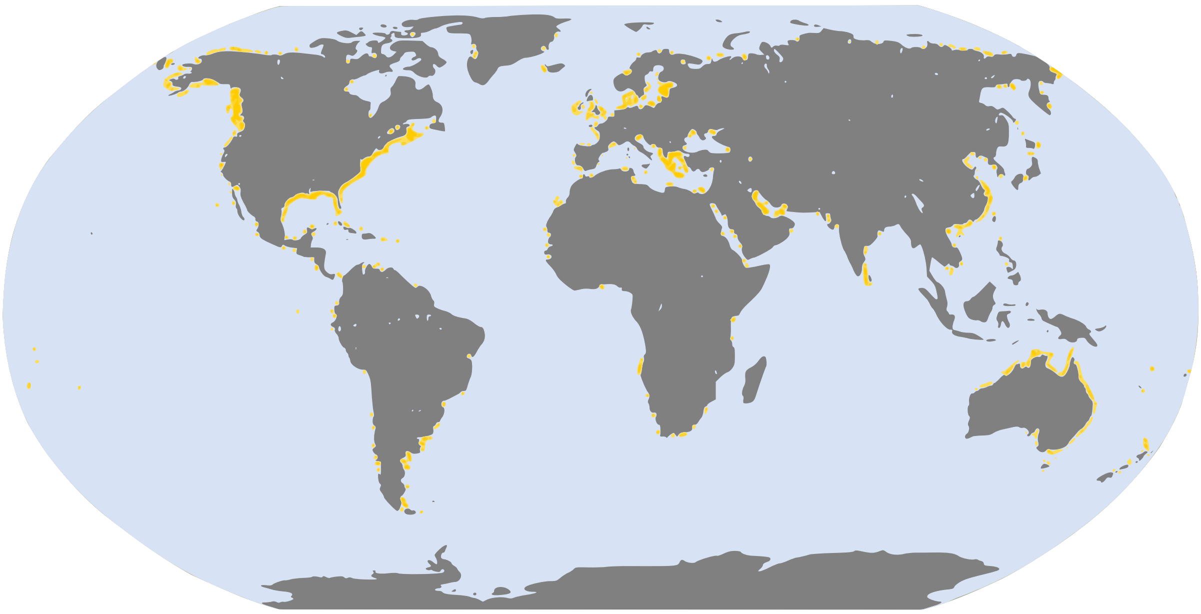

Figure 5.2: Global distribution of salt marshes in yellow after Mcowen et al. (2017); previously published in Jordan and Fröhle (2022).

thrive in this environment, but vascular plants, so-called halophytes, which are adapted to the conditions, can. These plant species have developed various strategies against the high salinity, including amongst others ion barriers on roots (e.g. *Puccinellia maritima*), salt glands (e.g. *Armeria maritima*) or desalination hairs (e.g. *Atriplex portulacoides*). Some species compensate for the high salinity levels by taking up additional water (e.g. *Salicornia europaea*). Further inland, beyond the transition to the terrestrial, hence no longer intermittently flooded area, the salt-tolerant halophytes are increasingly supplanted by the non-salt-tolerant glycophytes (Kollmann et al., 2019).

A characteristic feature of the salt marsh habitat is the vegetation zonation caused by its marginal location at the sea. The high tide line, as the extreme of the living conditions in the transition zone between land and sea, represents an important boundary line from which the number of species of plants and animals settling both above and below it increases (Stock et al., 2012). Depending on the elevation above sea level, and thus also the frequency of flooding and the salinity, three typical vegetation zones emerge (see figure 5.3), which are subject to succession (Kollmann et al., 2019; Stock et al., 2012; Zerbe and Wiegleb, 2009).

- **Pioneer Zone**: The pioneer zone begins approximately 40 cm below the mean high tide line and extends up to just above it. On average, this zone is still flooded daily. Here, mostly annual glasswort communities can be found.

- **Low Salt Marsh**: The low marsh ends approximately 35 cm above the mean high tide line and is therefore, depending on the elevation, flooded between 100 to 400 times per year. Species-poor dominant populations such as common saltmarsh-grass communities form the predominant vegetation here.

- **High Salt Marsh**: The high or upper marsh succeeds the low marsh. Situated above the spring high tide line, this zone is only flooded between 40 to 70 times per year. The predominant vegetation are species-poor dominant populations like red fescue communities (*Festuca rubra*).

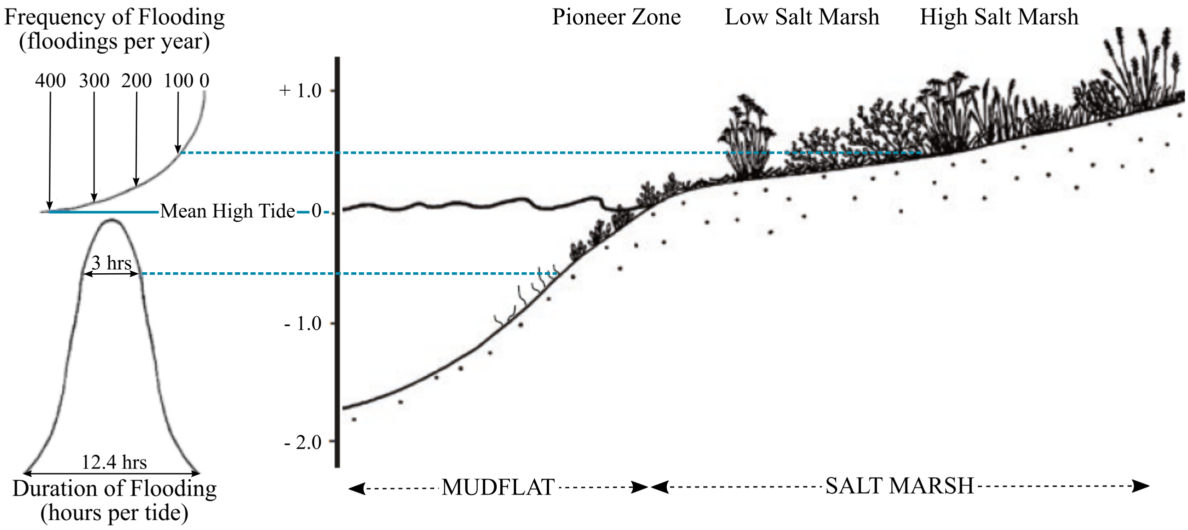

Figure 5.3: Vegetation zonation in salt marshes depending on frequency and duration of flooding after Erchinger (1985) and Kollmann et al. (2019); previously published in Jordan and Fröhle (2022).

The three zones are not to be understood as clearly defined sectors. The transitions between the zones are smooth and vary from site to site. Thus, species of the lower salt marsh occur in the pioneer zone and typical species of the upper salt marsh in the lower marsh. Grazing on salt marshes also leads to a shift in vegetation zonation.

> *With regard to the investigation area:* In north-western Europe, there are 40-60 species of vascular plants that are adapted to saline conditions and can be described as halophytes (Kollmann et al., 2019). Typical species in the pioneer zone are European glasswort (*Salicornia europaea*) as depicted in figure 5.4 and common cordgras (*Spartina anglica*). The common saltmarsh-grass (*Puccinellia maritima*) and sea purslane (*Atriplex portulacoides*) for example, can be found in the low marsh. The high marsh is characterised by couch grass (*Elymus athericus*) or red fescue (*Festuca rubra*) (Rupprecht, 2015).

Salt marshes are intertidal ecosystems. Therefore, they are subject to flooding and, if healthy and undisturbed, can tolerate and resist frequent flooding with saline water as well as mechanical stresses induced by currents, waves or sometimes ice scour (Rupprecht, 2015). Nevertheless, salt marshes range among the most heavily used and therefore threatened ecosystems on earth (Kirwan and Megonigal, 2013), which are degrading at an estimated global loss rate of 1-2 % yr^{-1} over the last decades (Duarte et al., 2008b). The

reasons for these losses are manifold. Natural extremes - in coastal areas mainly extreme storm events - can be the cause for salt marsh losses, as was e.g. historically the case with the first ‘Grote Mandränke’ in 1362 (Böse et al., 2018), one of the first well documented devastating storm surges in the North Sea that caused severe loss of life, property and land in the area. Most threats however, are caused by human-induced alterations to the ecosystem itself or the surrounding landscape. Elevated atmospheric CO_2 concentrations, increased temperatures and eutrophication represent negative indirect human impacts or threats. Direct human modifications, which pose threats to salt marshes, are shoreline development and embankment of salt marshes to gain arable land. Historically, activities like peat cutting also resulted in the loss of many salt marsh communities, for example along the south-eastern North Sea coast. Hydrological alterations in salt marshes like ditching for soil drainage may threaten the ecosystems’ stability as well (Rupprecht, 2015).
Assessing a salt marsh’s sensitivity to such threats is highly complicated, because salt marshes like many other coastal ecosystems show an ‘alternative stable state behaviour’. They can in fact exist in various different stable states but once a certain threshold is passed, may collapse entirely (Rupprecht, 2015). Depending on sea level rise projections and available suspended sediment concentrations, salt marshes are estimated to be extremely resilient to sea level rise. They can either migrate landward where sufficient space is available or keep up with sea level rise by sediment accretion. If sediment is not sufficiently available, and landward migration is hindered by man-made structures, salt marsh ecosystems can drown, marking the transition to subtidal landscape. Besides, under the accelerated rise in sea level, there most probably is a critical stability threshold below which salt marsh ecosystems can survive and above which they drown. Thus, sea level rise poses the major threats to salt marsh stability and survival (Best et al., 2018; Bouma et al., 2014; Kirwan et al., 2010; Marijnissen et al., 2020). Depending on emission scenarios, the IPCC (2019) is projecting a global wetland loss of 20-90 % by the end of the century. This includes salt marsh ecosystems as well as mangroves and seagrass meadows. At a local scale, total losses of wetland ecosystems are projected under the RCP8.5 emission scenario with medium confidence.

> *With regard to the investigation area:* A study by Suchrow et al. (2012) concluded that most salt marsh communities in the German North Sea can outpace a conservatively predicted sea level rise of about 0.1-0.2 cm yr^{-1}, but only about half of the marsh areas might be able to keep up with a sea level rise of 0.6 cm yr^{-1}.Thus, salt marshes in the Wadden Sea might not be endangered in the first half of the 21st century but a critical threshold could be passed in the second half.

Coastal protection processes Salt marshes, like several other wetland ecosystems, can make an important contribution to coastal protection. For example, when Hurricane Sandy struck the north-eastern US coast in 2012 including the heavily urbanised coastlines of New York and New Jersey, it is estimated that temperate coastal wetlands like salt marshes reduced property damages by more than 10 % on average and damage reduction benefits reached as high as 29 % in case of Maryland (Narayan et al., 2016b). Processes within salt marshes ecosystems that provide coastal protection can be divided into direct and

indirect mechanisms (Gedan et al., 2011) and either have an impact on the reduction of hydrodynamic loads, shoreline stabilisation and erosion control or water retention.
Salt marshes can effectively attenuate wave energy and current flow through wave breaking caused by limited water depth and damping as well as plant-flow interactions (Fröhlich and Rösner, 2015; Narayan et al., 2016a; Rupprecht, 2015; Sutton-Grier et al., 2018), though the effect of friction on wave characteristics is very small compared to the limitation of water depth. The main, indirect mechanisms that causes wave attenuation and affects wave propagation in the salt marsh therefore is the marsh's ability to built up peat and soil, thus altering the bathymetry (Gedan et al., 2011). This causes wave dampening through changes in water depth. In addition, the salt marsh vegetation has a direct impact on the dampening of wave energy and, hence, wave height through friction between water and vegetation (Narayan et al., 2016a). This process, the dissipation of waves by vegetation, is very complex and variable (Rupprecht, 2015), and depends on a number of different biophysical and hydrodynamic characteristics or factors. Standing biomass, buoyancy, vegetation density, height of the canopy and width of the marsh are important vegetation characteristics to be considered (Anderson et al., 2011; Bouma et al., 2014; C. C. Shepard et al., 2011). The vegetation property of primary interest is the plants' flexibility (Anderson et al., 2011), as it defines the amount of flow resistance plants provide. Important hydrodynamic conditions are water depth or inundation height of the plants and the incident wave characteristics such as wave height and length (Anderson et al., 2011; C. C. Shepard et al., 2011). Although wave attenuation generally is greater, the larger the salt marsh is, even short marsh transects of less than 10 m width can show significant wave attenuation (C. C. Shepard et al., 2011). According to a meta-analysis of sixty-nine scientific studies by Narayan et al. (2016a), salt marshes can reduce wave heights by 72 % (95 % CI: 62-79 %).
A comprehensive review on wave dissipation by coastal vegetation in general - not only by salt marshes - is provided by Anderson et al. (2011). They identify Dean's approach (Dean, 1978), which later on was further developed by Knutson et al. (1982) to better describe the response of plants to wave forcing (e.g. swaying), as one of the first hydrodynamic models for wave attenuation. Although these first advances to quantify the wave attenuating effects of coastal vegetation were published almost 40 years ago, the complex behaviour of different plant species is still not fully incorporated into wave attenuation formulas and there still is research to be done to accomplish this goal. As a current example, the work by Zhang et al. (2020) on smooth cordgrass (*Spartina alterniflora*) can be mentioned. They worked with the wave decay rate by Dalrymple et al. (1984), which assumes that linear wave theory is valid and wave energy dissipation occurs only due to the plants, and which was later extended to random waves by Mendez and Losada (2004). Representing the single plants as rigid cylinders the wave decay rate according to Dalrymple et al. (1984) is

$$\frac{H_x}{H_0} = \frac{1}{1+\alpha x}, \tag{5.1}$$

where H_x and H_0 are the wave heights at the reference point 0 and at the distance x from the reference point in the direction of wave propagation, and α is a wave damping factor theoretically defined by Dalrymple et al. (1984) and later extended by Mendez and Losada (2004). The accuracy of the wave damping factor α largely relies on a proper estimation of

the vegetation-specific bulk drag coefficient C_D, for which Zhang et al. (2020) developed a new formula valid for flexible plants, thus better accounting for the actual plant behaviour when exposed to hydrodynamic forcing. They validated their approach in a field survey in a Chinese salt marsh dominated by smooth cordgrass.
Bouma et al. (2014) developed a strongly simplified and partly measurement-based formula to estimate habitat dimensions needed to significantly contribute to wave attenuation. Their method is valid for areas with shallow to intermediate foreshore slopes where wave attenuation mainly occurs due to friction and not breaking. Under the assumption of the decrease in wave height roughly following an exponential decay, with the main modifiers being cross-shore length L [m] of the habitat and the water depth h, the wave height after attenuation by the coastal habitat (H_L) can be estimated as

$$H_L = H_0 e^{-KL}, \tag{5.2}$$

with H_0 being the incoming wave height and K the decay coefficient. The decay coefficient K after Bouma et al. (2014) is

$$K = k_{habitat} \frac{B}{B_{max}} e^{-dh}, \tag{5.3}$$

with $k_{habitat}$ $[m^{-1}]$ being the habitat-specific, measurement-based decay constant - 0.01 to 0.05 for salt marshes - B and B_{max} being the (maximum) percentage coverage ratio of biota along the coastal habitat's cross-shore length, and d being a measurement-based decay coefficient for the loss of friction with water depth. When deriving the significant wave height by

$$H_0 = 0.3h \tag{5.4}$$

based on the depth-limitation of incoming waves in shallow waters and following the estimation of $d = 1.5$ by Bouma et al. (2014) based on measurements in salt marshes, the wave height after maximum attenuation by a salt marsh habitat (thus maximum coverage, $B = B_{max}$, and $k_{saltmarsh} = k_{saltmarsh,max} = 0.05$) can be approximated by

$$H_{L,saltmarsh} = 0.3he^{-(0.05e^{-1.5h})L}. \tag{5.5}$$

Shoreline stabilisation or erosion protection is provided through various processes and characteristics of salt marsh ecosystems by either changes in the ground structure or the lowering of hydrodynamic loads (Baptist et al., 2019; Fröhlich and Rösner, 2015; Gedan et al., 2011; Sutton-Grier et al., 2015). Aboveground biomass, i.e. branches, stems and leaves, have a direct effect on hydrodynamic loads from currents and waves and can thus promote sedimentation (Baptist et al., 2019). In case of a typical salt marsh canopy, the vegetation exerts a drag force counter the direction of water movement and therefore causes a reduction in turbulence, a deceleration of the flow velocity of the water and a reduction in shear stresses near the seabed (Gedan et al., 2011). Direct effects below ground are caused by the plants' roots. They stabilise the soil and slow erosion rates by enhancing cohesion and tensile strength of the surrounding soil substrate they are growing in, which in turn causes an increase of the soil's shear strength. Furthermore, roots can act as a physical barrier between open water and soil, e.g. along tidal creeks or channels

in the marsh (Gedan et al., 2011; Möller et al., 2014). Even after larger storm events, which cause breakage of vegetation stems, the stabilising function of the root system is maintained and resistance to surface erosion is kept up (Möller et al., 2014). Indirectly, the belowground biomass in the form of decaying roots has a positive effect on erosion stability through the build-up of humus, which is rich in organic material. Compared to typical mineral soils, this type of soil is considerably more resistant to erosion (Gedan et al., 2011).
Besides wave attenuation and shoreline stabilisation, salt marshes have a large water retaining capacity. They can mitigate coastal flooding by reducing storm surge duration and flood peaks through water uptake and holding capacity (Barbier et al., 2011; C. C. Shepard et al., 2011). In the event of a dike breach for example, this capacity can also limit the amount of water flooding the hinterland. Additionally, salt marshes secure the base of a dike against the permanent influence of the tide and thus make a dike foot revetment dispensable (Thorenz, 2014).

Ecological and societal value In a study by Costanza et al. (1998), which attempted to estimate the value of the world's ecosystems by assigning values to different ecosystem services they provide, coastal wetlands like salt marshes were rated among the most valuable ecosystems on earth. In addition to regulating services like coastal protection and erosion control as described above, salt marshes provide a number of other ecosystem services, which benefit humans and nature. Salt marshes represent important linkages between marine, coastal and onshore ecosystems and the services they provide. Supporting services by salt marshes include the high rate of primary production and nutrient cycling within the marsh. Furthermore, they allocate habitat for a large number of flora and fauna, equipped to the specific and harsh conditions (Hassan et al., 2005).
Due to the salt marshes' limited accessibility, provisioning services of coastal marshes include the allocation of important nursery grounds for young fish as well as shrimp and shellfish (Barbier et al., 2011; Kirwan et al., 2016). For a large number of bird species salt marshes are essential for breeding, foraging and resting (Hassan et al., 2005; Rupprecht, 2015).

> *With regard to the investigation area:* The productive salt marshes of the North Sea coast are an important food source for various animal species. In spring and autumn, they are used by flocks of resting migratory birds. These include, for example, Eurasian wigeons and oystercatchers (see figure 5.4, right), brent geese and barnacle geese. In addition to being an essential food source, they are also important breeding grounds for birdlife (Kollmann et al., 2019).

Important regulating services are the improvement of water quality (Kirwan et al., 2016) as well as carbon sequestration (Kirwan et al., 2016; Mcleod et al., 2011; Siemes et al., 2020). Salt marshes sequestrate carbon with an average rate of 210 g m^{-2} yr^{-1} (Chmura et al., 2003).
Cultural ecosystem services are provided by the landscape and, e.g., the bird life in salt marshes in the form of aesthetic ecological values. Birds also serve as important indicators of ecosystem conditions (Hassan et al., 2005). Tourism and recreation constitute further cultural services that are directly related to the landscape and nature.

Figure 5.4: Patches of glasswort in the pioneer zone of a salt marsh in Westerhever, Germany (left), and a flock of Eurasian oystercatchers at a drainage creek in the salt marsh on Föhr (right); previously published in Jordan and Fröhle (2022).

Mangroves

The term mangrove describes both the ecosystem as well as the plant families (Barbier et al., 2011). According to FAO (2007), there are 50 to 70 different species that are considered to be mangrove-type vegetation. The species richness in one location largely depends on the prevalent wave load, the range of air and water temperatures, the tidal amplitude, mineral nutrients, light, rainfall variation and the frequency of tropical storms (Augustinus, 1995). In Asia conditions seem to be especially favourable, as the highest species diversity can be found here, followed by eastern Africa (FAO, 2007). Mangroves are perfectly adopted to loose and wet soils, periodic tidal submergence and saline to brackish waters. They fringe the shorelines or the intertidal zone of estuaries, occupying the waterlogged and anoxic soils (J. L. Gutiérrez et al., 2011). Mangroves are often falsely regarded as merely the tropical equivalent of salt marshes, although they differ from salt marsh ecosystems in two defining aspects. Instead of herbs, their vegetation structure is composed of trees and shrubs, and, with respect to their position to the mean high water line, they can grow in lower areas than salt marshes due to their rooting system (Augustinus, 1995).

Where mangroves develop, they are often pioneers to the area, e.g. colonizing newly formed mudflats (Alongi, 2008). As an adaptation to the tidal conditions, some mangrove species produce viviparous seedlings (e.g. *Rhizophoraceae* or *Avicenniaceae*). Compared to regular seeds, the propagules have the advantage that they can take root faster when they touch the ground since they do not have to germinate first (Augustinus, 1995). Mangrove development or successful establishment is characterised by three threshold stages as described by Balke et al. (2011).

1. **Anchorage**: After stranding on a mudflat, mangrove propagules require a minimum inundation-free period to anchor in the soil. Seeds need to germinate first and therefore require more time.

2. **Growth**: In order to be able to withstand hydrodynamic disturbances by waves and currents, the seedlings' roots need to exceed a minimum length.

3. **Resistance**: To resist further disturbances, e.g. from removal of sediment around the seedling, the mangroves' roots need to grow to a sufficient length.

Of course there are no exact values that can be regarded as sufficient root length, as hydrodynamic disturbances as well as boundary conditions such as the soil composition are highly site specific.

In mid-elevation coastal zones, which are home to salt marshes in temperate region of the world, mangroves thrive in the tropics and subtropics (J. L. Gutiérrez et al., 2011; Quang Bao, 2011; Stock et al., 2012), as shown in figure 5.5. Globally, mangrove forests cover an estimated area of around 138,000 to 152,000 km^2 (World Bank Group, 2016; Mcleod et al., 2011) and can be found in 123 countries (World Bank Group, 2016). 75 % of the world's mangroves are concentrated in just 15 of these 123 countries, of which Indonesia has by far the largest mangrove population, accounting for 22.4 % of the global total. When comparing the continents, the largest extent of mangroves can be found in Asia with 42 % of the global total, followed by Africa with 20 % (Giri et al., 2011).

Figure 5.5: Global distribution of mangroves in yellow after Spalding et al. (2010); previously published in Jordan and Fröhle (2022).

The most noticeable and well-known aspect of mangroves is their aerial rooting system. Mangrove roots are completely or partly exposed to the atmosphere at least part of the day, when not covered by water during high tide (FAO, 2007). The above-ground parts allow gas exchange with the below-ground parts through air holes or lenticels, while the below-ground parts are in charge of anchorage in the muddy soil as well as the absorption of nutrients (Augustinus, 1995; FAO, 2007; Marchand, 2008). The different typical rooting systems, e.g. of three main mangrove species (Avicennia, Rhizophora and Bruguiera), depicted in figure 5.6, allow easy differentiation of species. The Avicennia type has a star-shaped network of cable roots radiating out from the trunk. From these cable roots, anchor roots are shooting downwards and aerial roots, so-called pneumatophores, are shooting upwards. Rhizophora-type mangroves are characterised by a system of prop roots, which arch out from the trunk and anchor the mangrove plant in the soil. The roots of the Bruguiera type radiate out from the bottom of the trunk growing alternating above and below the surface (Augustinus, 1995).

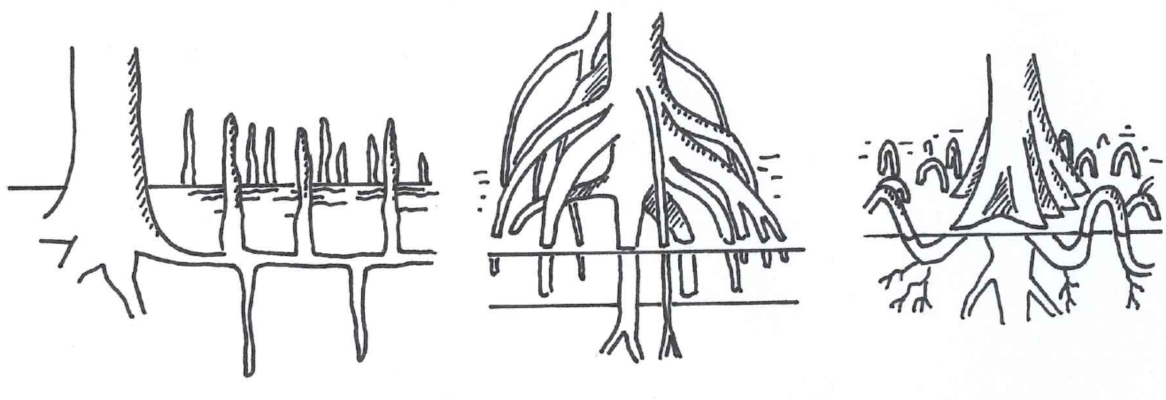

Figure 5.6: Drawings of mangrove rooting systems of Avicennia, Rhizophora and Bruguiera, from left to right, after Marchand (2008); previously published in Jordan and Fröhle (2022).

Despite the area they inhabit, mangroves are actually not very fond of saline water, as it poses a physiological stress factor to them (Marchand, 2008). Nevertheless, they are able to tolerate a broad range of salinities from 0 up to 90 PSU (upper salinity limits occurring in warm and dry tidal areas which are only inundated a few times per year) (Augustinus, 1995), with the usual upper boundary ranking around 2.5 times the salinity of seawater (Hassan et al., 2005). The plants expose themselves to the saltwater-induced stress and compensate for it through various mechanisms, as it gives them a key competitive advantage over other, higher-growing plants that cannot grow in this area under these conditions (Augustinus, 1995; Marchand, 2008). In general, mangrove forests show zonation, with mono-specific zones succeeding one after the other from the waterline going landward (Augustinus, 1995). These zones form due to the varying tolerances of the different mangrove species to the changing boundary conditions.

Comparable to salt marshes, mangroves also range among the most exploited and therefore threatened ecosystems on our planet (Kirwan and Megonigal, 2013), and are degrading at an estimated global loss rate of 1-3 % yr^{-1} over the last decades (Duarte et al., 2008b). Changes in the ecosystem that lead to its degradation may be based on natural processes, such as land subsidence or the reduction of fluvial sediment (Alongi, 2008; Nguyen et al., 2015). Natural weather extremes like the Indian Ocean Tsunami of 2004 also bear the potential to destroy mangroves with a single event. However, most threats to mangrove ecosystems are of anthropological origin. Indirect human impacts are industrial development and excessive pollution (Hassan et al., 2005; Nguyen et al., 2015), pressure from the expansion of the tourism industry (Nguyen et al., 2015) and climate change related phenomena like a rise in atmospheric CO_2 concentrations, increasing air and water temperatures, changes in precipitation (Alongi, 2008) as well as hydrological changes like an increase in wave energy or the intensity and frequency of storms (Hassan et al., 2005; Nguyen et al., 2015). Human-induced land use changes, thus direct human impacts, account for the major part of mangrove losses worldwide. The removal or cutting of trees for firewood and construction material and the conversion of mangrove-covered land to allow for agriculture and aquaculture (Hassan et al., 2005) leave behind fragmented mangrove patches and damaged trees and shrubs, unable to offer sufficient resistance to the attacks of the sea. Thus, they break away and erode as can be seen in figure 5.7. According to Barbier et al. (2011), shrimp farming alone accounts for 38 % of global mangrove loss (aquaculture in total accounts for 52 %), and the use of mangrove wood is responsible for 26 % of mangrove loss globally.

Figure 5.7: Patches of heavily damaged mangrove forest through overexploitation at the west coast of Cà Mau Province in southern Vietnam, damages from cutting (left) and fragmentation (right; previously published in Jordan and Fröhle (2022)).

Sea level rise is also a major threat to mangroves (Alongi, 2008; Hassan et al., 2005). Where landward progression of mangrove forests is hindered by structures, industry or settlements, the ecosystems only have two options. Depending on the limitation of sediment resources, they either outgrow sea level rise by sufficient sediment accretion or they will slowly erode, starting at the seaward margin. Strongly depending on the different location variables, e.g. on the available sediment supply, threshold rates are likely to exist, beyond which mangrove forests can no longer keep up with sea level rise through sediment accretion (World Bank Group, 2016). Thus, they might ultimately drown (World Bank Group, 2016), as projected by the IPCC (2019) for 20-90 % of the world's wetland ecosystems by 2100, depending on emission scenarios.

Coastal protection processes Mangroves have the potential of being an integral part of coastal protection systems. Especially since the Indian Ocean Tsunami in 2004, global interest in their role as a protective barrier against storm events and flooding, shielding coastal communities and property from the destructive impacts, has risen notably (Barbier et al., 2011). Based on Gedan et al. (2011), the processes which provide coastal protection can be divided into direct and indirect mechanisms. They reduce waves and currents, diminish the destructive forces of storms and tsunamis, and stabilise the coastline.

Mangroves have proven to be effective in attenuating wave energy and thus reducing wave heights reaching the shore (Chowdhury et al., 2019; Hassan et al., 2005; van Coppenolle et al., 2018). Wave-trunk interactions and wave breaking cause the dissipation of wave energy in mangrove forests (Quang Bao, 2011). Thus, waves are dampened directly by the mangroves' structural presence (Gedan et al., 2011). Even over a relatively small distance mangroves have the potential to significantly reduce waves (Quang Bao, 2011), since the largest reduction in wave heights in relation to distance travelled occurs near the mangroves seaward edge, declining exponentially with distance travelled through the mangrove belt (World Bank Group, 2016). The processes underlying these protective effects are highly complicated and dependent on a variety of indicators and characteristics regarding the vegetation, the topography and the initial wave or storm. Vegetation characteristics, such as tree density and structural complexity, mostly depend on the dominant species or the mix of species but also on the general mangrove forest structure features like forest width and density (World Bank Group, 2016). Of course, these properties are interconnected. For example, with a smaller width of the mangrove belt but an increased density of vegetation and individual plants, the same wave attenuation can be achieved as with a larger width but lower density (Quang Bao, 2011). Key hydrological characteristics are initial wave height and the water depth. The water depth is of particular importance, as it influences the type of vegetation - aerial roots, trunks, branches or canopy - that the waves are passing through (World Bank Group, 2016). Indirectly mangroves dampen waves through the increased bed roughness, stabilisation of the soil and sediment accretion (Gedan et al., 2011). As Narayan et al. (2016a) concluded in his study, all these mechanisms within mangroves can reduce wave heights by 31 % (95 % CI: 25-37 %). Since the magnitude of energy absorbed strongly depends on vegetation structure and initial wave conditions, Quang Bao (2011) developed a formula based on cross-shore distance, mangrove structure and initial wave height as major input values or determining influences. Derived from field investigations in two regions of coastal Vietnam, according to Quang Bao (2011), the wave height behind a mangrove forest belt can be determined as

$$W_h = ae^{bB_w}, \tag{5.6}$$

with W_h [cm] being the wave height behind the mangrove habitat, B_w [m] being the cross-shore mangrove forest band width. Intercept coefficient a describes a function of the initial wave height I_{wh} [cm],

$$a = 0.9899I_{wh} + 0.3526, \tag{5.7}$$

and slope coefficient b describes a function of the forest structure,

$$b = 0.048 - 0.0016H - 0.00178ln(N) - 0.0077ln(CC), \tag{5.8}$$

with the average tree height H [m], tree density N [tree/ha^{-1}], and canopy closure CC [%]. Given an initial wave height I_{wh} [cm] (cf. equation 5.7) and a targeted or 'safe' wave height W_h [cm] behind the mangrove ecosystem, the necessary mangrove band width B_w [m] depends on the forest structure (cf. equation 5.8) and can be determined as

$$B_w = \frac{ln(W_h) - ln(a)}{b}. \tag{5.9}$$

Another indirect effect on waves, besides wave attenuation, is the reduction of wind speeds over the water surface through the mangrove canopy, which decreases the likelihood of waves increasing in height within the mangrove area (World Bank Group, 2016).
Current velocities can also be reduced significantly within mangrove forests by the sheer density of tree trunks, branches and aerial roots (J. L. Gutiérrez et al., 2011). The flow of water is resisted by drag forces due to the high number of vegetation obstacles, the bottom friction caused by the uneven sea bed as well as the eddy viscosity that originates from the turbulent flow of water though narrow openings between the mangroves' trunks and branches (Mazda et al., 2005).
The mangroves' ability to attenuate tsunamis, coastal storms or flooding largely depends on their ability to reduce the impact of waves and currents as well as the factors and characteristics underlying these processes, as described above (Alongi, 2008; World Bank Group, 2016; Hassan et al., 2005). Additional tsunami specific factors that influence the mangroves' effectiveness are size and speed of a tsunami and its angle of incursion relative to the coastline. Storm surges that are moving slowly are likely to be rather unaffected by mangroves, as they have time to flow through the vegetation. Fast-moving tsunamis, however, can be reduced by mangrove presence. Naturally there are certain limits to the mangrove trees' ability to withstand the forces of a tsunami, but usually, even after severe damages and some resulting tree mortality, the forest's structural complexity is maintained, and the mangrove band can recover and rebuild its protective function (World Bank Group, 2016) if the initial conditions of the mangrove forest are sufficient.
Fringing mangroves also have a stabilising function and reduce shoreline erosion along sandy and muddy coasts (Alongi, 2008; Barbier et al., 2011; Gedan et al., 2011; Hassan et al., 2005). Direct mechanisms that benefit shoreline stabilisation are the stabilisation of sediments and the retention of soils through the mangroves root structure (Barbier et al., 2011). Furthermore, mangroves actively trap even fine sediments by slowing down the water movement and generating stagnation zones behind the plants so that sediments can settle and accrete (Alongi, 2008; Gedan et al., 2011). Indirect mangrove effects are the increased rigidity and consolidation of the ground. The mangroves extensive underground rooting system increases the rigidity of the soils and through the extraction of water from the soil, it is compacted and consolidated (Augustinus, 1995).

Ecological and societal value In the previously mentioned study by Costanza et al. (1998), mangroves were rated as equally valuable as salt marshes. Since mangroves are the primary source of nutrients and energy in the coastal environments where they thrive, they benefit nature and people with supporting ecosystem services of major significance (Quang Bao, 2011). Mangrove forests actively promote biodiversity, offering a unique habitat to a wide range of insects, fish, reptiles, birds and mammals (Atkinson et al., 2016; T. L. Cosslett and P. D. Cosslett, 2014; GIZ, 2014; J. L. Gutiérrez et al., 2011; Hassan et al., 2005). Mangroves provide habitat similar to that of terrestrial forests, with

the difference or paradoxical feature being that their relatively low tree species diversity enables a relatively high faunal biodiversity (J. L. Gutiérrez et al., 2011).
Mangroves offer a variety of provisioning services to coastal communities and wildlife. As they provide sheltered habitats with areas of limited accessibility for larger animals, mangroves play an important role as nursery grounds for marine organisms and other animals (GIZ, 2014; Hassan et al., 2005). To coastal communities, mangrove forests are an important food source, e.g. through the provision of fishery resources (Atkinson et al., 2016; World Bank Group, 2016; GIZ, 2014; Hassan et al., 2005) as well as a supplier of firewood and construction material (World Bank Group, 2016; T. L. Cosslett and P. D. Cosslett, 2014; Hassan et al., 2005). When handled sustainably and non-destructive, in balance with the natural mangrove ecosystem and the locations it provides, mangroves can even support agricultural activities like rice cultivation (Hassan et al., 2005).
As far as regulating services are concerned, mangroves are processing pollutants (Hassan et al., 2005) and sequester carbon (Atkinson et al., 2016; GIZ, 2014). Similar to the value for salt marsh ecosystems, Chmura et al. (2003) estimates the carbon sequestration by mangroves at an average rate of 210 g m^{-2} yr^{-1}.
The biodiversity supported by mangrove ecosystems is also of great cultural and aesthetic value. Coastal communities are often closely connected with the ecosystem and their cultural heritage as well as their traditional knowledge is tied to its health and functioning (Walters et al., 2008). Furthermore, ecotourism activities are cultural services that can financially benefit and develop coastal communities whilst promoting the protection and conservation of mangroves (Friess, 2017).

Seagrass meadows

Seagrasses are a group of about 60 different angiosperm species (Duarte et al., 2008a; Green and F. T. Short, 2003; Ondiviela et al., 2014), which grow in soft substrates preferably under wave-sheltered conditions in depths where at least approximately 11 % of the surface light still reaches the sea floor (Barbier et al., 2011). Seagrass grows in the form of meadows. Seagrass meadows are usually monospecific - only meadows in the tropics or subtropics may contain several species, especially in the Indo-Pacific region where seagrass species diversity is greatest (Duarte et al., 2008a). In the temperate zones in higher latitudes, the eelgrass types (*Zostera spp.*) are most common and form large meadows in estuarine and near-shore coastal areas, while in the tropics and subtropics large areas are often covered with manatee (*Syringodium filiforme*) and turtle grass (*Thalassia testudinum*) (Hassan et al., 2005).

> *With regard to the investigation area:* The four seagrass species that are native to European temperate waters are eelgrass (*Zostera marina*), dwarf eelgras (*Zostera marina*), neptune grass (*Posidonia oceanica*) and little neptune grass (*Cymodocea nodosa*) (Ondiviela et al., 2014). On the upper, protected tidal flats of the Wadden Sea, perennial dwarf seagrass meadows develop preferentially. The above-ground parts of the plants usually die in winter due to their susceptibility to frost, but the extensive root system that penetrates the mudflats survives and enables them to resprout in spring. (Stock et al., 2012).

As angiosperms or flowering plants, seagrasses are seed-bearing vascular plants. For reproduction purposes and habitat maintenance, they pollinate on the water surface or under water and produce fruits and seeds. Their primary mode of reproduction or expansion, however, is clonal growth (Duarte et al., 2008a). Clonal growth is of particular importance during the colonization of new habitats as well as during recovery from disturbances such as storm events. The spread of clones is facilitated via the rhizomes. New roots, shoots and branches typically form in the internodes of rhizomes (Marbà et al., 2004).

Seagrasses occupy the soft-bottom areas of the world's oceans from the tropics to the temperate zones (Hassan et al., 2005), extending from the intertidal zone to depth of up to 40 m (J. L. Gutiérrez et al., 2011). As can be seen in figure 5.8, which displays the global distribution of seagrass meadows, the ecosystem can be found along the coasts of all continents with the exception of Antarctica. The global aerial extend of seagrass is hard to estimate, since documentation is poor for the coasts of many developing countries. A conservative estimate of global seagrass areas compiled by Green and F. T. Short (2003) amounts to 177,000 km^2, which is in general considered much too low (Duarte et al., 2008a). More progressive estimations of global seagrass area range up to values of 600,000 km^2 (Mcleod et al., 2011).

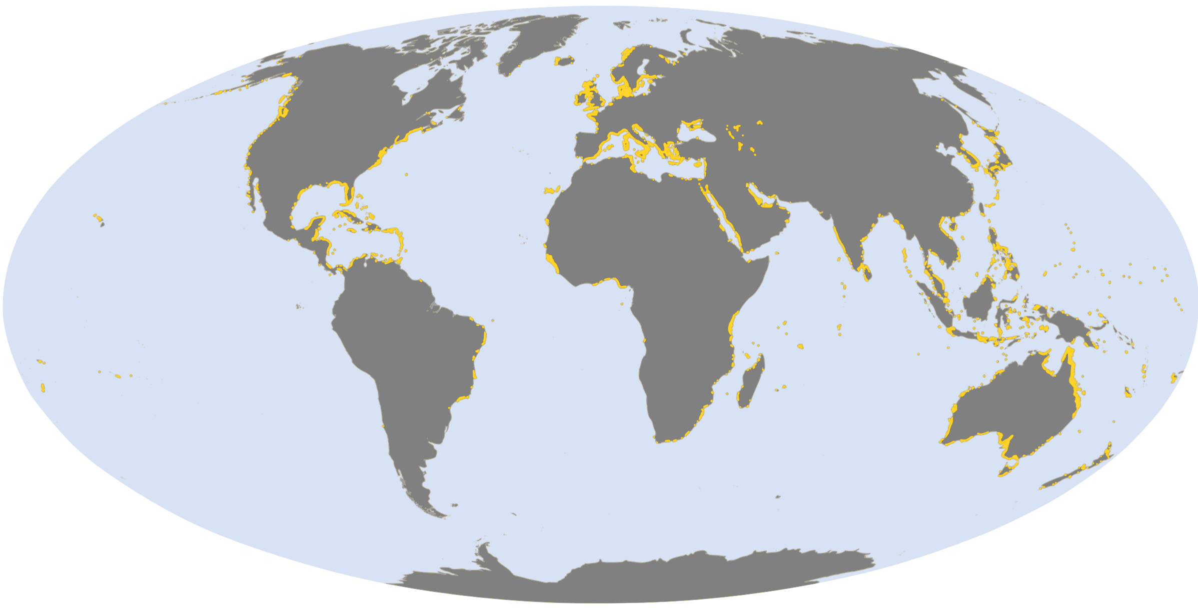

Figure 5.8: Global distribution of seagrass in yellow after UNEP-WCMC and F. T. Short (2020); previously published in Jordan and Fröhle (2022).

With regard to the investigation area: Historically, about 150 km^2 of the western Wadden Sea were covered with eelgrass (*Zostera marina*), which was more abundant than dwarf eelgrass (*Zostera noltii*), until the so-called 'wasting disease' struck in the 1930s. Almost 90 % of the eelgrass population in western Europe were lost during this decade due to the proliferation of a pathogenic slime mold (*Labyrinthula zosterae*) in the leaves of the seagrass species. Most areas formerly covered by eelgrass did not recover from this (Green and F. T. Short, 2003). Nowadays, eelgrass and dwarf eelgrass can still be found in the Wadden Sea (MELUR, 2015), although extensive dwarf eelgrass meadows are only present in the area of Schleswig-Holstein, and even there only in the protected tidal flats of North Frisia (Stock et al., 2012), as depicted in figure 5.9.

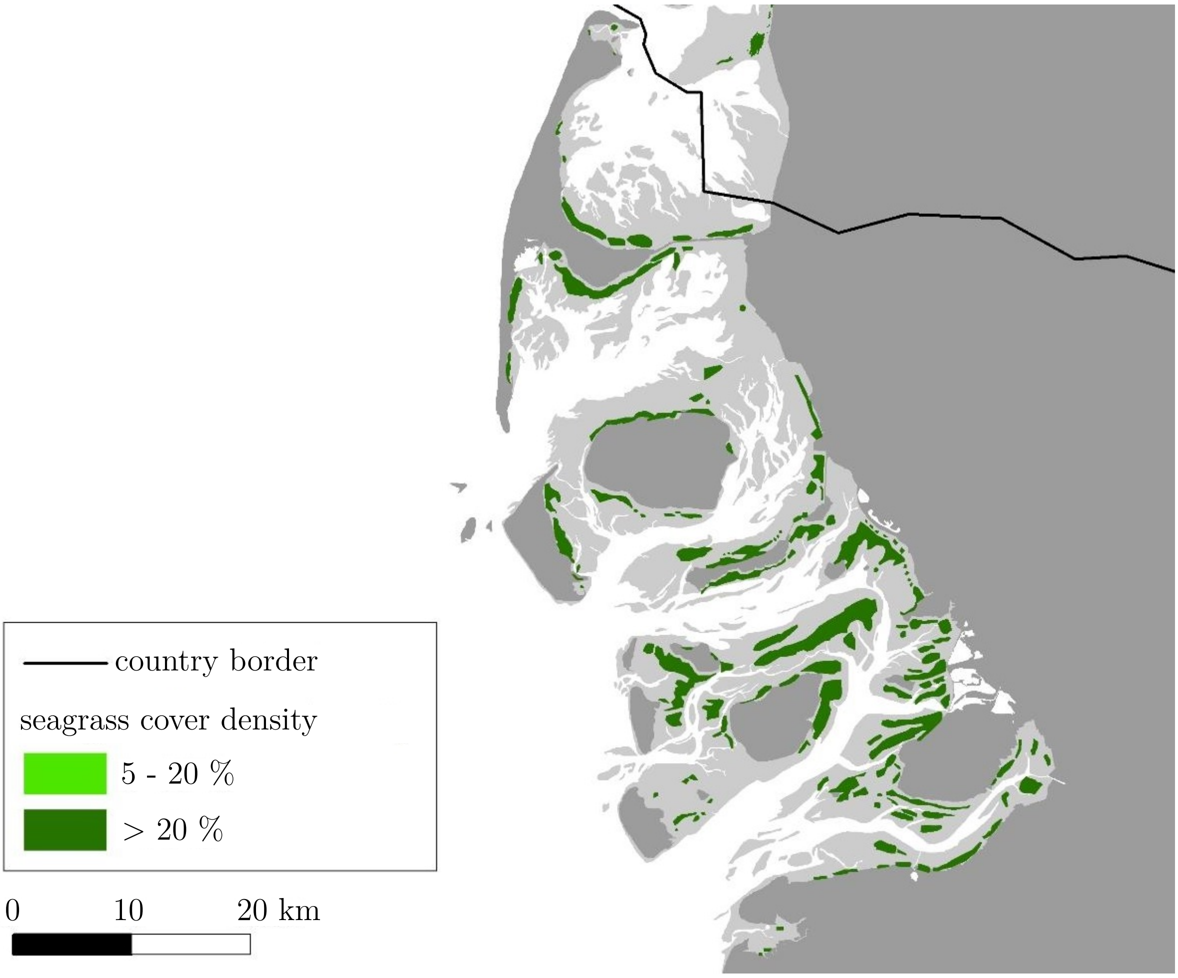

Figure 5.9: Spatial distribution of seagrass beds in the North Frisian Wadden Sea (as of 2015) after Dolch et al. (2017).

Seagrass meadows often occur in the proximity to other coastal ecosystems such as coral reefs, mangroves or salt marshes and are ecologically linked with them (Duarte et al., 2008a; Green and F. T. Short, 2003). The different seagrass species have developed a number of adaptations and adaptation strategies to enable their survival in the niche where they thrive. They are able to grow whilst being completely submerged and can tolerate varying high salinities. To withstand stresses caused by water movement, their root system anchors them into the soft soil and to expand and reproduce under these harsh conditions, seagrasses developed a submarine pollination system as well as clonal growth, as explained above. Flattened and elongated, strap-like leaves as well as the extensive root and rhizome system are widespread characteristics among seagrass species, which have developed over time due to these adaptation (Green and F. T. Short, 2003). Furthermore, seagrass meadows can actively alter their environment to improve conditions for them and promote their growth and reproduction by reducing turbidity and in turn increasing light availability (van der Heide et al., 2007).

Since seagrass meadows grow at the land-sea margin, they are especially vulnerable to anthropogenic impacts and alterations to their environment. As estimated by Duarte et al. (2008b), the global mean loss rate of seagrass meadows over the last decades is nearly twice as high as loss rates of mangroves or salt marshes and amounts to 2-5 % yr^{-1}. Human activities in the coastal environment like boating and anchoring, coastal development and dredging (Duarte et al., 2008a; Hassan et al., 2005) as well as habitat conversion for algae farming (Hassan et al., 2005) or oyster and mussel aquaculture (Green and F. T. Short, 2003) pose direct threats to seagrass meadows and are partly responsible for their drastic decline, especially in proximity to urbanised areas. Negative indirect impacts are hypersalinisation and siltation, resulting from changes to inflows (Hassan et al., 2005), and, above all, reduced coastal water clarity (Duarte et al., 2008a; Green and F. T. Short, 2003). Seagrasses are vulnerable to reduced light penetration. Increased turbidity, caused by either the discharge of large amounts of sediments into coastal waters or by increased nutrient loading and subsequent eutrophication of coastal waters and algae blooming, thus is responsible for the destruction of many seagrass beds.

> *With regard to the investigation area:* Invasive species can also hinder seagrass expansion or replace existing populations. In western Europe, more precisely also in the North Sea, Japanese wireweed (*Sargassum muticum*) is spatially competing with eelgrass, as it grows in locations with similar conditions and gradually takes over eelgrass beds (Green and F. T. Short, 2003).

Climate change-induced sea level rise also threatens seagrass beds. Since they require a lot of light, which no longer reaches the seabed in sufficient strength with increasing water depth, seagrass meadows either have to migrate landwards to remain in shallower waters, or they eventually disappear. As projected by the IPCC (2019) with medium confidence for the sea level rise under the RCP8.5 emission scenario by the end of the century, coastal wetlands in general are under high risk of total local loss. The effects of the increase in global temperature on seagrass are hard to estimate because nearly all aspects of seagrass metabolism and growth is affected by it. A moderate increase in temperatures may even pose chances for seagrass expansion, as pointed out by Duarte et al. (2008a), since it could enhance species diversity in the subtropics and expand the distribution of cold-water seagrass species to higher latitudes.

Coastal protection processes Like other coastal wetlands, seagrass meadows influence certain hydrodynamic processes, through which they in turn provide regulating ecosystem services like wave energy attenuation or shoreline stabilisation.
Seagrass beds are known to dampen wave energy and, hence, wave height (Ondiviela et al., 2014; Schoonees et al., 2019). Waves are being attenuated directly through friction,

caused by the structural presence of the vegetation in the water column (Gedan et al., 2011; Narayan et al., 2016a). A variety of different factors, both biophysical-vegetational and hydrodynamic, influence the degree of wave attenuation. Standing biomass, plant flexibility, shoot density and leaf length or height of the canopy are decisive vegetation characteristics (Ondiviela et al., 2014; Rupprecht, 2015). Incident energy flux (Ondiviela et al., 2014), wave height and even more so wave period (Maza et al., 2012) as well as water depth represent influential hydrodynamic factors. The water depth or, in other words, the proportion of the water column occupied by the seagrass meadow is of particular importance. The larger the portion of water column occupied by the meadow, the more successful seagrass is in attenuating waves because the interaction surface in vertical and horizontal dimension is the key to the degree of attenuation. Thus, in deeper coastal water attenuation abilities of seagrass meadows are more limited, whereas in shallow areas seagrass are more effective in attenuating waves (Barbier et al., 2011; J. L. Gutiérrez et al., 2011; Ondiviela et al., 2014). Another influence factor regarding wave attenuation is seasonality (Ondiviela et al., 2014), which plays a particularly important role in temperate zones. During winter, when hydrodynamic forcing in coastal areas of the temperate zones is highest, most of the above-ground biomass of seagrass dies, resulting in wave attenuation capacity being at its lowest. According to the previously mentioned study by Narayan et al. (2016a), wave heights can be reduced by an average of 36 % (95 % CI: 25-45 %), as concluded from analysed studies for seagrass and kelp beds combined. After Bouma et al. (2014), the wave decay coefficient for seagrass meadows $k_{seagrass}$ $[m^{-1}]$ can be estimated between 0.001 and 0.01, as derived from field measurements. Based on equations 5.2 and 5.3 the wave height after maximum attenuation by a seagrass meadow (thus maximum coverage, $B = B_{max}$, and $k_{seagrass} = k_{seagrass,max} = 0.01$) can be approximated by

$$H_{L,seagrass} = 0.3he^{-(0.01e^{-dh})L}. \tag{5.10}$$

Current flow and current velocity are also attenuated by seagrass meadows (Maza et al., 2012; Ondiviela et al., 2014; Schoonees et al., 2019), which promotes sedimentation within the beds (Bouma et al., 2014; Ondiviela et al., 2014; Schoonees et al., 2019). The seagrasses extensive above- and below-ground biomass directly reduces erosion and traps sediment. While the canopy encourages the deposition of sediments and prevents its re-suspension, the extensive root and rhizome systems bind the deposited sediment over the longer term and secure the seagrass meadow's accretion (Duarte et al., 2008a; Green and F. T. Short, 2003). Furthermore, seagrass beds indirectly favour sedimentation as they dampen the effects of waves and currents on the sea floor and, thus, prevent scouring action of waves (Green and F. T. Short, 2003).

Ecological and societal value Regarding the value of provided ecosystem services, Costanza et al. (1998) assessed seagrass meadows to be of even more value than other wetland ecosystems like salt marshes or mangroves. Many of the seagrass meadows' ecosystem services are based on the following two supporting services. Seagrass beds exhibit high primary production (Green and F. T. Short, 2003) and provide crucial habitat for a large number of different species of fish and invertebrates (Duarte et al., 2008a; Green and F. T. Short, 2003; Hassan et al., 2005) as well as large herbivores like dugongs and sea turtles

in the tropics and swans or geese in temperate zones (Duarte et al., 2008a).
Concerning provisioning services, seagrass serves as a food source for many of these species and poses important nursery areas, especially for coral reef fishes in the tropics (Hassan et al., 2005).
Regulating services include the filtration of nutrients and contaminants from coastal waters as well as oxygen production from photosynthesis, which improves water quality and supports the existing fauna (Green and F. T. Short, 2003). Furthermore, like the other wetland ecosystems featured before, seagrass meadows sequester carbon at a rate of 69-169 g m^{-2} yr^{-1} (Duarte et al., 2010).
Important cultural services are linked with the habitat provision for certain species. Seagrass beds help safeguarding threatened species like sea horses, sea turtles or sirenians. Some of these animals are perceived by local communities as well as tourists and nature-enthusiasts as being of particular cultural or aesthetic value (Green and F. T. Short, 2003).

5.2.2 Beach ecosystems

Beach ecosystems consist of often highly interacting beach and dune areas. Beaches and dunes by themselves and in combination with each other function as bulwarks as well as dynamic buffers for storms and extreme events on the coast. They also provide space for a variety of tourism and sporting related activities and serve as habitat, resting sites and nursery for a range of animal and plant species.

Beaches and foreshore areas

Beaches, which per definition describe shores that are covered with sand or shingle (F. P. Shepard, 1973), represent the world's largest type of open shoreline (Defeo et al., 2009) and a physically dynamic ecosystem (IPCC, 2019). The prevailing nature of a beach is strongly characterised by the acting hydrodynamics, tides, waves and currents as well as the extent of the near-shore, surf, and dry beach zones (Finkl, 2004; A. D. Short, 2006). Beaches can be classified as micro- (<2 m), meso- (2-4 m) or macro-tidal (>4 m) based on the existing tidal ranges as defined by Davies (1964). Other classifications, like in Finkl (2004), state that, regarding the affects on beach morphology and hydrodynamics, the dissipation of incident wave energy is the decisive factor - especially in micro-tidal environments. However, with increasing tidal range this changes and tide-related processes begin to have stronger influences (Finkl, 2004), meaning that the interaction of the two drivers need to be considered when classifying beach ecosystems. Based on the works of Wright and A. D. Short (1984) and A. D. Short (1991), Masselink and A. D. Short (1993) developed a conceptual classification approach which takes four variables into consideration - breaker height, wave period, high tide sediment fall velocity, and tidal range. From these values they distinguish between the three main beach type groups of reflective, intermediate and dissipative beaches. Reflective beaches are usually coarser in grain size and have no surf zone, intermediate beaches feature a surf zone with bars and rips, and dissipative beaches are fine-grained and have extensive surf zones with multiple shore-parallel bars and troughs (Defeo et al., 2009; Finkl, 2004).

Through long-shore and cross-shore sediment transport, storage and exchange beach ecosystems are closely linked to the surf zone on the seaward and to coastal dunes on the landward side (Defeo et al., 2009). Depending on the availability of sand, three states of interacting beach-dune systems can be differentiated after Doody (2013). Focussing on the beach ecosystem these are

- **Erosion**: With little to no vegetation, bare sand areas are prevalent and sand movement on the beach is high. The sediment budget is deficitary with the amount of removed sand outweighing the amount of gained sand on the beach;
- **Dynamic Equilibrium**: The beaches in this state are highly mobile and react to changing weather conditions by moving landward or seaward. In equilibrium over the year, storms flatten the beach and move sand to the lower beach level (during winter in temperate regions, during monsoon season in the tropics) while in the storm-free season it gradually builds up on the upper beach;
- **Accretion**: With sediment availability in abundance, the shoreline can move seaward, as the beach accumulates further sediment and allows vegetation and therefore foredune development.

Beach ecosystems form naturally at low-lying coastlines where sand is available and transported long-shore and cross-shore by waves and currents (Barbier et al., 2011). If there is sufficient mobilised sand in the foreshore, beaches can also form when sandbanks migrate towards the coast from the sea and gradually attach themselves to the island or mainland (Rabe et al., 2018). Nowadays, many beaches around the world are maintained or even widened and enlarged artificially through the practice of sand nourishments - either performed directly on the beach or in the foreshore area. During decades of practice these techniques have proven to be very successful in counteracting coastal erosion and stabilising shorelines (Niemeyer et al., 1996; Sørensen et al., 1996; Wiegel and Saville Jr., 1996). Sand, of course, is an increasingly valuable resource (Bridges et al., 2018) that can only be removed from designated dredge sites. Possible sediment sources include navigational channels that require excavation, terrestrial or riverine sand deposits, the intertidal area or offshore dredging sites and pits (Carley and Cox, 2017; Hanley et al., 2014). If designed and constructed well, the artificial nature of such beaches may be undetectable to most people. To meet the local conditions and keep harmful environmental impacts as low as possible, however, the nourished sand should match the naturally prevalent sand in grain size, colour, shape, fall velocity, mineralogy and biogenic fraction. Physical impacts and the ecological disturbance of habitats is to be avoided (Carley and Cox, 2017).

> *With regard to the investigation area:* The Kniepsand on Amrum displays an example of a sandbank that gradually wandered towards an island's coast over centuries (Müller and Fischer, 1937a). Nowadays, the Kniepsand forms the vast beach (see figure 5.10, left) that stretches along the entire west and southwest coast of the island. On Föhr, on the other hand, artificial nourishments

have been used for decades to secure the beaches on the south coast (e.g. figure 5.10, right). The first of its kind on Föhr, was performed in 1963 (Stadelmann, 2008).

Figure 5.10: Boardwalk towards the North Sea on the vast Kniepsand off Nebel, Amrum (left; previously published in Jordan and Fröhle (2022)), and the regularly nourished, narrower Nieblum beach with beach chairs, Föhr(right).

As can be seen in figure 5.11, beach ecosystems occur on all continents except Antarctica with an increase in relative occurence in the lower mid-latitudes as well as the subtropics between 20° to 40° (Luijendijk et al., 2018).

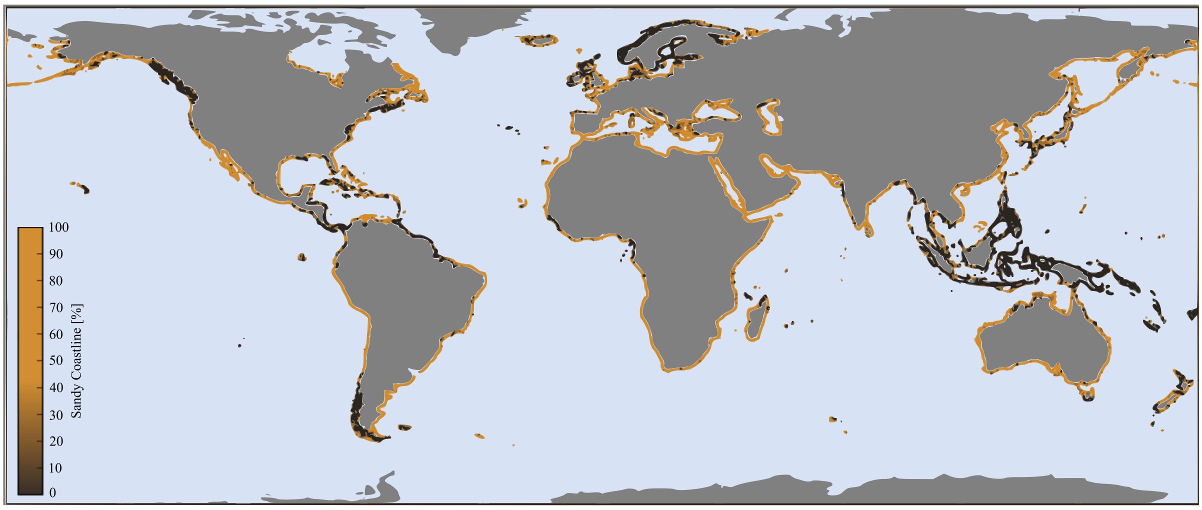

Figure 5.11: Global distribution of sandy coastlines after Luijendijk et al. (2018); previously published in Jordan and Fröhle (2022).

Regarding the total length of sandy beaches, Australia ranks highest with 13,200 km total beach length, followed by the USA (12,800 km), Brazil (6,100 km), Denmark (4,600 km) and Mexico (4,900 km) (Hinkel et al., 2013). According to Hinkel et al. (2013), four of these countries (USA, Australia, Mexico, and Brazil) are also amongst the five countries

most affected by land loss without nourishment under SRES scenario A1B (approximately equivalent to RCP6.0 (IPCC, 2019)) by 2100. In terms of absolute costs, they concluded that the USA, Japan, Germany, Denmark and the Netherlands rank highest. Looking at the big picture, several studies show that beaches worldwide are under threat of erosion and partly even extinction (e.g. Luijendijk et al. (2018), Morris et al. (2018), and Vousdoukas et al. (2020)).
Threats to beaches and the foreshore area are manifold. They range from pollution to overexploitation by sand mining or groundwater extraction and the harvesting of beach organisms (Brown and McLachlan, 2002). Excessive coastal developments in combination with coastal protection with passive structures lead to a hardening or armouring of the coastal environment and therefore often to disruptions in the sand balance and dynamics (Brown and McLachlan, 2002; Hanley et al., 2014; Hassan et al., 2005). Urban expansion and touristic developments in combination with climate change related processes and events, such as sea level rise, storm surges of increased frequency and intensity, and changes in offshore winds and weathering regimes (IPCC, 2019) - resulting in the phenomenon of coastal squeeze - are the major long-term threat to beach ecosystems worldwide (Defeo et al., 2009). Narrow sandy beaches are particularly threatened to disappear due to coastal squeeze (IPCC, 2019). According to projections of medium confidence of the latest IPCC report (IPCC, 2019), the aforementioned changes under the RCP8.5 scenario translate to a substantial risk for beach ecosystems by the end of the 21st century.

Coastal protection processes In terms of coastal protection, beach ecosystems can be regarded as adaptive, resilient structures. They respond to changes in their environment in order to maximise their persistence and minimise harmful effects (Hanley et al., 2014). As displayed in the scheme in figure 5.12, the energy of waves that reach the shore is directly attenuated or dissipated by the beach slope (Barbier et al., 2011; Doody, 2013), which displays one of the most important processes affecting the beach morphology as well as beach hydrodynamics (Finkl, 2004). Coastal erosion resulting from storms and waves interacting with the beach is a highly complex process and depends on various storm parameters such as air pressure, mean water level, wind speed and direction as well as wave height (Anthony, 2013). But thanks to the beaches ever-changing character and the ecosystem's responsive nature, regeneration from erosion damages due to severe storm surges can take place within a few weeks (Niemeyer et al., 1996) - of course dependent on the sediment availability and hydrodynamic transport conditions.
In principle, natural and dynamic formation and shaping processes play an essential role in coastal protection. For example, in high energy environments with increased wave action, sandy beaches can respond by flattening their profile. The cross-shore sediment transport is increasingly shifted offshore into the sublittoral zone. The foreshore shallows and multiple rows of submerged bars can form with the additional sediment, hence a wider dissipative surf zone can develop. This causes wave breaking well offshore, so that wave impact on the beach and dunes is greatly reduced. In less energetic environments, the beach is usually more permeable and less saturated with ocean water. Therefore, shorter and steeper waves arriving at the beach can transport sediments back onshore, causing an enhanced accretion and steepening of the beach, which in turn becomes more reflective. If inundation times are sufficiently low, allowing the sand in the upper parts of the beach

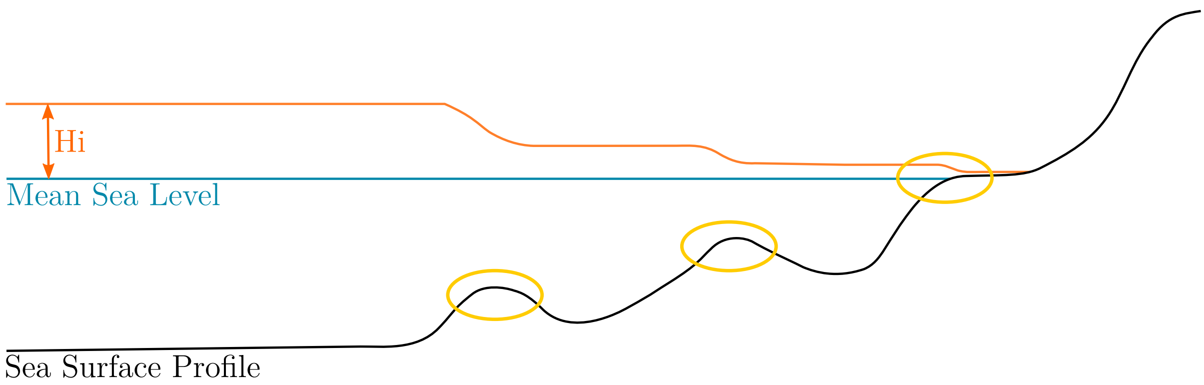

Figure 5.12: Scheme of wave attenuation over the cross-shore section of a foreshore-beach-system, attenuation occurs over the sand bars in the foreshore area and on the beach; with H_i = initial wave height; areas of increased long-shore sediment transport are marked in yellow; previously published in Jordan and Fröhle (2022).

to dry out, onshore winds can transport the sand back into adjacent dune ecosystems (Hanley et al., 2014).
Wave energy dissipation by beaches is a non-uniform process, that results from the complex interaction of various different forces. On the foreshore wave-bottom interactions are mainly responsible for energy dissipation, whereas in the surf zone turbulence due to wave breaking dominates energy dissipation. Even though wave bores that reach the swash zone only bear a small percentage of the wave's initial energy that has not been dissipated yet on its way onto the sandy coast, this wave run-up is often responsible for considerable damages on the beach, in the dunes or to property in the adjacent hinterland. Since waves continue to lose energy in the swash zone due to turbulence, bottom friction and percolation, wider beaches offer greater levels of protection than narrow, fringing beaches (Stutz et al., 1998). Through combination and alignment of these interactions, beach ecosystems are able to absorb up to 90 % of the initial energy of waves when they arrive at the coast (R. Palmer and Limited, 1996).

With regard to the investigation area: The west coast of the island of Amrum is naturally protected by the Kniepsand - a former sandbank that nowadays forms the beach ecosystem in front of Amrum's dunes. In its greatest extension, the Kniepsand is 1.5 km wide, thus effectively dissipating the energy of waves that wash ashore. The beaches in the south of Föhr, on the other hand, are rather narrow and require regular nourishments to uphold their protective function. Since the first sand nourishment in 1963 (Stadelmann, 2008), a total of 3.3 million m^3 of sand have been nourished onto the shores of Föhr until 2011 (Thorenz, 2014).

Furthermore, accounting for another regulating ecosystem service of beach ecosystems beside the aforementioned storm surge protection and erosion control, beaches are often interlinked with adjacent dune ecosystems for which they store and with which they dynamically exchange sediments.

Ecological and societal value Beach ecosystems support a unique biodiversity, as they provide habitat for species of vegetation, benthic fauna and sea birds, that cannot be found in any other environment (Defeo et al., 2009; Hassan et al., 2005).
Beaches provide feeding grounds for migratory birds as well as nesting areas for sea birds and sea turtles (Defeo et al., 2009; Hassan et al., 2005), which are particularly dependent on these ecosystems for reproduction. They also provide an easily accessible source of sand as construction material, the extraction of which, though, is detrimental to almost all other ecosystem services (Doody, 2013).
Regulating ecosystem services, aside from the dissipation of wave energy and the facilitation of sediment exchange, include the breakdown of organic materials and pollutants, water filtration and purification, and the transport of terrestrial nutrients to the coastal system. Due to the discharge of nutrient-rich groundwater, beach ecosystems connect the land-based dune aquifers with the ocean (Defeo et al., 2009; Hassan et al., 2005).
Culturally, beaches provide a variety of ecosystem services. Above all, beaches are the main driver of coastal tourism in holiday destinations worldwide, since they offer opportunities for a wide range of recreational activities such as sunbathing, sports and games, ocean access or simply walking (Doody, 2013; Hassan et al., 2005). Besides, beaches are places of great aesthetics, which, as holiday photographs and a variety of artworks illustrate, form a large part of the visual appeal of coastal landscapes (Doody, 2013).

Dunes

Dunes are highly dynamic geomorphic structures and coastal ecosystems that continuously change their form both in the short and long term (Barbier et al., 2011; Hassan et al., 2005; Kollmann et al., 2019). They usually occur along extensive beaches where sediment is abundantly available and can extend for several kilometres along the coast reaching tens of metres up to 100 m in height. But coastal dunes may also form as non-dominant, narrow linear structures, interspersed by cliffs and rocks headlands or other coastal ecosystems such as salt marshes or mangroves (Doody, 2013). Coastal dunes depend on waves to transport sand onshore and wind to drive the sand further inland. Therefore, the sediments that make up a dune need to be light enough to be transported by the wind whilst being heavy enough not to be in suspension in the air, which results in dunes consisting of a rather narrow grain size spectrum. The sand in dunes varies in the range of 0.06-4 mm in diameter (Doody, 2013). Therefore, it is easily movable, low in nutrients, initially mostly rich in lime and has a low water-holding capacity (Kollmann et al., 2019).
Sand dunes are closely linked with adjacent beach ecosystems and are interacting with them through various processes - mainly storage, transport and exchange of sand (Defeo et al., 2009) - acting as a sand reservoir for the beach and the surf zone (Wiegel and Saville Jr., 1996). As mentioned above with regard to beach ecosystems, there are three states of interacting beach-dune systems according to Doody (2013), depending on the availability of sand. Focussing on the dune ecosystem these are

- **Erosion**: Due to a deficitary sediment budget and little to no vegetation on the beach, developed foredunes only survive until the next storm. Losses of inland dunes can hardly be prevented, therefore, the dune front typically has a steep face;

- **Dynamic Equilibrium**: The foredunes in this state are highly mobile and react to changing weather conditions by moving landward or seaward, always in a semi-stable state or natural balance;
- **Accretion**: Foredunes can move seaward, as the beach accumulates further sediment and allows vegetation development. Former foredunes, now lying landward of the newly developed ones, can continue to accrete sediment and eventually become inland dunes.

Freshwater reservoirs or ‘cushions’ that float on the brackish water of the subsoil due to their lower density form under dunes. These freshwater cushions are vital for many dune plants, which reach down to the groundwater with their deep rooting systems (Kollmann et al., 2019). There are two broad vegetation types that can be distinguished - one associated with the temperate and cold regions and the other with the tropics (Doody, 2013). In both cases though, the presence of vegetation in general is of significant importance for dune ecosystems because dune vegetation is what stabilises and shapes an environment that would otherwise be highly unstable and shifting (J. L. Gutiérrez et al., 2011; Hanley et al., 2014).

Pioneer vegetation, thus early colonising species in sand dunes, all display similar mechanisms to cope with the harsh conditions of the environment they grow in. Since they are severely impacted by storms, broken up, transported elsewhere by waves or winds, or buried under washed up sediments they all produce rhizomes, stolons and suckers to form new colonies when being relocated on the beach (Doody, 2013). Dunes then begin to form naturally in such places, under the protection of this pioneer vegetation or also behind beach debris or mussel shingle (MELUR, 2015), as can be seen in figure 5.13 on the left. A chain of processes must link together for dunes to develop (Doody, 2013). The erosion of sand and water-driven transport through river flow or tidal currents represent the first processes. Next, sands need to be washed ashore a beach where the inundation or swash free time is long enough for the sand to dry out, and which is wide enough to guarantee sufficient wind exposure for the sand to be moved across the beach. Finally, when encountering obstacles such as pioneer vegetation, two different mechanism can cause the deposition of the sand and the beginning formation of an incipient foredune (Pethnick, 1984). Either a boundary layer formed around the vegetation dissipates the wind energy or sand grains actually hit the plants’ surface and drop down. As can be derived from these interlinking processes, several factor have a significant impact on the formation of an incipient foredune. The most important ones are plant characteristics such as height, distribution or density, the present wind velocity and the rates of sediment transport (Hesp and Walker, 2013). These, in combination with several other impact factors like storm erosion or occurrence of overwash, determine the success of the development of an incipient foredune. Established foredunes develop from incipient foredunes over time. Under higher rates of sand supply foredunes become rather wide than tall, creating a series of ridges and expanding over a larger area, whereas when sand supply is negligible, single foredunes become taller as the deposition of the sand is not spread as widely as in the former case (Hanley et al., 2014; Hesp and Walker, 2013). Over time, more and more sand can deposit in the vegetation’s or obstacles’ surrounding area, causing the foredune to grow further and starting the successive process of dune development - from incipient and established foredunes to white or yellow, then grey and finally mature, fixed or brown dunes with shrubs and woodland.

Figure 5.13: Dunes on Amrum: incipient foredunes exposed to the sea (left) and the transition of a grey dune to a mature dune with patches of both marram grass and common heather (right); previously published in Jordan and Fröhle (2022).

Regarding human interventions in dune development and dune management, there are two approaches that need to be distinguished. What is known today, ‘dynamic coastal management’ implies little to no interference in the dune ecosystem, whereas ‘soft engineering’ involves human interference to promote dune development or stabilise exiting dunes (Jong et al., 2014). The latter has been good practice for centuries in some dune ecosystems. Brushwood sand fences are constructed to reduce wind velocities and thus allow sediment accumulation and facilitate faster colonisation by pioneer dune vegetation. This technique is used to extend and strengthen existing dunes, close gaps or create new dunes. Furthermore, active planting of sand-binding dune vegetation or even forestation in established dunes is conducted to stabilise already existing dunes (Hanley et al., 2014; Wiegel and Saville Jr., 1996). Historically, dunes were fixed this way in many places to prevent their migration, as they threatened settlements, pasture and farmland (Ellenberg and Dierschke, 2010; Müller and Fischer, 1937a).

> *With regard to the investigation area:* Coastal dune management on the North Frisian island of Amrum dates back to the late 17th century when the first decree on stalk picking and cutting was issued. Since then, Amrum’s dunes have been actively stabilised, fixed and extended - to protect the dunes themselves, ensure a necessary level of coastal protection provided by them, and prevent their migration towards and the in-flow of sand onto the adjacent fertile island area in the east (Müller and Fischer, 1937a).

Coastal dunes occur extensively around the world and can be found in the cold of the Antarctic as well as in the humidity and heat of the inner tropics (Doody, 2013; Kelletat, 1999). The global distribution of well developed dune systems, areas where dunes are a significant or the dominant structure in the transition zone between land and ocean, is depicted in figure 5.14. The distribution of further small sand dune areas along the coasts, which are interspersed with sandy shore, rocky headlands or vegetation patches, e.g. in the Antarctica, Greenland, northern Russia or Canada, can be found in the original figure by Martínez et al. (2008).

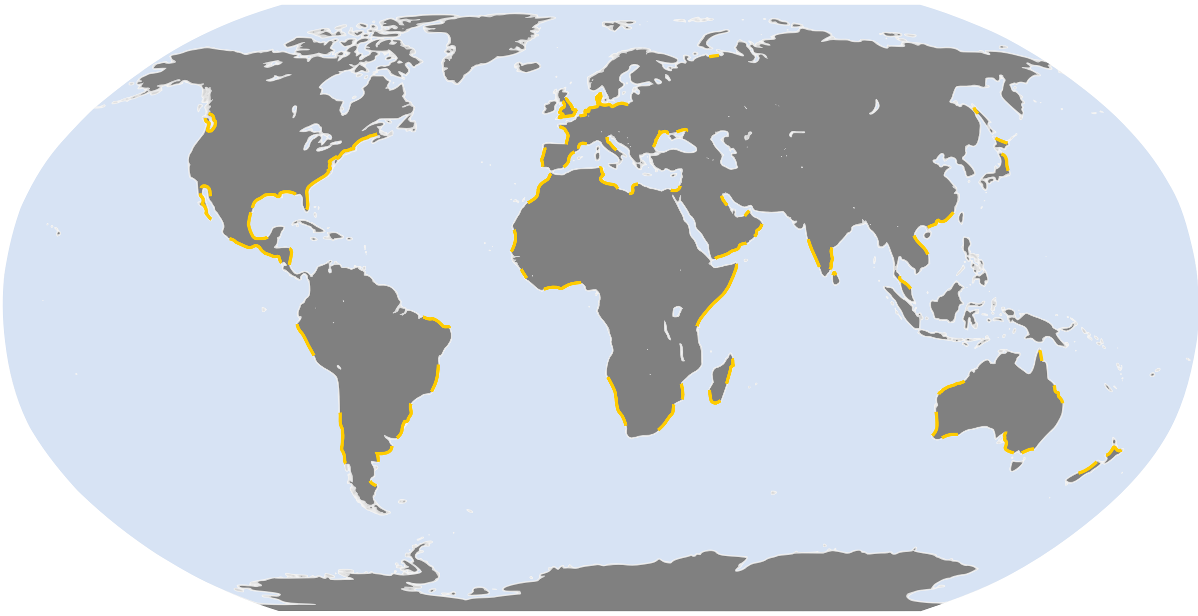

Figure 5.14: Global distribution of well developed dune systems in yellow after Martínez et al. (2008); previously published in Jordan and Fröhle (2022).

Coastal dunes can be classified geomorphologically according to their shape or on the basis of the vegetation present. According to their form, dunes are first divided into free dunes, i.e. dunes that develop freely on a surface, and bound dunes, i.e. those that are bound to relief or vegetation influences as sand accumulation on obstacles (Dikau et al., 2019; Zepp, 2017). Different types of free dunes can occur on sandy coasts. Transverse dunes, which form at right angles to the dominant wind direction when there is a sufficient supply of sediment, are common and usually form straight-line dune ridges. Parabolic dunes are also not uncommon on coasts and mainly emerge behind the first row of dunes. This curved dune form develops when sand transport is frequently impeded on the sides by increased roughness, e.g. by vegetation (Hesp and Walker, 2013; Zepp, 2017).
The classification of dunes based on the zonation of dune vegetation offers the advantage of being able to describe dunes as a habitat. The characteristic ecological differentiation of the site conditions and the associated vegetation zonation is caused by the increasingly weaker influences of wind, sand dynamics and salinity as the distance to the sea increases. Accordingly, the five zones of vegetation and dune types are distinguished below and briefly described starting from the sea or beach moving inland corresponding to the dune and vegetational succession (Hesp and Walker, 2013; Kollmann et al., 2019).

1. **Incipient Foredune**: Incipient foredunes or embryo dunes develop behind pioneer plants on the backshore of beaches (see figure 5.13, left). They can grow up to a few centimetres and are very rich in salt and nutrients.

2. **Foredune**: Foredunes or primary dunes are usually coherent, low dunes in front of the foot of a continuous chain of higher dunes. They are exposed to strong salinity and occasional flooding but also to summer drought and nutrient deficiencies. They grow 10-30 cm per year but rarely exceed 1-2 m in height.

3. **Yellow Dune**: Yellow or white dunes develop from foredunes and represent the first higher and coherent chain of dunes closest to the beach. They lie beyond the influence of the high tide but are strongly exposed to winds that cause either sedimentation or erosion. Yellow dunes usually reach heights of 10-30 m and are covered with deep-rooted grasses.

4. **Grey Dune**: Grey dunes are flatter, older dunes that develop on the leeward side of the yellow dunes and can be several hundred metres wide. Compared to the yellow dunes, the micro-climate and soil properties change. The soil is more acidic, less nutritious, and low-growing plant species dominate the area.

5. **Mature Dune**: Mature, fixed or brown dunes are found in the older areas with largely stabilised sands. They are also shallower than the dunes in the front rows and can extend inland for several kilometres. A closed vegetation cover of dwarf-shrub communities along with dune forest adds organic matter to the soil of the mature dunes, resulting in the development of a relatively thick layer of raw humus (see figure 5.13, right).

   With regard to the investigation area: Typical pioneer vegetation of the North Frisian Wadden Sea that triggers the development of incipient fordunes are the European searocket (*Cakile maritima*) or prickly saltwort (*Kali turgidum*). The dominant species in the yellow dunes is the lush marram grass (*Ammophila arenaria*). In the mature dunes, heath plants such as the common heather (*calluna vulgaris*) thrive in great abundance (Schutzstation Wattenmeer, 2021).

While, with certain site-specific differences, a white dune can develop from a foredune within a few years, the development into a grey dune takes another 10-20 years and the transformation into a mature dune about 60-70 years (Kollmann et al., 2019). In coastal dunes, dynamic phases usually alternate with phases of stability (Provoost et al., 2011). Vegetative succession can proceed more or less undisturbed as long as no external stressors influence the processes within the dune ecosystem.

In general, the concept of sediment budget is a useful tool to assess the likelihood of a dune ecosystem to extend, be stable or decline (Doody, 2013). If there is a lack of sediment supply, a dune will be very likely to erode. This can lead to the loss of the dune or dune system. Coastal armouring, the hardening of coastlines through the construction of hard coastal protection assets such as breakwaters, groynes, revetments, or sea walls, generally poses a large threat to dune systems. Hydrodynamic regimes are changed on a local scale, thus sediment supply and subsequently the sediment budget of a beach-dune system is altered (Everard et al., 2010; Hanley et al., 2014; Kollmann et al., 2019). Besides coastal armouring, dune systems are under threat and decline due to several further stressors.

For example, since 1900 about 25 % of the European dunes have been lost (Delbaere, 1998) and Heslenfeld et al. (2008) estimate that 85 % of the remainder are under threat of decline or disappearance.
Improved agricultural practices and urban development are major reasons for dune decline. Uncontrolled expansion of tourism and recreation also threaten dune ecosystems (Everard et al., 2010). Extensive summer house developments, such as in Denmark, create a multitude of trampling paths in the dunes, which damage the vegetation and thus create bare surfaces prone to the wind and blow-outs (Kollmann et al., 2019). Regular grooming of tourist beaches not only removes litter but also propagules of dune plants from the beach (Defeo et al., 2009), which prevents the establishment of pioneer plants and the formation of incipient foredunes. Increasing eutrophication, which can be exacerbated by agricultural or tourism practices, is another threat that permanently alters dune ecosystems (Kollmann et al., 2019).
Climate change related threats that will challenge coastal dunes in the future are locally predicted increases in storm intensities and frequencies (Everard et al., 2010; Hanley et al., 2014). If dunes are free to migrate landward, sea level rise as such does not represent a major problem for dune ecosystems. Unfortunately, many coastal areas are densely populated and population and tourism pressure continues to grow, which in turn causes coastal development for urban expansion, recreation and industry. Coastal dunes therefore suffer from coastal squeeze, being pressured by the rising ocean from one and spatial restrictions through development and construction from the other side (Everard et al., 2010; Hanley et al., 2014; Kollmann et al., 2019).

Coastal protection processes Coastal dunes form a natural form of coastal protection and play an important role in coastal defence along the world's sandy coastlines. Where dunes occur, they can take on the central flood protection function by acting as a physical barrier to protect the hinterland from flooding and make other coastal protection structures superfluous (e.g. on typical barrier islands off the coast). Comparable to dikes, which determine the man-made, artificial coastal protection on many coasts, dunes provide effective natural protection of the hinterland from floods and inundation and contribute to coastal conservation. The coastal protection and sediment storage capacities represent two of the coastal dunes' most valued regulating ecosystem services. The higher dune ranges in the first row, in the area of the yellow dunes, play a particularly decisive role. These dunes form the natural barrier against high water levels and prevent flooding of the hinterland, reduce wave action, serve as a sediment reserve and stabilise the sandy coasts (Hassan et al., 2005; R. Palmer and Limited, 1996; Rabe et al., 2018).

> *With regard to the investigation area:* On the west coast of the island of Amrum, coastal protection is ensured by a coherent dune area of approximately 12 km in length in combination with the adjacent Kniepsand. The dune area has a maximum width of about 1 km and individual dunes reach heights of up to 30 m (LKN.SH, 2017). It stretches from Amrum Odde in the north of the island up to the village of Wittdün in Amrum's south.

While dune vegetation plays a key role, if not the key role, in the formation and stabilisation of coastal dunes, the geomorphological characteristics of a dune are primarily

responsible for and determine its coastal protection properties. Therefore, the dune morphology as well as sediment supply, accumulation and stabilisation are important factors for the dunes coastal defence capacities (Hanley et al., 2014). Unlike a dike, the dune body actually erodes partially during storm surge events. Hence, dunes that serve as part of the coastal protection system need to be able to withstand a certain amount of erosion and storm surge damage (Roscoe and Diermanse, 2011).
Hanley et al. (2014) describe coastal dune ecosystems very aptly as a 'moveable last line of defence'. Depending on the intensity of the storm event, sand is eroded from either the foredune or the seaward foot or face of the yellow dune and then moved by the water onto the beach or as far as the foreshore area (Bijker, 1996; Doody, 2013; Everard et al., 2010). In general, erosion only occurs at the peak of the storm surge during a relatively short time period, and the eroded sand stays within the breaker zone and is deposited in the so-called erosion profile (Bijker, 1996), as depicted in figure 5.15. Hence, the material does not get lost during a storm event but is rather relocated within the dynamic dune-beach system. During the storm event the relocated sand helps to replenish the beach and foreshore area, thus improving wave dissipation in the area in front of the dunes (Doody, 2013; Everard et al., 2010). The concept of the erosion profile has been analysed in several scientific works - two of the most widely recognised were the studies by Vellinga (1986) and van Gent et al. (2008). The remaining part of the dune that has not been relocated continues to provide a protective barrier and prevents the persistent swell from washing over the dune and thereby flooding the hinterland.

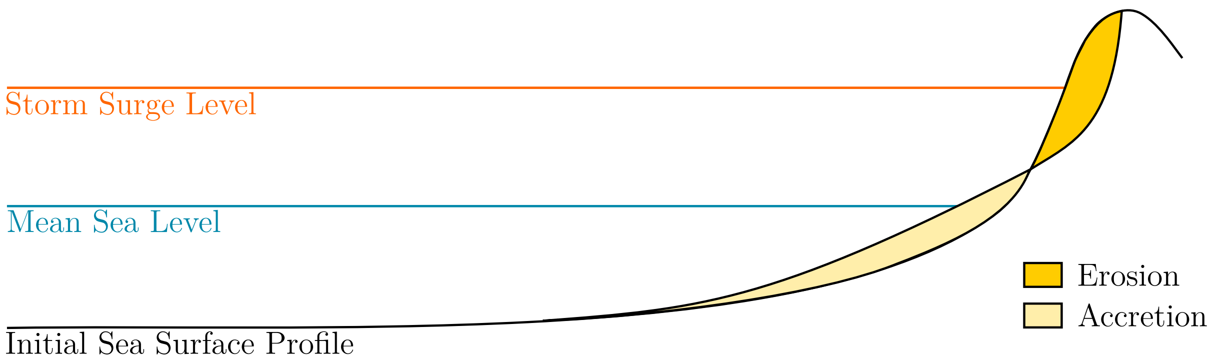

Figure 5.15: Scheme of an initial cross-shore profile and erosion profile due to dune erosion during a storm surge after; previously published in Jordan and Fröhle (2022).

After the storm has passed, the sand is gradually transported back onto the beach by waves, dries out, and is transferred to the dunes by wind. The formation or re-formation of the dunes starts anew. If the beach is sufficiently wide for enough sand to dry out and for enough wind transport capacity to be generated, dunes can regenerate within month after storm surge events (Niemeyer et al., 1996). This, of course, is highly site-specific.

Ecological and societal value A major supporting ecosystem service by coastal dunes is the provision of habitat for a variety of different species that are equipped to live in dynamic, nutrient-poor environments (Kollmann et al., 2019). Dune ecosystems support a high biodiversity, particularly including seabirds, invertebrate species and dune plants

(Hanley et al., 2014; Hassan et al., 2005). Furthermore, as successional habitats, dunes facilitate other services through soil formation (Everard et al., 2010).
Provisioning services of dunes are limited. They provide breeding and feeding grounds to the aforementioned seabirds (Hassan et al., 2005) and are as such of particular importance for a variety of migratory birds. Traditionally, especially grey and mature dunes were used as grazing land for cattle and supplier of raw materials like timber (Hanley et al., 2014; Kollmann et al., 2019; Provoost et al., 2011). As with beach ecosystems, dunes provide the opportunity for sand extraction at relatively low effort, however, this is at the expense of most of the other ecosystem services (Doody, 2013).
Regarding regulation, aside from coastal protection and sediment storage and exchange (Doody, 2013), dunes are likely to purify groundwater and in some cases even drinking water from rivers is being infiltrated into dune systems for purification purposes (Everard et al., 2010). In addition, the fresh water cushion that is formed below the dunes serves the dune vegetation as a source of water (Kollmann et al., 2019) and is also occasionally being tapped by humans to obtain drinking water (Geelen et al., 2017).
Cultural services are amongst the most widely appreciated services by coastal dune ecosystems. Dune areas are highly valued as a source of recreation, allowing several sporting activities, walking, bird watching or simply offering a place of rest and relaxation (Doody, 2013; Everard et al., 2010; Hanley et al., 2014; Hassan et al., 2005). Like the adjacent beaches, coastal dunes are areas of great aesthetic appeal and therefore play a significant role in the visual experience of low-lying coastal areas around the world (Doody, 2013).

5.2.3 Reef ecosystems

Corals, shellfish and oysters are ecosystem engineers that form reef ecosystems, which can protect coastlines from waves and storms by acting as a natural submerged breakwaters in the near-shore zone. Furthermore, supporting an abundance of fish and other marine species, they offer a large biodiversity.

Coral reefs

Corals are autogenic ecosystem engineers (Jones et al., 1994), changing their surrounding environment via their own physical structure. Thus, corals reefs are structurally complex limestone habitats formed by the corals themselves. The formation and construction of the reefs is not facilitated and driven by the soft corals but only by the hard, reef-building corals - the so-called scleractinian corals (Allemand and Osborn, 2019). While there are less than 10 reef-building coral species known in cold waters, several hundred warm-water scleractinian coral species exist (J. L. Gutiérrez et al., 2011). From here on, due to their greater relevance, warm-water coral reefs will be examined more closely, referred to simply as coral reefs.

Coral reef ecosystems occur in the shallow coastal waters of the tropics and subtropics (Barbier et al., 2011), on average in depth between 0 and 30 m, as their distribution mainly depends on light availability and the water temperature (Allemand and Osborn, 2019). While the majority of coral growth usually occurs in water depth between 10 to 20

m, reefs can extend to depth of up to 50 m (World Bank Group, 2016) or, as mesophotic reefs, reach areas that are more than 100 m under the surface of the ocean (Allemand and Osborn, 2019).
Coral reefs can be distinguished by the main types of atolls, barrier reefs, fringing reefs, or patch reefs (World Bank Group, 2016; Hassan et al., 2005), illustrated in figure 5.16. For most reef types the typical zonation from offshore to inshore, as shown in figure 5.17, includes a fore reef, usually with a steep slope in case of atolls and fringing reefs, the reef crest, a broader reef flat and back reef zones, which can vary in the extreme between several kilometres for barrier reefs and non-existence for near-shore fringing reefs (World Bank Group, 2016; Quataert et al., 2015).

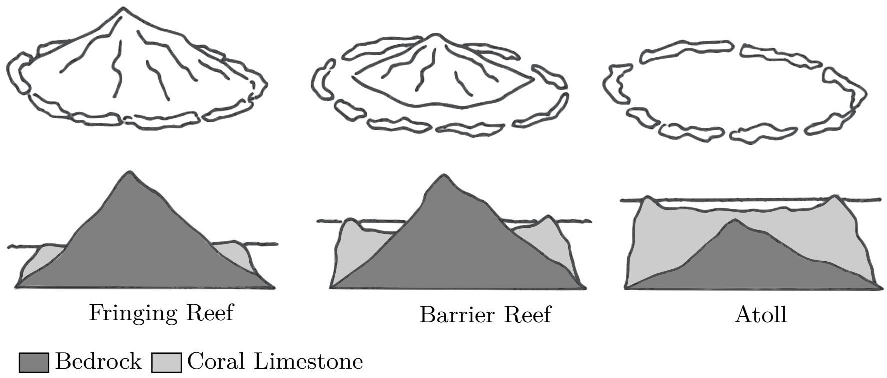

Figure 5.16: The three main types of coral reefs after Probert (2017); previously published in Jordan and Fröhle (2022).

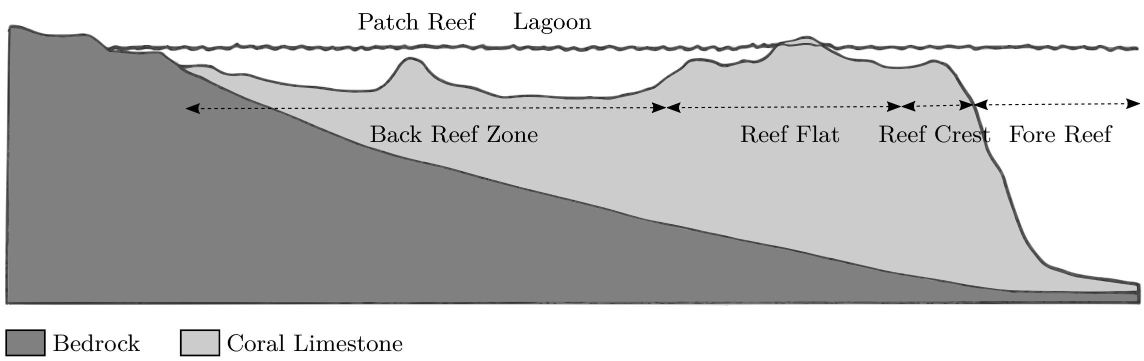

Figure 5.17: Coral reef zonation including patch reefs in the back reef zone after Probert (2017); previously published in Jordan and Fröhle (2022).

Calcium carbonate ($CaCO_3$) is the structural basis of coral reef ecosystems, being synthesised by reef-building corals to form a skeleton and accumulated over thousands or even millions of years (Allemand and Osborn, 2019). These accumulated dead coral skeletons make up the majority of the coral reef structure (Barbier et al., 2011). Only the thin outer layer of the reef consists of live coral tissue that is still growing and accreting more calcium carbonate. In their study, for example, Smith and Kinsey (1976) discovered that the $CaCO_3$ production rate in well-flushed seaward reef areas in the Pacific can be as high as 4 kg m^{-2} yr^{-1}. Putnam et al. (2017) even refer to values as high as 10 kg m^{-2} yr^{-1}.

Coral reefs are mainly distributed between 30 °N and 30 °S (Allemand and Osborn, 2019), as depicted in figure 5.18. In total, they cover an estimated area of 285,000 km^2 (World Bank Group, 2016) to 620,000 km^2 (Duarte et al., 2008b). Around 25 % of the world's coral reefs can be found in the Pacific Ocean and South-East Asia (World Bank Group, 2016). Concerning countries, Australia and Indonesia are the countries with the largest coral area. Both are home to about 17 % of the world's coral reefs each (Allemand and Osborn, 2019). According to Burke et al. (2011), today 27 % of the world's coral reefs are within marine protected areas, but there is considerable geographic variation to this value. Outside of Australia, where 75 % of the reefs are protected, the share drops to an average of 17 %.

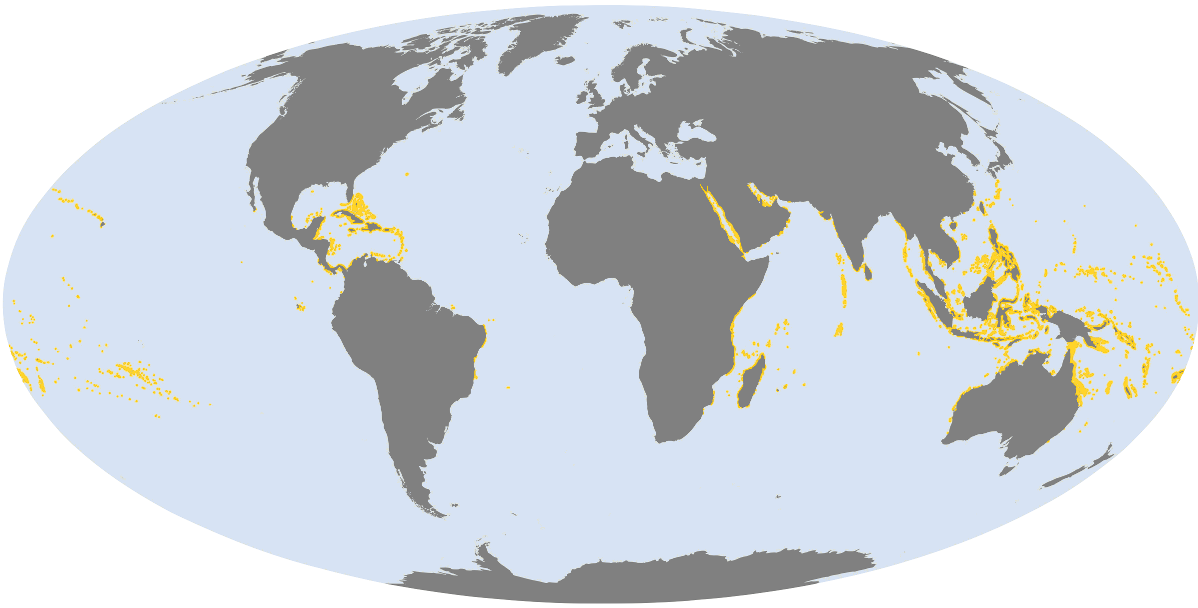

Figure 5.18: Global distribution of warm-water coral reefs in yellow after UNEP-WCMC et al. (2018); previously published in Jordan and Fröhle (2022).

Corals can successfully thrive in the relatively nutrient-poor waters of the tropics (Hassan et al., 2005) thanks to a key biological process - a symbiotic life with a unicellular algae known as zooxanthellae (Allemand and Osborn, 2019; Putnam et al., 2017). At a density of about 1 million algae per cm^2 coral tissue, the zooxanthellae live inside the endodermal cells of the coral tissue. This symbiosis, or more specifically the exchange between the coral and the micro-algae, enables the coral to gain energy from sunlight. During photosynthesis, which the algae perform, they produce sugars (photosynthates) that serve as food for the corals. Furthermore, they provide the oxygen needed for coral respiration (Allemand and Osborn, 2019). In return, the coral host provides the zooxanthellae with a safe and stable environment as well as inorganic nutrients, which are being recycled from the corals' metabolism (Putnam et al., 2017).

Coral reefs are very sensitive to anthropogenic stressors and can react quite drastically to changes in their environment with so-called disturbance-induced phase shifts, a process during which at a certain threshold, biologically diverse coral reef ecosystems irreversibly turn into impoverished wastelands (Bellwood et al., 2004). Global loss rates for coral reefs over the last decades are as high as 4-9 % yr^{-1} (Duarte et al., 2008b), i.e. twice as high as global loss rates of seagrass meadows.
Anthropogenic stressors or threats causing coral reef degradation are manifold and can be categorised into local and global scale stressors. At the local level, the most common threats include overfishing and destructive fishing practices such as dynamite or cyanide fishing, coastal construction and development, mining for construction material or marine and ornamental trade, pollution and sedimentation, inadequate sanitation and poor run-off control leading to eutrophication as well as unsustainable tourism practices (J. A. Albert et al., 2015; Allemand and Osborn, 2019; Barbier et al., 2011; World Bank Group, 2016; Hassan et al., 2005).
Global threats are closely linked to climate change. When surface waters take up atmospheric CO_2, a chemical modification of the coral reef environment occurs, resulting in a lower pH value (Allemand and Osborn, 2019; Putnam et al., 2017). This process, called ocean acidification, is leading to a reduction in coral coverage and therefore to reef destruction and structural degradation (Barbier et al., 2011; Quataert et al., 2015). A harmful physical modification of the reef environment is the increase in water temperatures, which causes a process referred to as coral bleaching (Allemand and Osborn, 2019; Hassan et al., 2005). An increase of 1 °C over long-term summer maxima can lead to a collapse of the vital symbiosis and a loss of the zooxanthellae (Putnam et al., 2017), which supply the corals with energy and oxygen. Thus, coral bleaching causes coral mortality and the degradation of coral reef ecosystems. According to highly confident estimations from the latest IPCC report (IPCC, 2019), coral reefs will decline by a further 70-90 % by the end of the century at 1.5 °C warming and vanish almost completely (> 99 %) at a warming of 2 °C.
Regarding sea level rise, healthy coral reefs are expected to be able to keep pace with rising waters due to their ecosystem engineering ability to generate and accrete large amounts of calcium carbonate (World Bank Group, 2016). Therefore, even in the face of accelerated sea level rise, many reefs can keep up the ecosystem services they provide, if not threatened and damaged by the anthropogenic stressors described above.

Coastal protection processes In comparison to wetland ecosystems with their flexible vegetation, coral reefs act as efficient breakwaters due to their rigid structure (Bouma et al., 2014) - also under exposure to higher and more powerful waves (Narayan et al., 2016a) - and successfully protect low-lying coastal areas against natural hazards from the oceans (Quataert et al., 2015). Through the presence of coral reefs, World Bank Group (2016) estimate that worldwide more than 200 million people benefit from the reduced coastal risks - for example coral reefs effectively attenuated up to 99 % of the incident wave energy during hurricane Wilma in 2005, thus sheltering the coast of Puerto Morelos and adjacent areas in the state of Quintana Roo on the Yucatan peninsula (Blanchon et al., 2010).
The effect of the reef on waves is dependent on its physical geometry and its roughness

because wave reduction or wave energy dissipation either occurs via wave-breaking as a result of changes in water depth or bottom friction induced dissipation (Narayan et al., 2016a; Quataert et al., 2015; Spalding et al., 2014). Wave breaking usually occurs at the steep fore reef or its transition to the reef crest, as shown in the scheme in figure 5.19. For a simple estimation of whether or not wave breaking occurs in shallow water, given the water depth h at the upper for reef or the reef crest, McCowan's breaking criterion (McCowan, 1894),

$$\frac{H_b}{h_b} = 0.78, \tag{5.11}$$

with H_b as the height of the breaking wave and h_b as the water depth at which the wave breaks, can be applied. In practice, when the sea state is irregular,

$$0.6 < \frac{H_b}{h_b} < 1.2, \tag{5.12}$$

and a surf zone establishes. Wave dissipation as a result of surface roughness, which creates frictional and drag forces, appears above the often wide reef flat. Hydrodynamic factors that influence the degree of wave attenuation are of course the initial wave length and height along with the depth of water above the reef surface. Significant coral reef characteristics are its cross-shore bathymetric profile, hence the fore reef slope and the reef flat width as well as the bottom roughness of the reef surface (World Bank Group, 2016; Narayan et al., 2016a; Quataert et al., 2015). According to Narayan et al. (2016a), coral reefs are able to reduce wave heights by an average of 70 % (95 % CI: 54-81 %). In a meta-analysis of 27 different scientific studies on wave attenuation in coral reefs, Ferrario et al. (2014) even identified an average wave energy reduction rate of 97 %, in which on average 86 % of the incident wave energy is already dissipated at the reef crest and a further 65 % of the remaining energy dissipates above the reef flat.

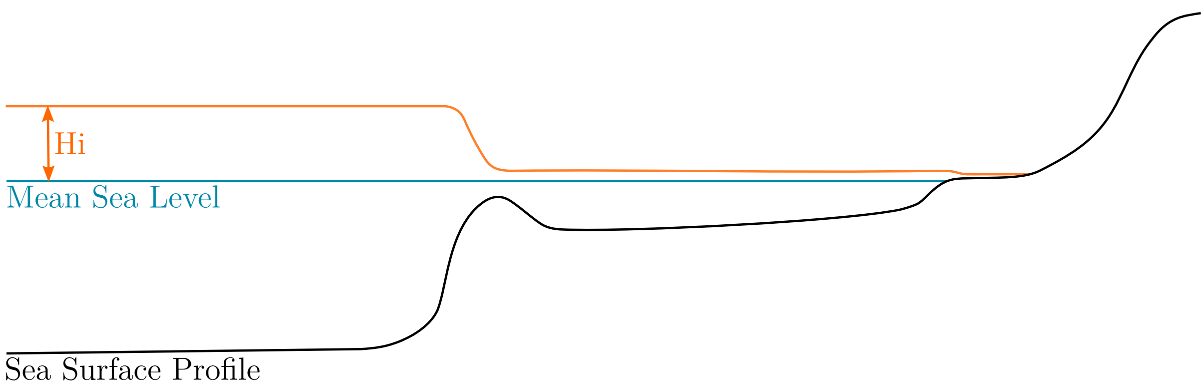

Figure 5.19: Scheme of wave attenuation over the cross-shore section of a coral reef, attenuation occurs at the steep fore reef or at the reef crest; with H$_i$ = initial wave height; previously published in Jordan and Fröhle (2022).

Regarding the stabilisation of the shoreline, coral reef ecosystems play a more proactive role compared to coastal wetlands, as they do not only trap but rather generate sediments (World Bank Group, 2016; Bouma et al., 2014). Hence, coral reefs contribute to the formation of beaches and sandy coasts in addition to securing and protecting them from erosion by calming wave conditions and providing a sheltered environment (Hassan et al., 2005).

Ecological and societal value In addition to the regulating ecosystem services of coastal protection and the generation of sand, which prevents erosion, coral reefs cater to the well-being of people and nature with several other ecosystem services. Coral reefs offer habitat to about 30 % of known marine species, including 25 % of marine fishes. They boast an enormous biodiversity, which is their main supporting service that underpins most others (Allemand and Osborn, 2019; World Bank Group, 2016; Woodhead et al., 2019).
As coral reefs are a major source of fisheries products, they provide tourists, export markets and above all coastal resident with diverse food (J. A. Albert et al., 2015; Allemand and Osborn, 2019; Hassan et al., 2005). Furthermore, they deliver coral-based products such as sand, construction material, and curios and ornamentals for aquarium trade (J. A. Albert et al., 2015; Hassan et al., 2005; Woodhead et al., 2019). Since corals also provide pharmaceutical compounds, they can additionally be seen as suppliers of medicines, significantly contributing to human well-being and health (Allemand and Osborn, 2019; Hassan et al., 2005).
Aside from the regulating services that help safeguard the coasts, coral reefs function as nitrogen fixers in the nutrient-poor coastal waters and provide certain water cleansing services, as they can transform, detoxify and sequester human-induced wastes up to certain limits (Moberg and Folke, 1999).
Culturally, coral reef ecosystems support a variety of recreational activities and offer cultural and aesthetic value to coastal communities and numerous tourists alike (World Bank Group, 2016). Apart from fisheries exports and aquarium trade, especially the reef tourism and diving industry is supporting the livelihoods of local communities (Moberg and Folke, 1999). Reef tourism is of particular economic importance in the Small Island Developing States (Allemand and Osborn, 2019) but also has a high economic value in other nations such as Egypt, Indonesia, Australia or the US (Spalding et al., 2017).

Shellfish and oyster reefs

Much like corals, reef- or bed-forming bivalves (*Bivalvia*) are ecosystem engineers which develop and form the underlying structure for their entire ecosystem themselves (Lenihan and Peterson, 1998). Formed by individual organisms growing on top of each other, they can create stable, complex, three-dimensional hard structures with effects on near-shore waves and sediment dynamics, which persist even after the organisms themselves have died (Bouma et al., 2014; Chowdhury et al., 2019; EcoShape, 2021). As they are filter feeders, bivalves require long periods of submersion to ensure food availability. They thrive in sheltered intertidal flats in the intermediate elevation zones, preferably in areas with lower impacts of waves and currents (Borsje et al., 2011; Folmer et al., 2017).

Structured habitats are usually comprised of only one species (Beck et al., 2009). Less commonly, few species can coexist in mixed habitats (Folmer et al., 2017). There are three different kinds of structured habitats formed by epibenthic shellfish according to Beck et al. (2009).

- **Reefs**: Bivalves that form reefs represent the dominant structural component of the benthos and their build-up mass provides vertical relief greater than 0.5 m. Prominent reef-forming species include the Pacific Oyster (*Crassostrea gigas*) as well as the Blue Mussel (*Mytilus edulis*).
- **Beds**: In beds, bivalves represent the major structural component of the benthos and their accumulated mass provides vertical relief of up to 0.5 m on an otherwise unstructured sea floor. European Flat Oysters (*Ostrea edulis*) are an example of bed-forming epibenthic shellfish species.
- **Aggregations**: Secondary structures, that are built on top of existing physical features, are called aggregations. Prominent examples are species from the family of Pen Shells (*Pinnidae*).

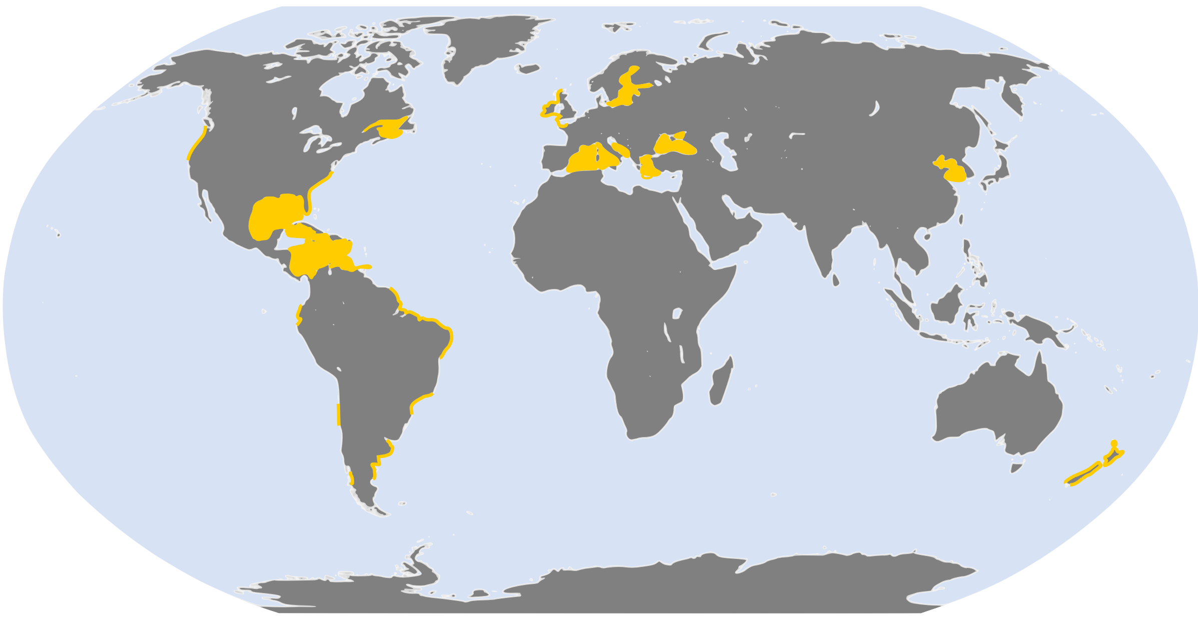

Figure 5.20: Global distribution of oyster reefs in yellow after Beck et al. (2009); including reefs of good, fair and poor condition; previously published in Jordan and Fröhle (2022).

Reef- or bed-forming bivalves can be found in the oceans around the globe. As oysters are the most prominently discussed reef-forming bivalve family with regard to NbS (e.g. Arkema et al. (2013), Bridges et al. (2018), Didderen et al. (2019), and Spalding et al. (2014)), figure 5.20 shows the global distribution of still functioning oyster reefs (Beck et al., 2009). With regard to the reefs historical abundance, Beck et al. (2009) rated their condition as either good, fair, poor or functionally extinct. European reefs were generally classified as poor or even functionally extinct in case of the North Sea and along the Atlantic coast of France and Spain. Australian reefs and the reefs along the west coast of North America are functionally extinct as well. Oyster reefs on the North American east coast and in Asia are mostly of poor condition, while the reefs in New Zealand, the Caribbean and South America are classified to be in fair condition. According to Beck et al. (2009), oyster reefs in good condition are only still present at the north coast of Brazil and along the Argentinian coast.

> *With regard to the investigation area:* Before the invasion of the Pacific Oyster into the Wadden Sea, the blue mussels represented the most abundant bed-forming epibenthic species in the intertidal zone (Folmer et al., 2017). Blue mussels were able to develop permanent beds even on the loose sediments of the Wadden Sea (MELUR, 2015). As depicted in figure 5.21, they are still widely distributed over the whole North Sea, but permanent beds or reefs were once much more widespread (Folmer et al., 2017).

Figure 5.21: Spatial distribution of blue mussels in the North Sea in green after FAO (2021).

Unfortunately, while epibenthic shellfish reefs can take decades to develop, one single anthropogenic disturbance can be enough to destroy them entirely (Didderen et al., 2019). Since they pose an easily exploitable resource due to their proximity to human populations along the coasts, Beck et al. (2009) estimate that 85 % of global oyster reefs have been lost in the course of the past century.
Man-made threats to shellfish reefs and beds are fisheries extraction and over-harvesting as well as destructive fishing practices, which directly damage or destroy the physical habitat structure. Coastal development and construction activities along with land reclamation

projects and dredging of navigational channel on shipping routes also threaten shellfish reefs and cause their destruction and extinction (Beck et al., 2009).
Natural threats are posed by waves and currents during storms, which have a destructive impact on the reefs. Ice-scouring during exceptionally cold winters also has the potential to permanently damage shellfish reefs in the intertidal zone (Folmer et al., 2017).
With respect to sea level rise, shellfish reefs increase in size over time and especially oyster reefs are expected to be resilient and grow with a rising sea level (Bridges et al., 2018; Chowdhury et al., 2019; Spalding et al., 2014) - of course not unlimited in quantity and above all not limitlessly fast.

Coastal protection processes As reefs and beds reduce wave forcing and alter the physical environment, they provide structural barriers and sheltered areas, which trap sediments (Bridges et al., 2018; Chowdhury et al., 2019) and reduce the loss of sediment from the tidal flats to the channels (Beck et al., 2009; Schoonees et al., 2019). Hence, by eco-engineering their physical environment, reef- and bed-forming bivalves promote sediment accumulation and prevent erosion by fixing the seabed over a wide area.
Furthermore, bivalve species that do neither form reefs nor beds also contribute to the reduction of erosion and shoreline stabilisation (Carss et al., 2020). They increase the surface stability of the sea floor through the formation of a structural layer of shells within the sediment. The biodeposition of fine-grained material and the production of mucus factor into the increase in stability as well. A prominent example for such bivalve species is the Common Cockle (*Cerastoderma edule*), which is present abundantly throughout the North Sea.
In comparison to flexible vegetation, reefs - coral and shellfish alike - act as effective, natural breakwaters due to their rigidity and successfully attenuate waves in the near-shore zone (Bouma et al., 2014; Schoonees et al., 2019). The effectiveness of bivalve reefs in absorbing wave energy that is directed at shorelines has been analysed in various studies (e.g. Beck et al. (2009), Bridges et al. (2018), and Chowdhury et al. (2019)). Especially with regard to larger waves (Chowdhury et al., 2019), more specifically among the highest 10 % of waves, reductions in wave height and wave energy are significant (Sutton-Grier et al., 2015).
Instead of wave breaking in reefs, dissipation caused by an increased bed friction is the main process behind wave energy reduction over mussel or oyster beds (Donker et al., 2013). On a much smaller scale, this also applies to aggregations of bivalves. When comparing natural oyster and mussel beds for the same physical wave forcing, oyster beds are found to be more effective in wave attenuation (Borsje et al., 2011). The measurement-based formula by Bouma et al. (2014) to estimate wave attenuation by intertidal habitats is also applicable to shellfish or mussel beds and oyster reefs. Derived from field measurements, Bouma et al. (2014) estimate a wave decay coefficient for mussel beds k_{mussel} $[m^{-1}]$ ranging between 0.05 to 0.15, and a wave decay coefficient for oyster reefs k_{oyster} $[m^{-1}]$ ranging between 0.15 to 0.3. Combining equations 5.2 and 5.3, the wave height after maximum attenuation by a mussel bed (thus maximum coverage, $B = B_{max}$, and $k_{mussel} = k_{mussel,max} = 0.15$) can be derived as

$$H_{L,mussel} = 0.3he^{-(0.15e^{-dh})L}, \tag{5.13}$$

and the wave height after maximum attenuation by an oyster reef (thus maximum coverage, $B = B_{max}$, and $k_{oyster} = k_{oyster,max} = 0.3$) as

$$H_{L,oyster} = 0.3he^{-(0.3e^{-dh})L} \tag{5.14}$$

respectively.

Ecological and societal value Shellfish reefs offer valuable habitat for fish and invertebrates (Chowdhury et al., 2019), which represents an important supporting service in addition to their high rate of primary production (R. M. Asmus and H. Asmus, 1991).
By serving as a nursery habitat for fish, they provide food and support recreational and commercial fisheries (Carss et al., 2020; Sutton-Grier et al., 2015) along with providing opportunities for aquaculture (Chowdhury et al., 2019). Furthermore, shellfish are still and have long been used by humans for ornamentation, as a currency, in construction and as a mineral resource (Beck et al., 2009; Carss et al., 2020).
Regulating ecosystem services by shellfish reefs include the removal of excess nutrients (Beck et al., 2009; Carss et al., 2020) as well as nitrogen (Sutton-Grier et al., 2015) from near-shore waters. Coastal shellfish beds or reefs also actively promote water quality through the bivalves enormous filtering capacity. As filter feeders, bivalves remove suspended solids from the water column and improve water clarity, thus in turn promoting e.g. adjacent seagrass growth and reducing the likelihood of harmful algae blooms (Beck et al., 2009; Didderen et al., 2019).

> *With regard to the investigation area:* The filtering capacity of bivalves is such that in summer the blue mussels and common cockles alone filter through the entire water volume of the Wadden Sea within a week (Stock et al., 2012).

Shellfish in general also provide cultural services, as there are countless images and references to shellfish in cultures around the globe (Carss et al., 2020), and the collecting of shells has made significant contributions to art, commerce and science since several centuries (Duncan and Ghys, 2019).

5.3 Relevance of Nature-based Solutions in the local coastal protection context

The relevance of NbS in coastal protection is first of all reflected in many long-established practices, which today can be summarised under the umbrella term NbS. In the North Sea region and in particular in the investigation area - Amrum and Föhr - for example, measures and concepts such as brushwood groyne construction to create foreland in front of the dike, sand trapping fences, stalk planting or dune management in general have a partly centuries-old tradition and even supposedly ‘new’ measures such as sand nourishments have been practiced for decades (cf. Chapter 4). Many of these measures represent long-standing best practices and an important part of the overall coastal protection concept, although in the past they have been established or maintained solely for their coastal protection benefits. Only recently, their multiple benefits have received attention.

The abundance of scientific publications and studies (cf. section 5.2 above where many of these are referenced) on the subject as well as the many project and experience reports on various pilot projects (e.g. compilations of pilot projects in Bridges et al. (2018) or Fröhlich and Rösner (2015)) is, seen globally, a further indication of the relevance and, above all, the topicality of NbS for coastal protection.

Thirdly and most importantly, a significant indicator and measure of relevance in the local coastal protection context, and above all for the chances of planning and implementing nature-based measures, is the perception, assessment and valuation of coastal ecosystems as NbS for coastal protection by the locally acting and responsible actors.

5.3.1 Assessment of NbS from the coastal protection perspective

Regarding the different actors involved in coastal protection, both authorities and science are of great importance. Their work is essential to advance the common practices of coastal protection, move the discipline forward or to test new approaches. Besides these aspects, the normative and practical role of authorities is crucial in negotiating and implementing coastal protection while science plays a major visionary and transformative role in tinkering and experimenting with as well as for adapting coastal protection. Out of the 35 semi-structured interviews conducted within the scope of this research, 14 interviews with actors from the responsible authorities, from universities and research institutions active in the German NSR are analysed here regarding the experts' assessment of the relevance of NbS in coastal protection.

Relevance In general, NbS are assessed very positively amongst most of the experts and appear to have gained importance over the recent years. The general shift in the mindset of many officials in coastal protection from grey to greener solutions is observed and expressed in the following quote:

> *'(...) that a lot has changed, especially with regard to coastal protection, when I think about the fact that people have started to consider nature more, that is, to have less, shall I say, concrete in their heads.'*

NbS are framed here as *'the future of coastal protection'* and *'best options'*, which are worth to be investigated further. The interviewees largely agree that, based on their experiences to date, *'one should really use such natural processes and not work against nature'* where it is possible to gain more experiences with NbS and get an insight into the effects NbS provide for coastal protection. Through modelling, laboratory tests, field investigations and pilot projects, knowledge about the performance of natural ecosystems for coastal protection has considerably improved in recent years. The insights gained here are important. To fill the still existing knowledge gaps, though, further research on large-scale applications in pilot projects is needed to generate openness for and interest in such

endeavours within authorities and research institutions. However, interest exists and is gathering momentum.
One has to bear in mind, however, that the focus is not set on the re-invention of coastal protection. On the contrary, current practices work well. The focus lies on opening the engineering discipline to natural and societal aspects to advance current measures, as articulated in the following quote:

> *'Not as a substitute, I say that every time, it is not a replacement for dikes, barriers and the like but as a useful addition.'*

Hence, coastal ecosystems as NbS in coastal protection are not supposed to (and are in most cases also not able to) replace existing structures or practices but to work as an addition to them or an adaptation of them to the changed boundary conditions, including societal demands and ideals.

Obstacles and challenges Regarding obstacles for the implementation of NbS in coastal protection, four major factors were identified by the experts interviewed. First, as in many construction projects, costs and the lack of sufficiently available material represent one reason why hard engineering solutions are preferred to nature-based concepts or ideas. Especially the availability of sand and the cost for the resource sand are a significant problem for large-scale sand nourishments in the NSR.
Secondly, regulations in nature conservation and protected areas display a challenge for NbS along the coast. This aspect becomes clearly apparent in the following quote where the problem of an intervention - even though naturally motivated - represents a problem as the implementation interferes with what is conceived as a natural process:

> *'And that will certainly be a big challenge in the future when you think about establishing such measures; because I'm looking at nature conservation again, even a nature-based solution first of all creates an intervention in nature conservation.'*

The third factor partly relates to the second. Nature-based coastal protection normally requires more space than traditional engineering concepts. Tetrapods, for example, need much less space than the establishment of a salt marsh for wave dampening. While both approaches may imply an intervention in nature and potentially protected areas, in Germany the required space is conceived as decisive regarding the intervention. In such cases, less flexible regulations result in the fact that the nature-based option cannot be implemented due to nature conservation guidelines. In addition, the greater space requirements also pose a problem for landward expansions of the coastal protection system with NbS in the narrow coastal zone. Residents rarely give up their property or farmers their agricultural land for coastal protection. The space available for coastal protection is therefore constricted and limited from both sides. Thus, there is a need with regard to the assessment of the severity of the impact on nature, which should not be based primarily on the space requirement but should include more the compatibility and naturalness of measures in the assessment. Furthermore, coastal dwellers should be introduced to the

advantages of nature-based coastal protection in order to increase their acceptance and commitment to making space available for their own safety as well as for natural and societal interests.
Fourthly, despite their potentials, there is still a lack of knowledge with regard to the exact modes of how natural coastal processes in NbS work. This creates a lack of trust in such measures and results in lack of acceptance which is depicted in the following quote:

> *'Yes, there is certainly potential to optimise coastal protection. That is not the question. The problem will be to establish it, yes, to create acceptance for certain measures.'*

This reveals a research gap from the societal perspective. To boost the acceptance of coastal ecosystems serving coastal protection purposes in combination with existing structures, integrative projects in which the topic of NbS is communalised and shared contexts of experience are established, can help to identify NbS' key societal issues against which NbS can be assessed. That way, local actors - first and foremost local coastal dwellers, but also people working in coastal protection or nature conservation - can identify the multiple benefits that many NbS have to offer for themselves and evaluate them against their personal key criteria regarding, e.g., safety or landscape aesthetics.

Limits Naturally, there are certain limits to the applicability and functionality of NbS for coastal protection, as for all kinds of coastal protection measures. For NbS though, in contrast to engineered structures, not only the technical but also natural, spatial and economic restraints play a decisive role. Hence, one has to engage with a fourfold problem setting in which costs - as highlighted in the following quote - play an important role:

> *'(...) and this is of course always an important point, cannot be implemented everywhere or cannot be implemented everywhere at a reasonable cost (...)'*

As to the interplay of natural and economic limits, mangroves do obviously not grow in the North Sea and while salt marshes do, they need specific conditions to thrive. These are either naturally existing or can, in some cases, be generated through more or less costly engineering interventions in the coastal environment. Hence, not every NbS is feasible at every location or makes sense in every place. Consequently, approaches and measures require a site specificity that is based on measurement data and the knowledge about the existing boundary conditions.
Other limits can be derived from the way in which natural ecosystems are functioning for coastal protection because there are natural limits to their positive, protective effects on the sea (e.g. wave dampening through salt marsh vegetation). When these limits are reached, because for example the water level above salt marsh vegetation is so high that the vegetation no longer has an effect on the waves, the coastal ecosystem salt marsh as a NbS *'no longer plays a role [for coastal protection] and the physical strength of the dike is decisive'*.
The limits mentioned above are either natural limits of existence and effectiveness or adaptation limits related to climatic change and its effects on the local boundary conditions.

The goal to overcome these limits, reveals another, rather engineering-oriented research gap. On the one hand, coastal ecosystems as NbS must be designed to permanently withstand the impacts exerted on them in order to survive and thrive at the location. On the other hand, as these coastal ecosystems are supposed to fulfil a certain function in the coastal protection scheme, their design must also fit the necessary dimensioning they need to permanently deliver this function. Criteria for the dimensioning of NbS are needed for clearer and more robust statements about the benefits of NbS for coastal protection in feasibility assessments as well as planning and implementation. In addition, possible and reasonable engineering interventions to overcome the limits enable the natural or man-made establishment of coastal ecosystems or support and strengthen the coastal protection effects.

Chances Despite these obstacles and limitations, according to the experts interviewed, the chances that NbS offer for coastal protection outweigh negative aspects. Almost all interview partners underline the relevance of the potentialities and the importance of developing NbS in general and also coastal protection in this direction.

> *'(. . .) because it opens up new opportunities, offers new possibilities for solutions, and in this respect - as in every discipline – coastal protection continues to evolve.'*

NbS are perceived as the development or evolution of coastal protection currently needed. They create *'win-win situations'*, provide coastal protection and a *'benefit of nature (. . .) and tourism'*. As an adaptation of or complement to the status quo, NbS offer the opportunity to react to change and *'get a grip on the problems we are going to have'* - without having to build ever-rising dikes along the coasts.

5.4 Summary and interim conclusion

Summary and discussion

Key features, occurrence and threats Coastal ecosystems thrive under various conditions and on all continents around the globe. Naturally, since they differ from each other in their structure, their components and characteristics as well as their needs in terms of site conditions, not all coastal ecosystems examined in this chapter exist on every continent or occupy similar areas in the coastal environment. As described in the sections beforehand, most coastal ecosystems are highly specified and perfectly adapted to their areas of distribution. The analysed ecosystems' key features, their distribution and favourable conditions are summarised in table 5.2.

Table 5.2: Key features and natural distribution of the different coastal ecosystems and favourable conditions for them to thrive.

Coastal Ecosystem	**Key Feature**	**Distribution**	**Favourable Conditions**
Salt marshes	Herbs	Mid-elevation coastal zones; Temperate climates	Sandy or muddy coast; Occasional submergence; Shallow, low-energy shoreline
Mangroves	Trees and shrubs	Mid-elevation coastal zones; Tropics and subtropics	Loose and wet soils; Periodic tidal submergence; Saline to brackish waters
Seagrass meadows	Flowering plants	All continents except Antarctica; Tropics to temperate zones	Soft substrates; Wave-sheltered environments; Light availability; Depth up to 40 m; Proximity to other coastal ecosystems
Beaches	Physically dynamic sand or shingle environment	All continents except Antarctica; Increased occurrence in lower mid-latitudes and subtropics	Abundance of sediment; Close linkage to surf zone and coastal dunes
Dunes	Dynamic geomorphic structures	Worldwide	Along extensive beaches; Abundance of sediment; Close linkage with adjacent beaches
Coral reefs	Structurally complex limestone habitats	Tropics and subtropics; Around the equatorial belt	Shallow coastal waters; Light availability; Usually depth up to 30 m
Shellfish reefs	Reef- or bed-forming bivalves	Worldwide	Sheltered, intertidal flats; Long periods of tidal submergence; Low impacts of waves or currents

Due to their very specific adaptations to the environment in which they thrive, coastal ecosystems are sometimes very sensitive to changes and threats in this very environment. Natural extremes, in coastal areas e.g. extreme storm events, can be harmful and destructive to all coastal ecosystems discussed above. Hence, changes in the hydrological and hydrodynamic conditions - caused by climate change or other modifications to the environment - and thus, ultimately in the loads on the ecosystems pose one of the major threats to all of them. Further main threats to coastal ecosystems may they be climate change related or caused by direct or indirect human impacts, as analysed in this chapter. They are summarised in table 5.3.

Table 5.3: Main threats to the different coastal ecosystems; no mark does not imply that the threat is not harmful to the ecosystem, it is simply none of the major threats; SM = salt marshes, M = mangroves, SGM = seagrass meadows, B = beaches, D = dunes, CR = coral reefs, SOR = shellfish/oyster reefs; *causing ocean acidification, **in combination with landward spatial restrictions (coastal squeeze).

Threat	**SM**	**M**	**SGM**	**B**	**D**	**CR**	**SOR**
Climate change related impacts							
Elevated atmospheric CO_2^*	✗	✗				✗	
Increased temperatures	✗	✗				✗	
Accelerated sea level rise**	✗	✗	✗	✗	✗		(✗)
Indirect human impacts							
Eutrophication	✗		✗		✗	✗	
Hypersalinisation			✗				
Sedimentation						✗	
Lack of sediment supply				✗	✗		
Reduced water clarity			✗				
Direct human impacts							
Shoreline development	✗	✗	✗	✗	✗	✗	✗
Industrial development/pollution		✗		✗			
Land reclamation							✗
Land-use changes		✗	✗		✗		
Groundwater extraction				✗			
Overexploitation		✗		✗	✗	✗	
Overfishing/destructive practices						✗	✗
Tourism pressure		✗		✗	✗	✗	
Boating/anchoring/dredging			✗				✗

Coastal protection All coastal ecosystems examined in this review provide certain processes or support certain developments that directly or indirectly benefit the regulating ecosystem services 'storm protection' and 'erosion control' (cf. table 5.1). The underlying systems are always certain processes or services that have an effect on the prevailing hydrodynamic or morphological conditions. A summary of the effects and developments which are described in this chapter is given in table 5.4. This overview underlines the high value that should be assigned to coastal ecosystems in terms of coastal protection and the fundamental role they can play in implementing and supporting coastal protection strategies and objectives.

Table 5.4: Coastal protection processes provided by the different coastal ecosystems; SM = salt marshes, M = mangroves, SGM = seagrass meadows, B = beaches, D = dunes, CR = coral reefs, SOR = shellfish/oyster reefs; * Terminology of the Millennium Ecosystem Assessment (Watson and Zakri, 2003), see table 5.1.

Coastal Protection Effect	SM	M	SGM	B	D	CR	SOR
Storm Protection*							
Wave attenuation	✓	✓	(✓)	✓	✓	✓	✓
Wave breaking				✓	✓	✓	
Prevention of flooding					✓		
Reduction of current velocities	✓	✓	(✓)				
Water retaining capacity	✓						
Wind speed reduction		✓					
Erosion Control*							
Sediment accretion	✓	✓	✓		✓	✓	✓
Ground soil stabilisation	✓	✓	✓				✓
Reduction of shear stresses	✓	✓				✓	✓
Sediment exchange and storage				✓	✓		
Sediment generation						✓	
Build-up of humus	✓						

Ecology and society Aside form their significant contribution to coastal protection (cf. section 5.1 - Water) coastal ecosystems also cater to the needs of Nature and People. A summary of the ecosystem services which are described in this chapter is given in table 5.5, stressing the high significance and astonishing diversity of services associated with these coastal ecosystems attending societal and ecological needs.

Table 5.5: Ecosystem services provided by the different coastal ecosystems; SM = salt marshes, M = mangroves, SGM = seagrass meadows, B = beaches, D = dunes, CR = coral reefs, SOR = shellfish/oyster reefs.

Ecosystem Service	**SM**	**M**	**SGM**	**B**	**D**	**CR**	**SOR**
Supporting Ecosystem Services							
Primary production	✓		✓				✓
Habitat provision	✓	✓	✓	✓	✓	✓	✓
Biodiversity		✓		✓	✓	✓	
Soil formation					✓		
Nutrient cycling	✓		✓				✓
Provisioning Ecosystem Services							
Nursery for marine organisms	✓	✓	✓				✓
Breeding/foraging/resting for birds	✓			✓	✓		
Food source for communities		✓				✓	✓
Food source for marine species			✓				
Freshwater source					✓		
Construction material		✓		✓	✓	✓	✓
Fire wood		✓			(✓)		
Agricultural activities		✓			(✓)		✓
Curios and ornamentals						✓	✓
Pharmaceutical components						✓	
Regulating Ecosystem Services							
Water quality improvement	✓	✓	✓			✓	✓
Breakdown of organic materials				✓			
Carbon sequestration	✓	✓	✓				
Underwater oxygen production			✓				
Water filtration				✓	✓		✓
Transport of terrestrial nutrients				✓			
Nitrogen fixation						✓	✓
Cultural Ecosystem Services							
Aesthetic ecological value	✓	✓	✓			✓	
Tourism and recreation	✓	✓		✓	✓	✓	
Cultural heritage and arts		✓		✓	✓		✓
Safeguard threatened species			✓			✓	
Visual appeal of landscape	✓	✓		✓	✓		

Relevance as assessed by experts The local expert assessment of

- the relevance,
- obstacles and challenges,
- the existing natural and functional limits, and
- the offered chances

of NbS for coastal protection based on the conducted interviews with experts from the German North Sea Region revealed similar results to comparable studies by DeLorme et al. (2022) and Ostrow et al. (2022) conducted in the US. The assessment here is therefore not only significant at the local level (Amrum, Föhr and the German North Sea coast), but can also be used in part for other locations due to comparable comments and assessments by US experts on the subject.
Generally speaking, in relation to the question of *how the relevance of NbS for future coastal protection is assessed by experts*, they are being assessed positively. There are still many knowledge gaps regarding the interaction of the coastal ecosystems serving as NbS with their surrounding environment and the existing and changing boundary conditions. Furthermore, a lack of experience and guidance is being perceived. But, if one is considering the challenges and the limits for the use of NbS, the interviewed experts attribute many chances for the future of coastal protection to them.

Interim conclusion

As depicted in this chapter, coastal ecosystems like salt marshes, mangroves, seagrass meadows, beaches, dunes, coral, and shellfish or oyster reefs *offer a chance to bridge the gap between coastal engineering and nature conservation in the land-sea transition zone*, since they provide benefits and support beneficial processes for Water, Nature and People alike. When, for example, using a salt marsh habitat as a NbS for an area, one does not have to choose between coastal protection and nature conservation or prioritise one over the other. By conserving and protecting a salt marsh, thus promoting its natural healthy state, one ensures that the salt marsh provides its greatest possible protection for the coast as well as supporting the greatest possible biodiversity.
Hence, in addition to the existing coastal protection structures and systems, which are currently working well and satisfactory in terms of protecting people and goods in the hinterland from flooding, related dangers and damages as well as shoreline preservation and erosion control, coastal ecosystems as Nature-based Solutions can be a promising, sustainable and multi-beneficial part of the coastal protection schemes along our coastlines. They offer a promising approach for the existing coastal protection to adapt to climate change related challenges, which coastal communities are already facing in the present day and which will most certainly intensify in the future (IPCC, 2019), while incorporating ecological and societal needs.

The overriding premise when working with coastal ecosystems as Nature-based Solutions is, of course, to work within the given, natural boundary conditions and not to create artificial landscapes as foreign bodies in the coastal environment. Regarding sandy coasts in general, all of the coastal ecosystems discussed above can be of relevance, given that the respective site conditions are favourable for the ecosystem to thrive. With a specific focus on the investigation area of Amrum and Föhr in the German Wadden Sea, salt marshes, seagrass meadows, beaches, dunes, and shellfish and oyster reefs can be found naturally in the area. Therefore, these ecosystems represent the range of possible and sensible NbS which can be implemented as part of the coastal protection there.

However, despite the need for sustainable adaptation measures, the extensive study on NbS performed within the scope of this chapter revealed critical knowledge gaps, which still impede the large-scale consideration and implementation of NbS in coastal protection. While there are numerous studies and there is ample information focussing on the coastal protection services of NbS as well as their ecological value (cf. the abundance of studies cited in this chapter), little attention is given to the NbS' properties or - speaking in engineering terms - 'design criteria' needed to sustainably thrive as well as provide these very services. Furthermore, studies of NbS for coastal protection tend to stop when it comes to society. So far, little attention is given to the NbS' impact on and perception in society nor their interaction with it.

The following two chapters will address these two aspects and thereby contribute to broadening the conceptual understanding of NbS from an engineering (chapter 6) and a societal (chapter 7) perspective.

6 Engineering scope in NbS for coastal protection

When looking into the future of coastal protection in the face of climate change, engineered structures like dikes remain, of course, indispensable in many places for the protection of our coasts. NbS, however, display a cost-effective complementary strategy worth investigating further at many locations (Temmerman et al., 2023). While 'grey' measures derive their entire function for coastal protection from rigid engineered structures, 'green' protection - or NbS - derive their protective functions from coastal ecosystems and their respective properties, which can change and adapt over time (Singhvi et al., 2022).
Since the various physical, ecological, societal and economic boundary conditions, to which the design of coastal protection measures has to match, are changing over time - nowadays maybe even more quickly and drastically than during the past decades or centuries - a certain adaptive capacity is key to sustainably provide the desired performance. As expressed before in chapter 5, this adaptive capacity is naturally high with NbS but little to non-existent with structural measures without expensive retrofitting. In combination with the persistence of NbS, this can make them preferable to structural measures as complementary adaptation strategies (Bridges et al., 2021).

To further promote the design and implementation of NbS for coastal protection, according to Kempa et al. (2023), inter- and transdisciplinary approaches as well as experiences from science and practice are needed and should be actively pursued and combined, as it is practised in the context of this work.
In the following, the **'Engineering Scope'** in NbS for coastal protection is being illustrated. Since the focus of this work is on coastal protection, possible solutions must permanently withstand the impacts opposed upon them to sustainably fulfil their coastal protection purpose. Therefore, their dimensioning must fit to the environment. If the dimensioning does not fit, the NbS will be detached from the overall concept of coastal protection after a short time, and would, of course, not be implemented as a coastal protection measure in the first place - no matter how promising ecological or societal assessments might be (Nevertheless, e.g. a salt marsh can be created in front of a dike, and the dike simultaneously be raised as the adaptation measure. The NbS salt marsh would then be detached from the coastal protection and only socially and ecologically relevant, but that is not the focus of this work.).
To (alleged) experts, this chapter illustrates possibilities and the engineering scope in NbS. Regarding (alleged) laymen, it provides a tool to elucidate and communicate the topic and its relevance for the future. With the main target of coastal protection in mind, the goal here is to broaden the knowledge in the field of NbS, making NbS more tangible for engineers, pointing out that there are certain parameters that can be influenced to

achieve a desired effect (or not, but they are known and can be judged realistically) and helping to enable the (re-)diversification of coastal protection (cf. chapter 4) by providing answers to the following two interconnected research questions:

- What properties or characteristics of a NbS are essential for it to **sustainably deliver its services**, and what are the corresponding dependencies between service and properties?
- What properties or characteristics of a NbS are essential for it to **sustainably exist at a location**, and what are the corresponding dependencies between resilience and its properties?

6.1 State of the art

There is an abundance of studies available on the performance of NbS, describing and analysing the ecosystem services of NbS benefiting coastal protection (cf. chapter 5 or e.g. Bridges et al. (2021) and Ostrow et al. (2022)). Many scientific publications document the work that is being performed to quantify these ecosystem services, the influences of coastal ecosystems such as salt marshes, seagrass meadows or mussel beds on current velocities, wave attenuation or sediment stabilisation (e.g. Bouma et al. (2014) and Ondiviela et al. (2014)), either by site-specific field and lab measurements (e.g. Balke et al. (2011), Balke et al. (2012), Baptist et al. (2019), Callaghan et al. (2010), Chowdhury et al. (2019), Möller et al. (2014), and Quang Bao (2011)) or by site-specific modelling studies (e.g. Brière et al. (2018), Donker et al. (2013), Maza et al. (2012), Quataert et al. (2015), Ranasinghe (2016), Siemes et al. (2020), Suzuki et al. (2011), and Temmerman et al. (2012)).
Regarding the design of NbS for coastal protection, however, beyond small-scale site-specific application for single pilot projects, universal information on a conceptual level is still scarce. While in traditional engineering design a structure like a dike would be sized in accordance with the determined or decided upon performance objectives resulting in controllable design parameters, the challenge with NbS is that they do not behave in the same way as a fixed, rigid structure. They can adjust themselves dynamically, hence their performance is harder to control and design parameters like vegetation or sediment characteristics can change both spatially and temporally (Ostrow et al., 2022). NbS need to fit functionally and spatially in the target area and require a sufficient size to resist disturbances (Andersson et al., 2017). They should be adaptive (Reguero et al., 2017), and their design process therefore has to be iterative (Bridges et al., 2022). In comparison to traditional structures, which usually only respond to one specific problem like erosion or flooding, NbS always cater to multiple objectives, which have to be brought together (Reguero et al., 2017) - even though one, like coastal protection, might be the main focus.

In order to help facilitate, promote and mainstream the implementation of NbS in coastal protection strategies, the two questions *'How does a NbS have to be designed to be able to deliver its services sustainably?'*, and *'How does a NbS have to be designed to sustainably exist in a certain location?'* will be addressed in the remainder of this chapter. These two

questions also reveal, or are aimed at, the two or actually three core competencies of NbS in coastal protection: **service**, **resistance** and **resilience**.
The *service*-aspect has been discussed thoroughly in chapter 5. In order to sustainably provide these services, an ecosystem has to be resistant. In order to exist sustainably at a certain location in the face of change and threats, an ecosystem has to be resilient. Regarding these two terms, various different definitions can be found in literature. Holling (1973) defines resilience as the property of an ecological system that determines the persistence of relationships within this system. Hence, the persistence or extinction of an ecosystem is the result of its resilience. Stability or resistance, on the other hand, is defined as the capability of an ecological system to return to an (optimal) equilibrium state after the system has been temporarily disturbed. Stability or resistance as the system's property is thus responsible for the degree of fluctuation around the equilibrium state, which is defined as the result. Later on, Holling (1996) refined his definition of resilience and differentiates between engineering and ecological resilience. Engineering resilience follows his former concept of stability or resistance and focuses on the ecological systems' stability near an equilibrium state, while ecological resilience focuses on changing stability domains where instabilities can cause a system to evolve into another equilibrium state in another stability domain.
In line with Holling's definition of engineering resilience (Holling, 1996), Andersson et al. (2017) classify a system to be resilient if it can absorb disturbances and reorganise without undergoing fundamental change. Bridges et al. (2021) further elaborate this definition as to defining resilience as the ability of a system to prepare for, absorb, recover from, and adapt to shocks or disturbances such as storm surges. In this approach, adaptive capacity, hence a system's ability to evolve under changing boundary conditions, is regarded to be the final concept of resilience, similar to Holling's concept of ecological resilience (Holling, 1996).
Another approach by Singhvi et al. (2022) differentiates between external and internal resilience of ecosystems. As the external resilience describes the ecosystem's capacity to protect the larger coastal system, this aspect focuses on the service of NbS. The competencies of resilience and resistance are included in the internal resilience, which is defined as the ability to endure disturbances and shocks.
Finally, the definition by Temmerman et al. (2023) will be mentioned here. They characterise resistance as the ability to avoid, and resilience as the ability to recover from damage. Temmerman et al. (2023) state that the effectiveness of NbS in coastal protection depends on their functionality, hence their services as well as on their persistence, which is a result of their resistance and resilience. Highlighting that tidal wetlands, exemplary for coastal ecosystems as NbS and under investigation in their work, have persisted over millennia, they acknowledge that coastal ecosystems possess a certain inert resistance in their interaction with the boundary conditions in the coastscape.

Be that as it may, regarding the anthropogenic, storm- or SLR-related threats that need to be responded to (Temmerman et al., 2023), NbS have certain functional and ecological limits (Reguero et al., 2017). Thresholds in terms of establishment as well as survival - hydrodynamic thresholds for the presence of vegetation at a marsh edge for example - have been examined in numerous studies (e.g. Balke et al. (2011), Balke et al. (2014), Balke et al. (2016), and Willemsen et al. (2022)). Seasonally recurring disturbances, such as storm events or the increase in the frequency of storms caused by climate change, can push coastal ecosystems until these thresholds are reached - until a tipping point beyond which they degrade and, over time, transform into mudflats or open water (Temmerman et al., 2023). The effects of anthropogenic impacts and climate change on the survivability of NbS, hence the degree to which the two compromise the NbS' natural resilience, have yet to be studied in further detail (Ostrow et al., 2022; Temmerman et al., 2023).

However, all these key competences like the services, the resistance, the resilience and all the processes within the interaction of NbS with the coastal environment are based on the properties of the NbS and can therefore, in theory at least, be influences through these properties. This linkage between **properties and service** has already been made and is described in several studies like the ones by Barbier et al. (2011), Bridges et al. (2015), Bridges et al. (2021), or Ostrow et al. (2022). Considered properties include for example the size, stability and biodiversity of ecosystems (Watson and Zakri, 2003), bed-level dynamics (Willemsen et al., 2022), cross-shore profile and slope, grain sizes, roughness, width, elevation, bathymetry, or herbal characteristics such as height, density or flexibility (Bridges et al., 2021). The linkage between **properties and resilience**, though, still poses a research gap. Furthermore, the consideration of engineering interventions to influence single properties of coastal ecosystems in order to ultimately influence services or resilience of these ecosystems has still not been investigated on a large-scale, conceptual level. Gijsman et al. (2021) mention engineering interventions but understand them as structures like wave breakers to prevent ecosystem failure and degradation, not as measures to influence single properties and enable the coastal ecosystem to develop itself with regard to service or resilience.

Guiding policies or manuals to support a standardised NbS design are still missing (Bridges et al., 2022; Reguero et al., 2017), since traditional performance-oriented design approaches to NbS (e.g. Bridges et al. (2021)) fail to include the aspects of resilience and resistance (cf. Singhvi et al. (2022)). Therefore, they cannot include the response of NbS to multiple stressors, the conditions under which they can persist or can be created or the management strategies under which they thrive and perform best (Temmerman et al., 2023). To tackle these research gaps, monitoring of coastal ecosystems is key (cf. Gijsman et al. (2021), Ostrow et al. (2022), and Willemsen et al. (2022)), and since monitoring budgets are usually tight and the procedure is elaborate and time-consuming (Bridges et al., 2021), one needs to limit the monitoring to the most relevant properties. These properties or design criteria have to be identified in combination with their impact on both service and resilience, while simultaneously being aware of the possibilities that engineering interventions might offer to influence them. Hence, the question is, *'Where is the engineering scope in NbS for coastal protection?'*

In the following, the engineering scope will be identified on a conceptual level and its role in NbS for coastal protection will be clarified, illustrated and emphasised in order to help answering some of the questions and fill some of the research gaps mentioned above.

6.2 Interaction between coastal ecosystems and boundary conditions

Deconstructing the system

To obtain a comprehensive understanding of the interaction between coastal ecosystems and the naturally occurring boundary conditions, a list of items relevant for this interaction was compiled in a first step. Therefore, the complicated system of the interaction between coastal ecosystems and boundary conditions was deconstructed into its various subsystems and their components (Benmia et al., 2022).
On the basis of the review on coastal ecosystems as NbS in coastal protection (see 5), all previously discussed coastal ecosystem are included in the compilation. Since the focus here is on coastal protection, all identified ecosystem services catering to either 'storm protection' or 'erosion control' (cf. Watson and Zakri (2003)) can play a role in the interaction.
Going further into detail on these ecosystem services, the question is which properties of the considered ecosystems have an effect on the outcome or the magnitude of the ecosystem services. Hence, which ecosystem properties naturally influence the ecosystem services or - from an engineering point of view - might be used or shaped to influence them? From this angle, based on the thoroughly conducted review in chapter 5 and aforementioned studies (e.g. Bridges et al. (2015), Bridges et al. (2021), Sauvé et al. (2022a), and Singhvi et al. (2022)), resulted a collection of ecosystem properties regarding

- dimension and location,
- vegetation, and
- subsoil.

The coastal ecosystems, which can serve as coastal protection (in combination with structural measures), are then confronted with the natural boundary conditions described in detail in section 3.3. These boundary conditions interact with the coastal ecosystems. On the one hand, they generate stresses that act on the ecosystems and which these have to withstand. On the other hand, they are in turn influenced by the coastal ecosystems and, for example, attenuated in the sense of coastal protection. The interaction of ecosystems and boundary conditions can, furthermore, be influenced by external stressors like climate change, anthropogenic disturbances or societal demands.
The complete compilation of the identified items that have to be taken into account for the analysis of the interaction between coastal ecosystems and boundary conditions is depicted in figure 6.1.

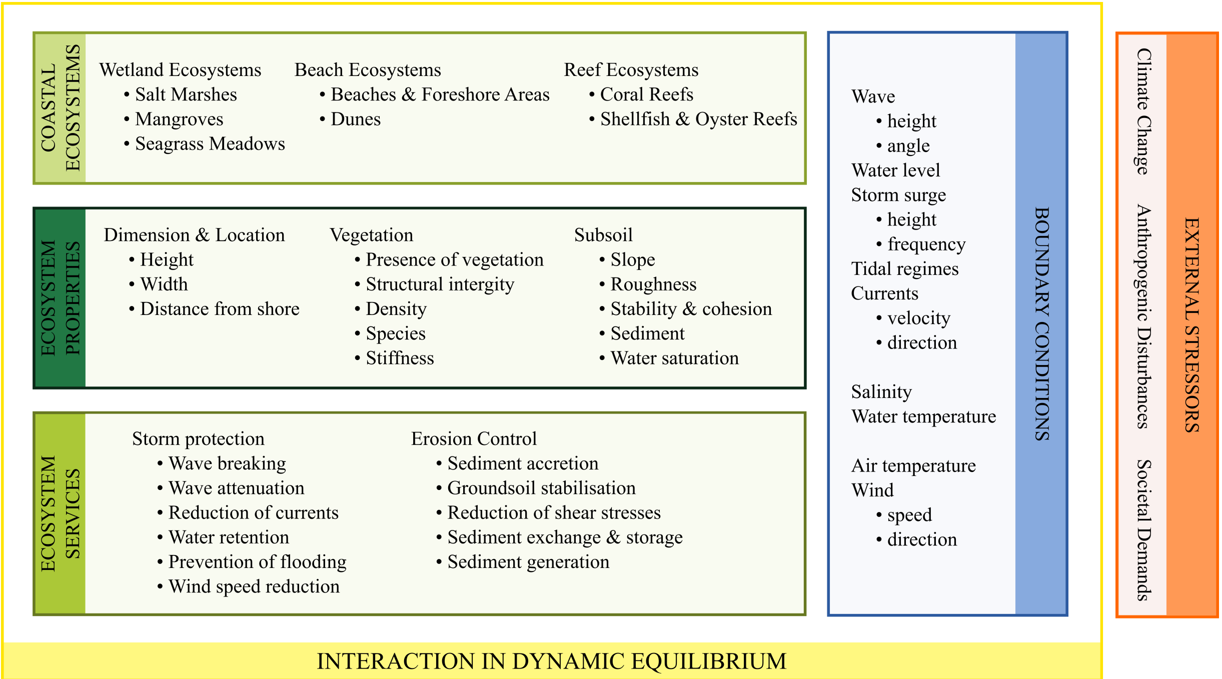

Figure 6.1: Compilation of relevant items regarding the interaction in dynamic equilibrium between coastal ecosystems and boundary conditions.

A conceptual framework

In order to highlight the engineering scope in NbS for coastal protection, a conceptual framework was developed, incorporating the three core competencies of NbS in coastal protection - service, resistance and resilience.

In the status quo, coastal ecosystems and boundary conditions interact in a dynamic equilibrium. Due to their inert resistance - their preparedness, absorptive capacity as well as recoverability (Bridges et al., 2021) - ecosystems can exist and thrive at coastal locations over long periods of time and successfully withstand the impacts acting upon them (cf. Temmerman et al. (2023)). This interaction is not bound to a specific equilibrium. Instead, the interaction can shift between different states within the dynamic equilibrium, since the ecosystems themselves, by nature, do not have single equilibria but rather different states between which they can move to maintain structure and diversity (Holling, 1996). As the interaction between coastal ecosystems and boundary conditions happens vice versa, there are two sides to it. Regarding the service, the coastal ecosystem can protect from coastal hazards through the interaction, whereas the resilience side focuses on the ecosystems' recoverability and especially their adaptive capacity (Bridges et al., 2021), hence their potential to adapt to coastal hazards. The developed conceptual framework is depicted in figure 6.2. Regarding its spatial scale, it is generally applicable to coastal ecosystems in interaction with boundary conditions. When used as part of the investigation of a NbS, the boxes have to be filled with the respective site-specific criteria and items (see the compilation above in figure 6.1).

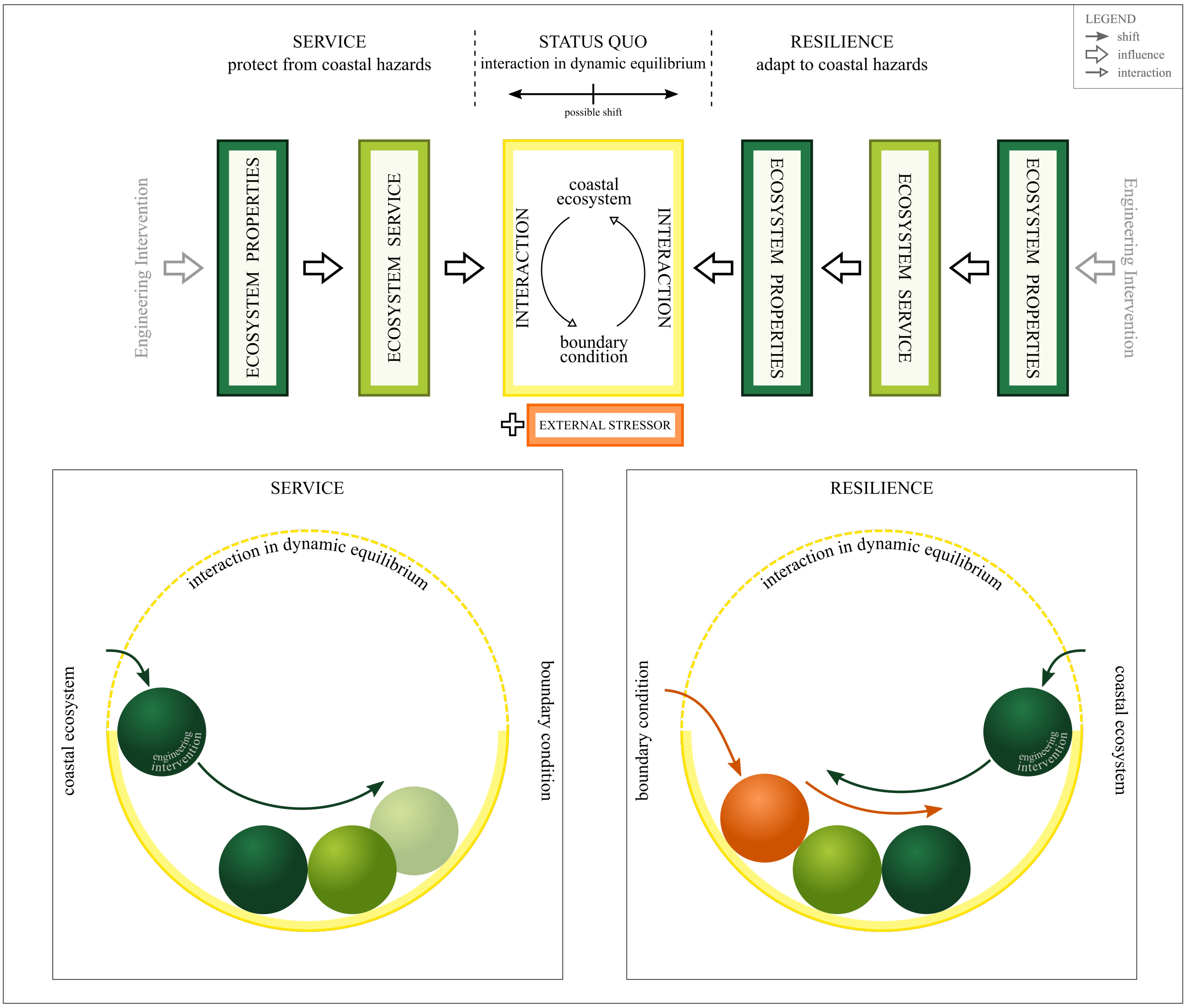

Figure 6.2: Conceptual framework for the identification of the engineering scope in NbS for coastal protection: relevant parameters and influential pathways with regard to status quo as interaction in dynamic equilibrium, service as protection from coastal hazards and resilience as adaptation to coastal hazards as well as the vantage point for engineering interventions.

On the service side, certain ecosystem properties (EP) sustain and support ecosystem services (ES) that influence the interaction between ecosystem and boundary condition to the benefit of coastal protection (see figure 6.2, top left). For example, the width (EP) of a mangrove forest sustains and supports its wave attenuation (ES) capacities, thus obtaining to coastal protection.
The ecosystem properties can either change naturally and intrinsically or be influenced through engineering interventions (EI) to strengthen and promote the coastal protection service, shifting the interaction in dynamic equilibrium to a new targeted state (see figure 6.2, bottom left). For example, a mangrove forest can expand naturally or new mangroves

can be planted (EI) in front of an existing forest to extend the width (EP) of the forest and thereby increase wave attenuation (ES).

On the resilience side, ecosystem properties also sustain and support certain ecosystem services, which in turn benefit the adaptability of other ecosystem properties. These properties are then the key to attenuate and prevent the ecosystems degradation and destruction through the impacts inflicted upon them by the existing boundary conditions (see figure 6.2, top right). For example, the density (EP) of mangroves in a forest sustains and supports ground soil stabilisation (ES), which contributes to structural integrity (EP). A healthy and structurally integer mangrove forest attenuates and prevents breaking and uprooting of mangroves through wave action.
If an external stressor comes into play and enhances the impacts inflicted upon the coastal ecosystem by the boundary conditions, thus threatening the ecosystem's existence in a specific location, coastal ecosystems either bear the strength to adapt naturally and intrinsically or engineering interventions can be used to strengthen the ecosystem properties. These can, in turn, improve the ecosystem's adaptability to changes within the interaction, ensuring its persistence (see figure 6.2, bottom right). For example, mangrove seedlings naturally sprout in existing gaps in a forest. New mangroves can be planted (EI) within the forest to close gaps and increase the mangrove forest's density (EP), promoting ground soil stabilisation (ES) and thereby an enhanced structural integrity (EP), that can help to withstand climate change induced increased wave action.

The engineering scope for including coastal ecosystems as NbS in coastal protection thus focuses primarily on the ecosystem properties. On the one hand, because the ecosystem properties display the parameters in the interaction that can be fine-tuned and influenced for coastal protection purposes. On the other hand, if an ecosystem is to be part of a coastal protection system or if the appropriate design parameters for establishing an ecosystem are to be determined, the relevant properties that have a potential influence on specific desired services must be identified, considered and evaluated.

6.3 Application at the selected investigation sites

In the following, the concept developed and described above for analysing and elaborating the engineering scope is applied exemplary to the selected investigation sites on Amrum and Föhr (description, see section 4.4).

Amrum, Steenodder Kliff

In order to tackle land loss and erosion problems at Steenodder Kliff (see the description of the challenges in section 4.4), one could either build a revetment to secure the coastline or promote the establishment of a salt marsh in front of the current coastline to prevent further erosion and dampen the destructive forces of waves and storm surges. A revetment represents the traditional, structural measures (or 'grey' as labelled in section 4.1), whereas a salt marsh is an example of NbS or 'green' measures. In the past, both types of measures have been implemented in the investigation area in general and on Amrum specifically, as described in detail in section 4.1. They have proven to be suitable for erosion control in comparable sandy coastal environments (cf. table 5.4).

Taking a closer look at the nature-based measure, salt marshes interact with various boundary conditions, e.g. with waves and storm surges. Regarding the service aspect, a salt marsh at Steenodder Kliff could provide wave attenuation (ES), thereby reducing the wave action that reaches the actual coastline and minimising the damage to the hiking path. The wave attenuation capacity of the salt marsh mainly depends on its height, width and slope, as well as the density and stiffness of the vegetation (EPs). Engineering interventions that can support and promote these properties are, for example, the creation of brushwood groyne fields to start the salt marsh establishment in the first place, a secured marsh edge, once a salt marsh has developed, or the planting and seeding of specific salt marsh vegetation to close gaps in vegetation density or foster specific species.
Furthermore, in case of a storm surge, a salt marsh bears a certain retaining capacity (ES), depending on its width, the type of sediment and the water saturation before the storm surge (EPs). Once a salt marsh has developed at Steenodder Kliff, its width could be enhanced through additional brushwood groyne fields. The type of sediment or sediment availability in general can be influenced through nourishments in the area (EIs).
With regard to resilience, the effects of climate change on waves and storm surges (see respective predictions for the investigation area given in section 3.3) might threaten the sustainable existence of a salt marsh at Steenodder Kliff by increased danger of breaking and uprooting through wave action or drowning due to SLR and longer submergence times. Ecosystem properties that attenuate and prevent these threats are the structural integrity of the marsh, its height, present species, and the stability and cohesion of the marsh's subsoil. Under normal conditions, these properties guarantee the salt marsh's existence in the interaction with the respective boundary conditions. With climate change altering these boundary conditions, the marsh's properties need to adapt as well. Ground soil stabilisation, the reduction of shear stresses, and sediment accretion are some of the salt marsh's provided services (ESs) that can alter the properties mentioned before to match the changed boundary conditions in the interaction. Thus, these intrinsic services help

the salt marsh ecosystem to adapt from within. They mainly depend on the density of the vegetation, its structural integrity and the occurring species as well as the available sediment and the salt marsh's width (EPs). In turn, these properties can be influenced by engineering interventions similar to those mentioned above to alter the provided services.

The most relevant interactions of a salt marsh with different boundary conditions (wave, water level, storm surge, and currents) with regard to service and resilience are illustrated in figure 6.3 in accordance with the developed concept.

Although developed to analyse and highlight the engineering scope in NbS, the concept can also be applied to traditional, structural engineering measures in coastal protection. This allows comparability of the nature-based and the structural measures discussed here and illustrates differences.
As for the service side, a revetment at Steenodder Kliff could also ensure erosion protection through the fixation of the coastline (Service). The properties of the revetment that guarantee this fixation are to be determined by technical design criteria based on the desired performance in the interaction with waves and storm surges.
Factoring in climate change and its effects on the relevant boundary conditions (see section 3.3) like waves and storm surges, the revetment will face the danger of scouring at its foot and the wrenching of single elements during storms in the foreseeable future. This might possibly render it unable to provide the needed fixation to prevent erosion and land loss. Properties that can prevent or attenuate such damages are the revetment's structural integrity as well as the choice of material. Unlike in the case of the salt marsh, the properties cannot adapt to new boundary conditions from within, but can only be adapted by constructional alterations to the original design - hence by retrofitting if possible, or demolition and new construction.

The most relevant interactions of a revetment with different boundary conditions (wave, water level, storm surge) regarding service and resilience are depicted in the conceptional scheme in figure 6.4.

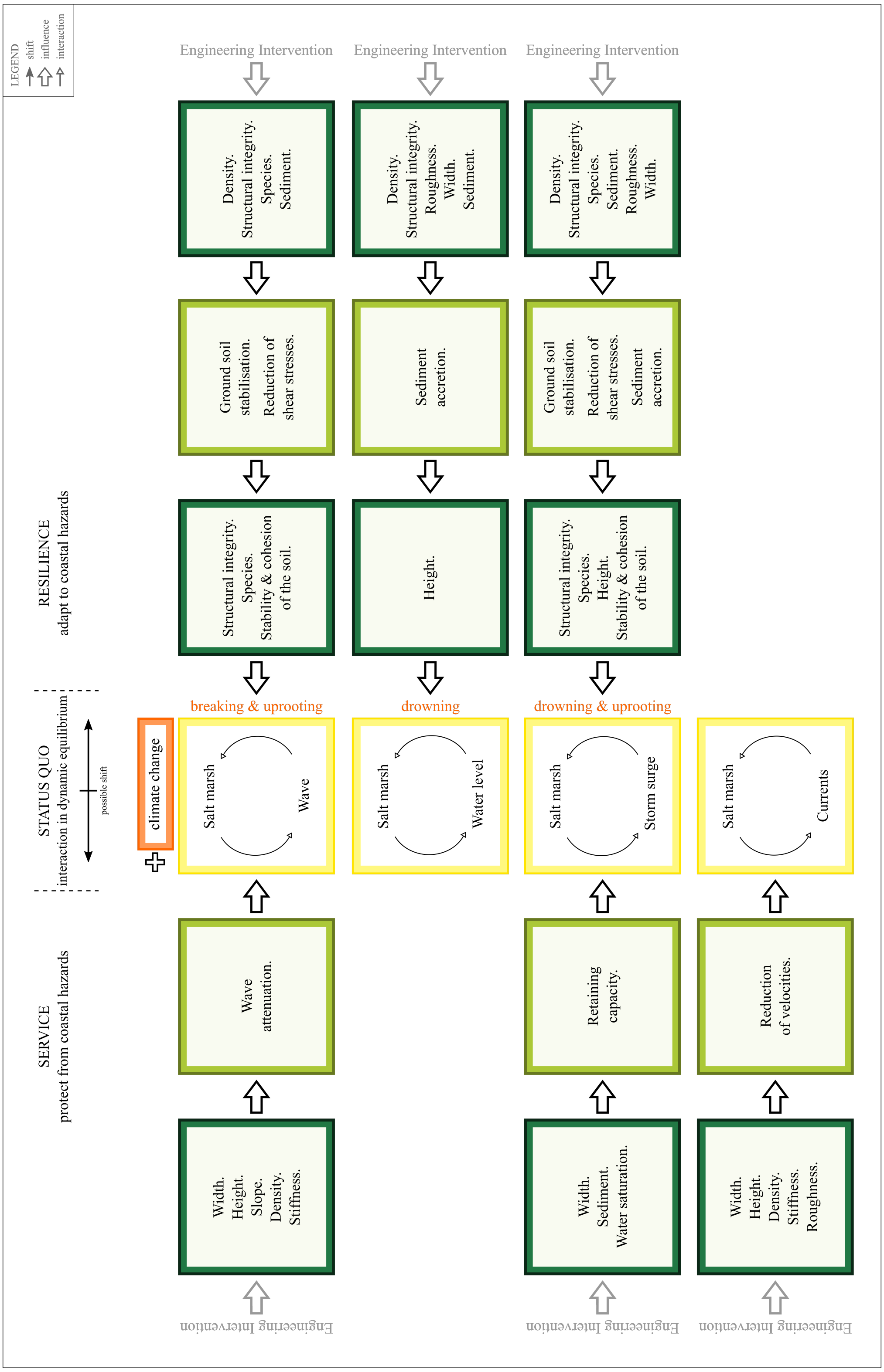

Figure 6.3: Application of the conceptual framework for the identification of the engineering scope in NbS for coastal protection for a salt marsh at Steenodder Kliff, Amrum.

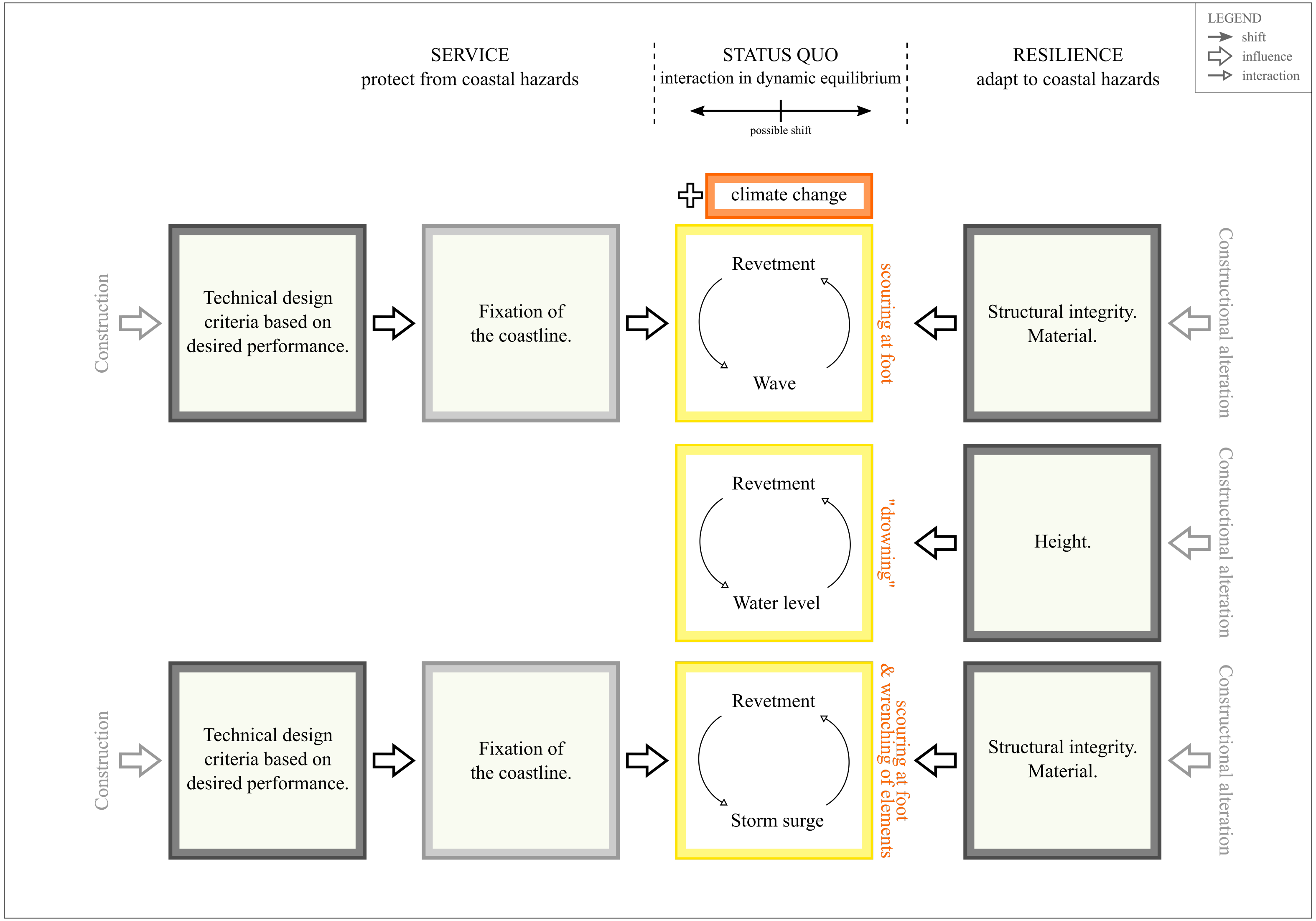

Figure 6.4: Application of the conceptual framework for the identification of the engineering scope in NbS for coastal protection for a revetment (non-NbS measure) at Steenodder Kliff, Amrum.

Föhr, Hedehusumer Geest

To prevent further erosion of the beaches or land losses of agricultural areas at Hedehusumer Geest (see the description of the challenges in section 4.4), either dune development could be promoted or a dune could be artificially built, as far as NbS or 'green' measures are concerned. Regarding traditional, structural measures (or 'grey' measures as labelled in section 4.1), one could also build a dike along Hedehusumer Geest to secure the coastline and prevent flooding. As described in section 4.1, both types of measures have proven to be suitable for similar challenges in earlier implementations in the investigation area.

Amongst various boundary conditions, a dune or a dune belt at Hedehusumer Geest, for example, interacts with the water level and storm surges. The service a dune provides in these interactions is the prevention of flooding of the hinterland (ES). Its ability to prevent flooding depends on the dune's height, width and structural integrity (EPs). These properties can change dynamically, as dunes are highly dynamic coastal ecosystems. Alternatively, changes to these properties can be triggered or supported through engineering interventions, in order to boost the service provided by the dune. Stalk planting, for example, promotes dune development and helps to fix already existing dunes in their place. Regarding the availability of sufficient sediment, beach nourishments can find a remedy.
The effects of climate change on water levels and storm surges (see respective predictions for the investigation area given in section 3.3) threaten the sustainable existence of dunes, since they increase erosion and the danger of breaching, when storms occur more frequently and with higher water levels than before. In the interaction in dynamic equilibrium, the dune's slope, height, and width, its structural integrity, its water saturation, the presence of vegetation, the overall sediment availability as well as the stability and cohesion of the soil (EPs) are the determining characteristics for the dune's sustainable existence. When faced with changing boundary conditions and therefore with changed loads on the dune, these properties need to adapt to match the new challenges in the interaction. The intrinsic adaptability of the ecosystem properties is ensured by the dune's ability to accrete sediment, stabilise the ground soil and store and exchange sediment (ESs). These services, above all, depend on the presence of vegetation and on sufficient sediment availability, usually provided or ensured by an adjacent beach (EPs). Stalk plantings or nourishments (EIs) can of course foster these properties and thus provide the impetus for the process of ecosystem adaptation.

The most relevant interactions of a dune with various boundary conditions (wave, water level, storm surge and wind) regarding service as well as resilience are shown in figure 6.5.

Similar to the procedure for the revetment at the investigation site on Amrum, the developed concept is also applied to the idea of a dike at Hedehusumer Geest on Föhr. A dike represents traditional, structural engineering measures in coastal protection. It will be discussed here in comparison to a nature-based measure to illustrate the differences of the two.
Regarding the provided services in interaction with water levels and storm surges, a dike at

Hedehusumer Geest can prevent flooding and ensure storm protection and erosion control. The dike's properties, such as height, slope or material, that safeguard these services, are to be determined in the technical design criteria based on the desired performance and the underlying dike construction.

When climate change comes into play, altering boundary conditions like the water level or storm surges, the structure is threatened. Overflowing and overtopping could undermine the service or the desired function. Slope and height of the dike are the main properties that need adjustment to counteract and prevent the threats posed and exacerbated by climate change. In comparison to a dune ecosystem however, these properties are not able to adapt dynamically. They can only be adapted to new boundary conditions through constructional alterations to the original design, hence through retrofitting or demolition and new, adapted construction.

The most relevant interactions of a dike with different boundary conditions (wave, water level, storm surge) in relation to service and resilience are illustrated in figure 6.6.

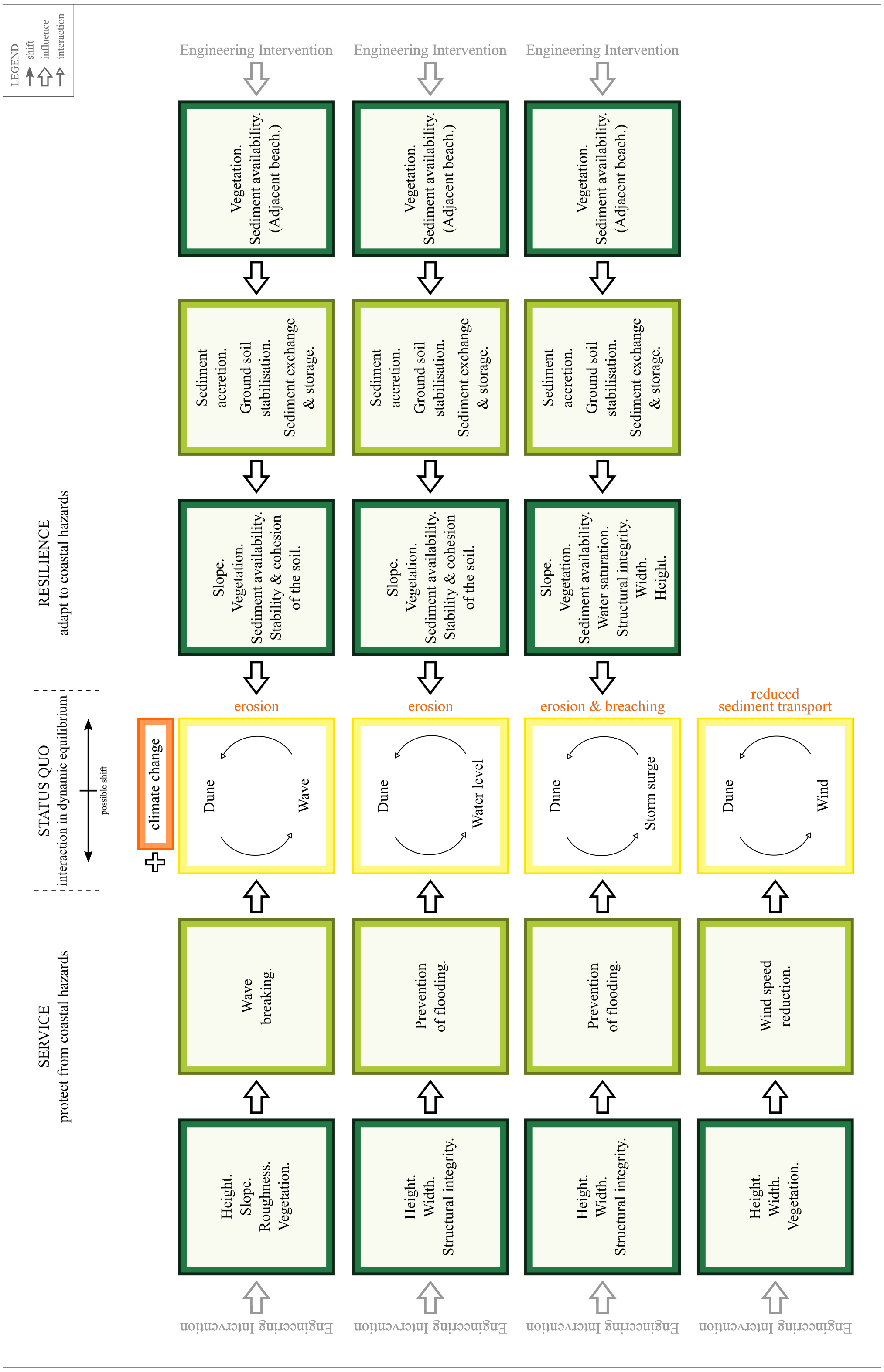

Figure 6.5: Application of the conceptual framework for the identification of the engineering scope in NbS for coastal protection for a dune at Hedehusumer Geest, Föhr.

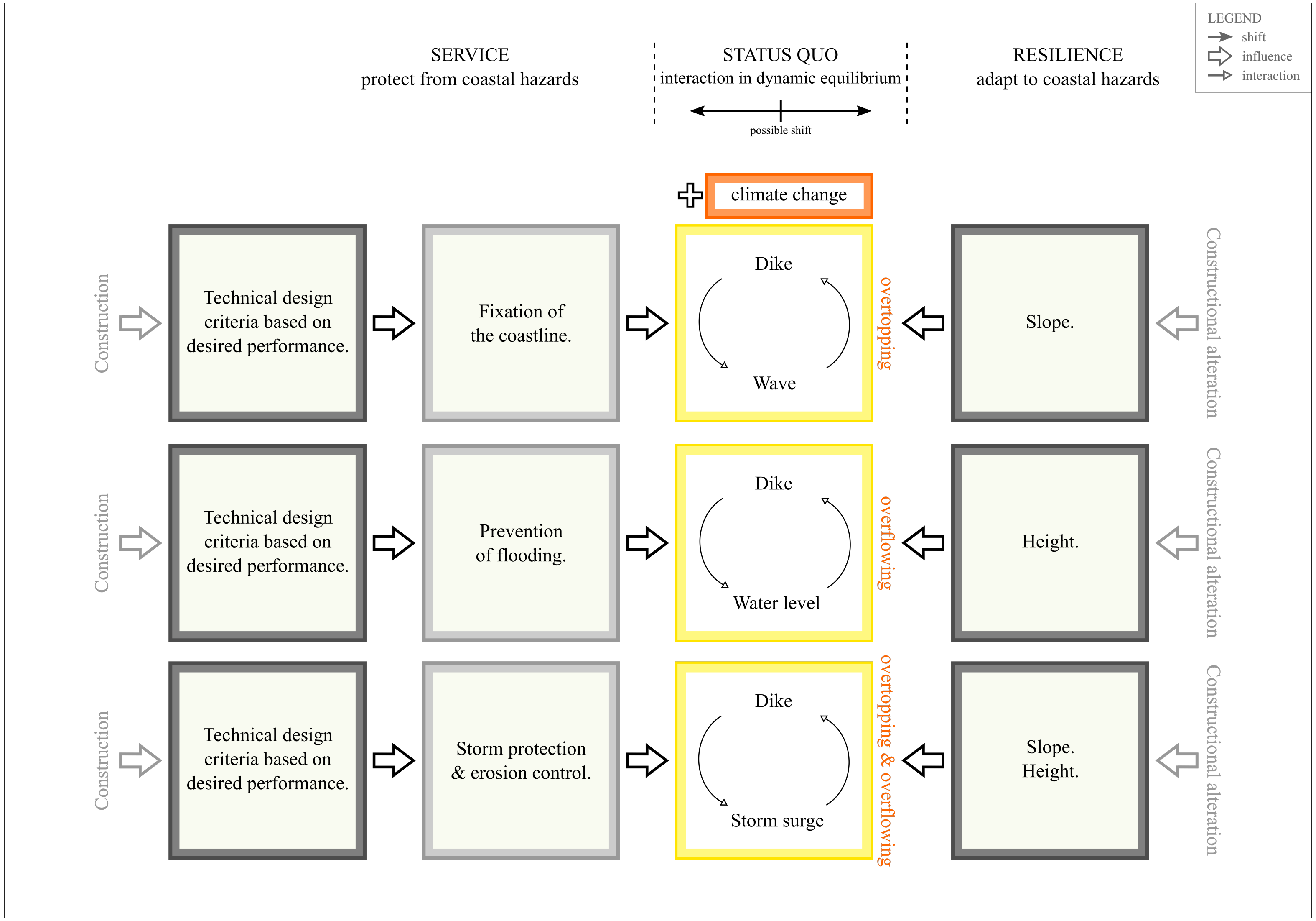

Figure 6.6: Application of the conceptual framework for the identification of the engineering scope in NbS for coastal protection for a dike (non-NbS measure) at Hedehusumer Geest, Föhr.

6.4 Summary and interim conclusion

In traditional, structural (or ‘grey’ as labelled in section 4.1) coastal engineering, structures are designed in accordance with the determined performance criteria to ensure the level of protection they were built to deliver. In contrast, the challenge with nature-based coastal protection is that the design parameters or properties of the NbS can change and the interrelations between functions and properties are complex and multi-layered. The core competencies of NbS - service, resistance and resilience - all depend on the properties and the ecosystems’ inner processes.
These processes have to be disentangled on a conceptual level to uncover the interrelationships, dependencies and paths of influence in order to shed light on the questions *‘Which properties or characteristics of a NbS are essential for it to sustainably deliver its services and to sustainably exist at a location, and what are the corresponding dependencies?’*

After a compilation of the relevant items within the interaction, covering ecosystem services, ecosystem properties and boundary conditions, a conceptual framework was developed that displays the most important connections. On the service side, engineering interventions can strengthen and promote properties, which in turn sustain and support services that influence the interaction (see figure 6.2, top left, moving right from the far left towards the interaction in the centre). Regarding resilience, engineering interventions can strengthen and promote properties, which in turn sustain and support services which benefit the adaptability of properties that attenuate and prevent harm or damage through changed boundary conditions to the ecosystem (see figure 6.2, top right, moving left from the far right towards the interaction in the centre).
The conceptual framework contributes to broadening the understanding of NbS from an engineering perspective in focussing on the inner processes and properties (or eventually design parameters), rather than the functions. It clearly shows that the properties represent the parameter in the interaction that can be fine-tuned and must be identified, considered and evaluated in the planning and implementation of NbS in the coastal protection strategy - they represent the engineering scope.

The exemplary application of the conceptual framework to the investigation sites at Steenodder Kliff on Amrum and Hedehusumer Geest on Föhr revealed the advantages of NbS for the future sustainable adaptation of coastal protection to climate change. Whereas structural measures like a revetment or a dike require constructional retrofitting or a completely new construction to be adapted to changed boundary conditions, nature-based measures such as salt marshes or dunes possess an inherent resilience and can adapt from within - given, of ourse, the suitable conditions outlined in chapter 5.
As stated before, NbS have certain natural as well as adaptation limits with regard to their functionality or service (e.g. the limited effect of wave attenuation over a salt marsh when the water level above the marsh is too high) and their persistence or resilience (e.g. a limited adaptability to SLR through sediment accretion when SLR accelerates too rapidly). Through engineering interventions, ecosystem properties can be influenced to overcome these limits, to enable the natural or artificial establishment of coastal ecosystems and to support and strengthen coastal protection. Furthermore, combinations of grey and green

measures can be beneficial for the both and represent a promising way to adapt existing coastal protection to the challenges ahead. By considering NbS and (re-)diversifying coastal protection, sandy coasts in general and in particular the coastlines of Amrum and Föhr can become more resilient and sustainably meet the multiple demands and interests in the coastal zone in the future.

However, due to these multiple interests and requests and against the background of sustainability, it is not sufficient to merely penetrate and consider the engineering perspective with regard to the adaptation of coastal protection. Particularly in the context of climate change, which is a challenge and task for society as a whole and concerns everyone, areas such as coastal protection can no longer be pursued without the active and extensive involvement of society. As coastal protection is a socio-technical endeavour (cf. chapter 4), society is key to the acceptance and thus the sustainability of measures. The following chapter therefore focuses on the societal perspective.

7 Societal scope in NbS for coastal protection

Climate change challenges the society as a whole and the adaptation of the socio-technical endeavour of coastal protection to climate change, can therefore not be done without society.
The analysis of past and present perceptions of coastal protection and its evolution performed in chapter 4 (section 4.3) helps to permeate the socio-technical fabric that is coastal protection. Thus, it allows to identify feasible and sustainable ways or approaches for the future based on past experiences instead of acting detached from the past evolution.
The assessment of the relevance of NbS in coastal protection from the perspective of (alleged) experts in the field provided in chapter 5 (section 5.3) discloses the potential of NbS in coastal protection. However, the assessment also illustrates existing challenges, such as the creation of acceptance for and trust in NbS amongst the coastal population as well as the authorities.
As stated in the outset of this thesis, coastal protection measures can only be truly sustainable if supported and valued by the coastal society. The topic of NbS has to be communalised, and shared context and experiences need to be established (cf. section 5.3). To be able to openly discuss measures like NbS for the future adaptation of coastal protection, key requests apart from safety have to be identified.

In this chapter, a review on the role and value of actors in coastal protection aims at taking a step back at first, before deepening the analysis with regard to existing studies on societal valuation and the requirements for coastal protection. Based on these findings, the analysis of interviews with coastal dwellers in the investigation area will aid in providing answers to the following research question:

- Which aspects or needs display the key requests the coastal population has for coastal protection, and what are the underlying images or experiences, that shape and define these requests?

7.1 Actors or stakeholders and their engagement in coastal protection

Franklin (2020) defines *stakeholders* very generally as *'people who are influenced by or can influence the activities of others'*. Beyond this general definition regarding people, the term stakeholder can also describe future generations, flora and fauna or even places,

hence inanimate actors (Franklin, 2020). From a more project-oriented viewpoint, Bridges et al. (2022) frame stakeholders as *'all who are interested in, have influence over, or are impacted by'* the project under consideration.
As becomes apparent in this definition, different stakeholders have different roles within a project and therefore different kinds and levels of responsibility. Governments and their respective coastal authorities, for example, are usually the ones to make the final decision when it comes to coastal protection measures, but they might include the local population in the process of coming to this decision. When these authorities then talk about stakeholders in the project, they consider locals or NGOs but might not recognise themselves as one of the stakeholders but rather an outside party due to the different levels in the process. Therefore, the term *stakeholders* will no longer be used in the following but will be referred to as *actors* in further consideration and analysis. The concept of *actors* is broader and, following the general definition by Franklin (2020), includes everyone and everything that influences or is influenced by coastal protection.

Taking a closer look at human actors (simply referred to as actors from here on) they generally interact based on either their own interests or the interests of a group, organisation or collective (Franklin, 2020). Due to the great diversity in coastal areas, actors have very different and often conflicting interests, perspectives and values. When interacting with multiple actors in coastal protection it is the challenge but nevertheless should be the goal to identify mutually value-producing measures or concepts (Andersson et al., 2017; Franklin, 2020; Sauvé et al., 2022b). The identification and classification of relevant actors can be based on multiple criteria depending on the nature of the project or measure in question (cf. e.g. an overview of different criteria in Areizaga et al. (2012)). Common methods for the identification of relevant actors in coastal protection are contacting responsible authorities, local people and organisations as well as field visits to the project area (Wang et al., 2018).
The impact of the actors and the importance of incorporating all relevant actors in a coastal protection project reveals itself when examining the paradigm shift in society and therefore also in coastal protection. Coastal protection authorities can no longer work by the 'decide, announce and defend' strategy as before (d'Hont and Slinger, 2022) but are required to change their approaches and ways of working from reactive to pro-active ones (Vriend et al., 2015). Furthermore, climate change and its consequences for coastal protection operate on time spans much longer than elected governments, which significantly set the direction of their subordinate authorities (IPCC, 2019). Thus, matters such as coastal protection cannot be left solely in the hands of politics. The public has to be actively engaged in them. However, time horizons are not the only reason to involve all relevant actors in coastal protection. Local acceptance is key for the successful and sustainable implementation of a coastal protection measure (e.g. Hofstede (2019b)). Hence, local actors can actively contribute to a measure's success or disrupt it, and their interaction occur - contradictory to what responsible authorities might assume - organically (Franklin, 2020). It is therefore even more important to know all relevant actors, to be aware of their interactions, values and preferences because, deliberately or not, they can and will either benefit or hinder a coastal protection measure such as a nature-based adaptation of the existing protection, for example.

The local population plays a unique role in coastal protection. Many people living on the coast are aware of the dangers of storm surges and the additional threats posed by climate change. Even more, their experiences with past storm surges and the way their ancestors dealt with the challenges of living on the coast contribute significantly to their regional identity, as exemplified by Holzhausen and Grecksch (2021), Ratter and Gee (2012), and Rheinheimer (2003) for the wider region of the investigation area. Hence, pursuing new ways in coastal protection (e.g. with a more nature-based approach to adaptation), i.e. challenging the existing concepts of coastal protection, also challenges the coastal dwellers' identity (Holzhausen and Grecksch, 2021). Being left out in the process of developing the future coastal protection as an adaptation to climate change, for example with NbS, coastal dwellers might perceive such approaches negatively right from the start due to lack of information, fear of losing land or mistrust in the NbS' function and then disrupt the implementation of measures (Doswald and Osti, 2011; Schroor, 2011). On the other hand, when being involved in the processes, all relevant actors including coastal residents can engage in finding compromises between the different interests and benefit the process through their deep-rooted connection with the landscape and their personal interests of preserving it (Döring and Ratter, 2021; Fröhlich and Rösner, 2015; Ratter and Gee, 2012). Involving actors in coastal protection strengthens these already existing interrelations between the coastal population and their environment and thus ultimately enables a sustainable development of future coastal protection (Holling, 1996). Through opening lines of communication, the engagement of actors facilitates the communication of complex (scientific) information, it builds mutual understanding and respect for one another, empowers all actors and also discloses their interest in the matter and their willingness to support (Kujala et al., 2022; Wang et al., 2018).

The engagement of actors in coastal protection allows for science- and experience-based concepts and measures to incorporate valuable local knowledge and become community-supported and thus eventually sustainable (cf. IPCC (2019)). According to Bridges et al. (2022), the engagement process should be iteratively integrated into all project phases and remain flexible. The three steps to every actor participation process are

1. deciding who should be involved and when,
2. designing the engagement process or selecting an appropriate format for actor engagement and
3. the evaluation of the engagement process in the end (Areizaga et al., 2012).

Actor engagement processes can be conceptualised from a wide variety of different formats - from questionnaires to interviews, from discussion rounds to workshops, from serious gaming to role-playing exercises - but in the end, they always need to be tailored to the specific problem or challenge in focus and depend considerably on the actors involved in the process.

7.2 Key Societal Requests towards coastal protection

As stated in the chapters before, coastal protection cannot be perceived as a purely technical, a purely engineering task or challenge. Coastal protection rather represents a socio-technical endeavour, which is embedded in socio-ecological systems - an aspect which becomes even more apparent when considering NbS for coastal protection (Andersson et al., 2017). Social aspects, inter alia, address what people define as values and they attribute these to coastal ecosystems serving as NbS. In brief, values play an important role in determining support or lack of support for these ecosystems (Andersson et al., 2017). As several studies (e.g. DeLorme et al. (2021), Holzhausen and Grecksch (2021), and Ratter and Gee (2012)) have shown, place attachment, or the coastal dwellers' connectedness with the environment they inhabit, also plays a vital role here. People who feel connected to their surrounding environments are generally interested and invested in its conservation and protection and carry certain expectations or requests - whether unconsciously or consciously - shaping their opinion and attitude towards issues like coastal protection. Hence, these requests also define the locals' support for the same. In order to be sustainable, coastal protection strategies, concepts or single measures need to be supported by the local population. Otherwise, with time, they will be replaced by another strategy, concept or measure which might have a more apparent value to the people. This applies almost to all coastal protection measures but is particularly relevant for coastal ecosystems as NbS, since the ecosystems require constant monitoring and maintenance (Andersson et al., 2017).

Co-benefits of coastal ecosystems for society and related ecosystem services are widely mentioned in literature (e.g. Bridges et al. (2021) and Watson and Zakri (2003)) and extensively discussed in chapter 5 (section 5.2). However, the connection of these societal benefits with the coastal society, the matching of available benefits or services with what the coastal society is actually requesting from coastal protection still poses a research gap. To know how to communicate and illustrate values of coastal protection measures - may it be 'novel' approaches with NbS or classic solutions like dikes as well - one has to know which needs coastal dwellers have and prefer regarding coastal protection.

According to Gümüşay (2021), people *'need categories. Classification and categorisation [with adaptable boundaries] help us humans to recognise patterns, make (...) decisions and react'*. With NbS for coastal protection, a new aspect enters an established category system. New aspects are often initially met with resistance or rejection because they cannot be placed or classified. However, if categories allow them to be placed in the system, people tend to be more receptive to them. As these categories, **'Key Societal Requests'** (KSR) are introduced here in order to make tangible and to clarify what needs or requests there are on the part of the coastal population for coastal protection. KSR reveal which values and standards are important to the local society in relation to coastal protection. So, they can play a decisive role in the conceptualisation, participatory planning and communication of future measures, for example incorporating NbS in coastal protection concepts. The state of knowledge related to this approach and the identification of KSR is further elaborated upon in the following sections.

7.2.1 State of knowledge

From an engineering or planning perspective, so far, KSR-like concepts have been approached from two angles. In a study on floodplain management Serra-Llobet et al. (2022) looked, for example, at the question at hand from the ecosystems' perspective, asking *'What do the ecosystems deliver and what are the delivered benefits related to?'* They identified categories such as safety, health, social ties, economy or equity as the main aspects to which ecosystem services cater. From an urban planning perspective, Borowczyk (2018) asked, *'What makes a society sustainable?'* and identified several social sustainability key themes, of which health, equity, sense of place, participation, safety and well-being are important aspects or dimensions to be addressed. As indicated by the aspects mentioned, the perspective of coastal dwellers' on coastal protection has not yet been examined.

In the social sciences, several studies exist, that take coastal dwellers' perception of their environment and their values under examination via interviews. While these studies are not explicitly addressing coastal protection, insights into issues such as perceptions and the relationship to the coast and the sea can be related to coastal ecosystems and coastal protection. In a study on cultural identity in the Wadden Sea region, interviewees kept referring to the special way they live with and from nature along the Wadden Sea coast, and how this has shaped their very own mentality (Ratter and Philipp, 2015). Thus, when being asked about it, people do recognise and value the way they and their lives are shaped by and interact with their coastal environment, in which coastal protection is ever-present and plays a key role in preserving it. A comparable study by Döring and Ratter (2015) in North Frisia (Germany) revealed that the locals feeling of 'Heimat' or sense of place is, amongst other aspects, closely connected to their perception of the seascape. The sea can appear dangerous, which discloses the locals' longing for safety and protection. On the contrary, the sea can also be perceived as something beautiful and the aesthetic value and the naturalness of the land- or better yet seascape is highly valued. The aesthetic value and the appreciation of the naturalness of the coastal environment are also mentioned and emphasised by several interviewees in a different study by Döring and Ratter (2021) on the relationships that human beings form with the physical environment they inhabit. When talking about the fight against the sea, many interviewees refer to past generations, their ancestors, and the accomplishments they have to show for regarding the reclamation of arable land and its protection. On the one hand, this reveals the importance of social ties, the way coastal dwellers still feel connected to their ancestors and their accomplishments in *'taming the mighty enemy water at last'*. On the other hand, it shows that the protection of their lands from the sea and their safety play a significant role for them. In this study by Döring and Ratter (2021), the most direct reference to coastal protection is made when interviewees reflect on the dikes - not as coastal protection measures though, but as a prominent feature in and part of their physical environment. Dikes are, of course, connected to a sense of safety and valued for their protective function. Furthermore, many people seem to connect dikes with recreation and leisure time, as they describe frequently taking a stroll on or along the dikes, hence they appreciate the dikes for their recreational value.

7.2.2 Identification of Key Societal Requests

With this state of knowledge about KSR and the cultural shaping of dikes in mind, the focus of the analysis in the following is specifically on coastal protection or, more precisely, the KSR regarding coastal protection, which determine and shape the coastal society's perception and evaluation of the same.

Out of the 35 interviews conducted within the scope of this work, 19 interviews with people living on the islands of Amrum and Föhr in the North Frisian Wadden Sea are included in the following analysis. In total, 12 KSR, which form the basis of what coastal dwellers demand from coastal protection and therefore value about it, were identified empirically during the analysis of the interviews. These 12 KSR are depicted in figure 7.1.

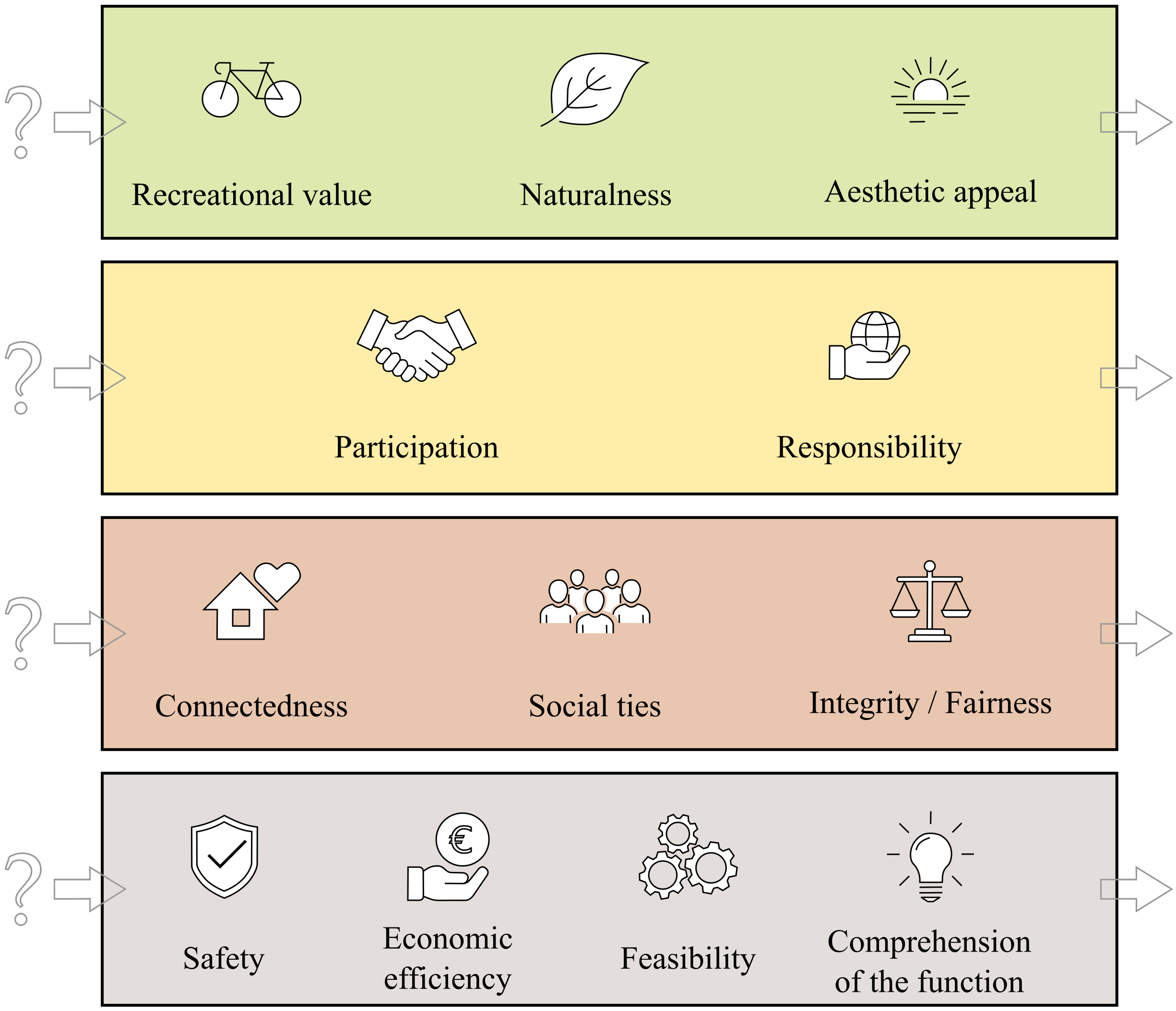

Figure 7.1: 12 identified Key Societal Requests (KSR) in focus, grouped thematically; grey question marks on the left indicate possible other or new KSR that might arise when conducting the analysis elsewhere; grey arrows on the right indicate KSR possibly moving out of focus when conducting the analysis elsewhere.

Looking at the bigger conceptual picture, these empirically developed KSR represent aggregated categories and serve as points of reference. They provide a guideline for a consideration of the societal scope, but do not represent a 'one-size-fits-all' approach. For a site-specific coastal protection problem, the KSR elaborated here should be considered in any case, but also specified. They can only be analysed and verified on a site-specific basis through a comparable interview study. Individual KSR may be less important elsewhere, or new ones may come into focus (as indicated with the grey arrows entering or exiting the KSR-boxes in figure 7.1).
For the present case, the following shows a hierarchy running from the most often mentioned KSR to the least, namely

- Safety (67 quotes by 17 interviewees),
- Feasibility (28 quotes by 15 interviewees),
- Economic efficiency (18 quotes by 12 interviewees),
- Naturalness (18 quotes by 9 interviewees),
- Responsibility (17 quotes by 9 interviewees),
- Integrity and Fairness (16 quotes by 9 interviewees),
- Recreational value (15 quotes by 9 interviewees),
- Comprehension of the function (13 quotes by 9 interviewees),
- Social ties (12 quotes by 8 interviewees),
- Aesthetic appeal (9 quotes by 9 interviewees),
- Participation (8 quotes by 5 interviewees), and
- Connectedness (3 quotes by 2 interviewees).

However, the number of citations does not necessarily indicate the weighting of the respective KSR but rather reflects the extent to which the KSR under consideration is linked to coastal protection in the coastal dwellers' mindsets. Safety, for example, is closely connected with the perception of coastal protection as highlighted in the previous chapters. Participation, on the other hand, represents a fairly new endeavour in coastal protection and is therefore not as present in the general perception yet.
The KSR *safety* represents by far the most often mentioned or referred to category of what people request from coastal protection, hence what they utmost value about it and what is most present in their perception of coastal protection. Ranked second is *feasibility*, followed by seven KSR in the middle range and of comparable value to people in the investigation area. *Aesthetic appeal*, *participation* and *connectedness* are not mentioned as often as the previous ones but nevertheless display different kinds of requests, needs or requirements people have towards coastal protection and features or services they value. Following the principle of Maslow's hierarchy of needs (cf. Maslow (1943) and McDermid

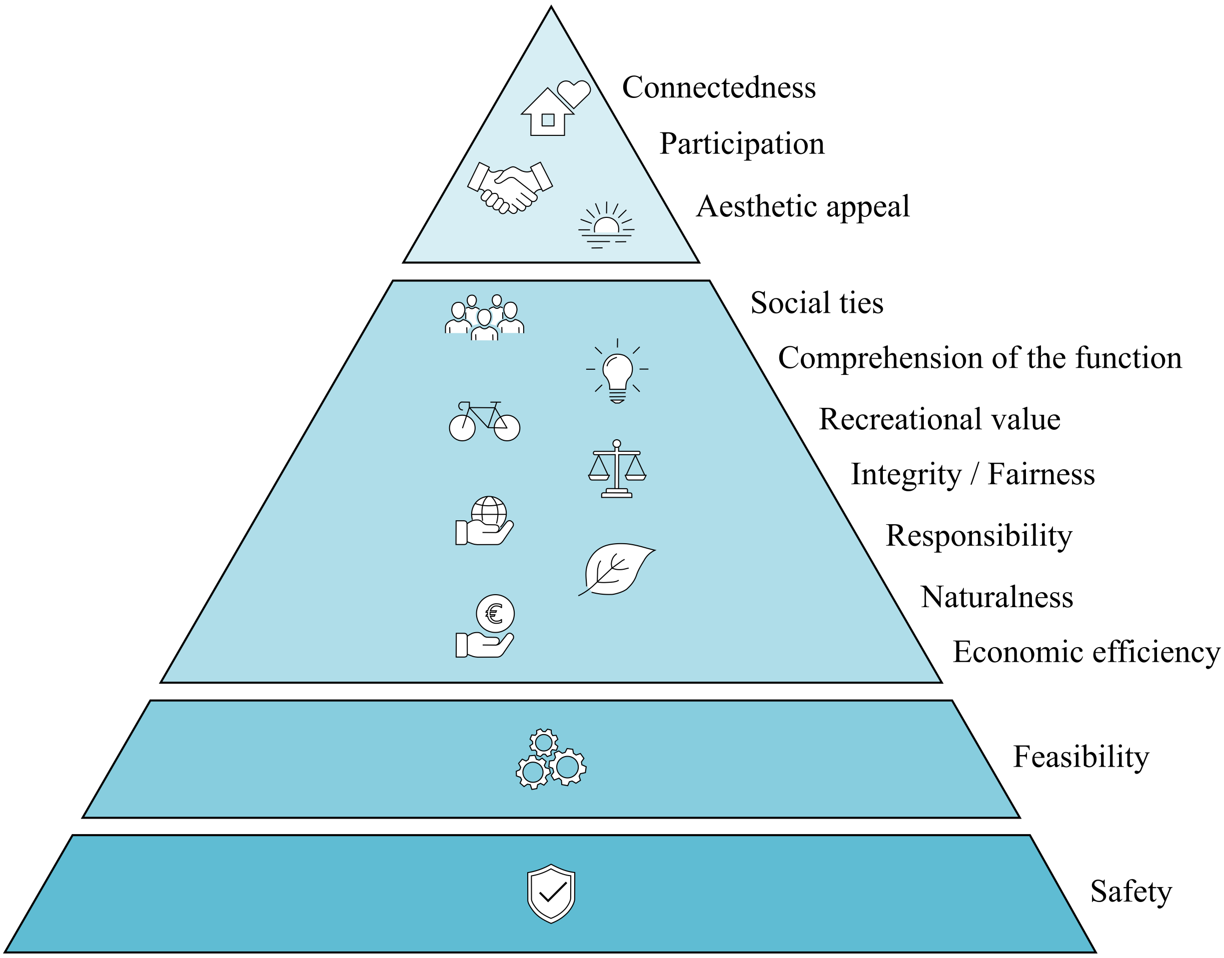

Figure 7.2: Site-specific quantitative ranking of identified Key Societal Requests in accordance with Maslow's hierarchy of needs (cf. Maslow (1943) and McDermid (1960)).

(1960)), the 12 KSR revealed are ranked quantitatively in accordance with the number of citations given above and displayed in figure 7.2.

In Maslow's pyramid, *physiological needs* and *saftey and security* form the base (Maslow, 1943; McDermid, 1960). In a society like the one in the investigation area, however, these basic needs can be assumed to be secure and given to such an extent that the general public can devote itself to the needs higher up the pyramid. This can be partly transferred to the KSR analysed for coastal protection. Safety through coastal protection as well as the feasibility of the measures are generally given and closely linked to the coastal population's image of coastal protection. Consequently, the focus of the coastal dwellers with regard to their requests for coastal protection can increasingly concentrate on the upper KSR, such as naturalness, recreational value or participation. These should therefore be given equal consideration and more attention in the conceptual design of future coastal protection measures, without disregarding the basis of safety and feasibility.

7.2.3 Analysis of Key Societal Requests in the investigation area

Based on the conducted interviews on the island of Amrum and Föhr, an overview of the 12 identified KSR and the respective subcategories assigned to them in the re-analysis can be found in appendix E. Of these 12 KSR emerging from the interviews, *safety*, *feasibility*, *naturalness*, *integrity and fairness* and *social ties* have been selected for a detailed analysis of paradigmatic examples taken from these five categories, as they directly relate to the adaptation of coastal protection with NbS. The analysis in the following sections will provide an in-depth analysis of their content and meaning.

Safety

When coastal dwellers on the islands in the investigation area talk about coastal protection, safety is, as expected, the request that is most frequently formulated or inferred in different ways. Safety represents the basis, the foundation of the KSR towards coastal protection. This mainly stems from the ever-present threat the sea or water poses in people's perception to their life on the island or by the coast, as expressed in the following excerpt:

> *'If the water enters Amrum - no matter where - then it's over here.'*

From this drastic depiction of a possible sudden end, the expectation that coastal protection will have to guarantee safety is naturally derived. Some interviewees, who still remember the last storm events that really harmed many people on the islands or to whom the thematic anchor of the 1962 storm surge is still present in their memory, point to conflicts of interest or a slightly blurred perception of the aspect of safety among the younger generations, e.g.

> *'1962 (...), the dike breached. There was no dike before. That's when it breached. And today people like to live ... one can understand that, by the water, but then they have to be prepared that the water might come into their homes.'*

This interview excerpt refers to the phenomenon that people want to live by the sea, since they value recreational benefits or the aesthetics of the landscape but presumably disregard the inherent dangers that come with living by the ocean. However, as underlined in the excerpt below, many coastal dwellers do perceive the underlying threat mentioned at the outset.

> *'We are actually in the fortunate position now that we have not had a bad storm surge on the North Sea in the last 20, 25 years. But it will come. It will come at some point and then everyone will be shouting, just like in the Ahr valley now, why didn't you do something before?'*

No matter how far in the past the last severe storm surge was, many interviewees hold the opinion that the next hazardous event *'will come'*. From this conviction derives, on the one hand, the justification of coastal protection per se and also the investment in

further protection for the future itself. On the other hand, it highlights that safety - even in absence of real harm to lives and livelihood on the islands for several decades - still is at the very core of the key societal requests regarding coastal protection. The fact that the existing coastal protection guarantees a certain level of safety is therefore positively perceived and highly valued.
This safety relates to various aspects of life on the islands. First and foremost, it concerns the protection of lives. Thematic anchors like the 1962 storm surge, which claimed several lives, are still present in people's mindsets. The safety of people's lives is most important. As indicated by an interviewee, this might not be taken seriously enough by some actors of the responsible authorities.

> *'I will say, you here, all of you sitting here, all of you delaying this year after year, you are playing with our lives.'*

This excerpt refers to the years of debate about a dike strengthening measure on Föhr. The expression *'playing with our lives'* stresses the importance of the KSR of safety for the local people. Furthermore, it suggests that some authorities or officials who decide on the fate of coastal protection on the islands from the outside are not able to assess the situation correctly or do not consider the islanders' explicit request for safety and the protection of their own lives important or urgent enough. This is an aspect that often surfaces in the interviews and, in the self-perception of the costal dwellers, encourages the aspect of *'being on one's own'*. This aspect is furthermore mirrored in the special appreciation of *'local knowledge'* in contrast to opinions coming from outside of the island.
Other aspects of safety, that emerge nearly as often as the protection of lives, relate to the protection of livelihoods, the protection of property and arable land, the protection of the landscape and the conservation of the general entity of the island, as the following two interview excerpts exemplify:

> *'Well, what is truly important to me is the certainty that all the people here can continue to live their lives in this way.'*

> *'I would say, I see it differently. This here is the coastal shelf. And we surely want to preserve it.'*

In this longing for and appreciation of safety, many interviewees implicitly refer to the image of *their island* as a fortress, shutting out the sea, keeping possible threats away and locking themselves inside this fortress for a feeling of safety, e.g.

> *'So, opening up could actually only primarily apply to the dike, right? (...) So that is not ... from my point of view, not justifiable.'*

In line with the image of the *fortress*, the *walls* that guarantee protection and safety are the dikes. Dikes, above all, literally and emotionally seem to convey a sense of safety, a sense of protection, and are often the first coastal protection measure people think of when reflecting on their needs for safety. For some, as expressed in the following excerpt, dikes pose the only option for reliable protection.

'But we can only protect ourselves - now against the sea level rise and have always been able to do so - by means of a solid dike.'

The suitability of dikes for the safety of people in the here and now but also in the future with regard to challenges such as *'sea level rise'* is justified by reference to the past (Jordan et al., 2023). The impression that coastal residents *'have always been able to do so'*, that one's ancestors successfully protected themselves in the same way is the main reason why the request for safety and the dike are so closely intertwined. Dikes stand for protection more than any other measure and building and maintaining dikes represents safety. In other words, the dike is the symbol for safety.

Feasibility

The key societal request referred to the second most is feasibility. Some interviewees value dikes for their unquestionable suitability to provide safety now as well as in the future, as described in the section on the KSR of safety. Others, however, especially with regard to the future development of climate change and sea level rise in mind, doubt that it can be feasible to still pursue the same coastal protection strategy.

'And you probably have to ask yourself how far you can go with - with such dike reinforcements? You know, this climate dike is being built with a crown about 5 metres wide, and if sea-level rise accelerates, it may receive another cap sometime in 50 or 100 years. So, you have a certain design reserve, right? And if it's ... if that's no longer enough, then probably other questions will arise ...'

Here, the question *'How far can you go?'* is looking into future dike construction in terms of feasibility and with regard to technical limits, restricting its feasibility. According to the coastal dwellers' key requests, coastal protection measures must be feasible and sensible. Otherwise, other more feasible solutions should be pursued or, as indicated in the interview excerpt above, societal paradigms must shift, e.g. towards managed coastal retreat.
Besides the technical possibilities and limitations, interviewees also take notice of

- natural (e.g. natural processes, resource availability),
- financial (e.g. coast of measures in relation to their benefit),
- societal (e.g. scepticism, lack of understanding and acceptance) and
- administrative (e.g. slow decision processes, lack of participation)

aspects that limit the feasibility of coastal protection measures, as shown in the following two quotes:

'Nevertheless, the sand always has to originate from somewhere, doesn't it?'

'(...) this means that entire projects and measures, which are certainly sensible, are simply put on hold for a very long time. And that's where I think we have to start, otherwise we lose credibility in terms of necessity.'

In the light of these limits of a varying and unpredictable nature that people are aware of – with regard to the KSR of feasibility – some interviewees, as is the case in the interview excerpt below, see the need for mitigation instead of mere adaptation to future challenges.

> *'And that's why something has to happen in terms of climate protection, something very big indeed. It will do us no good if we just keep building the dikes higher and higher, that won't help us in the end.'*

Some other important aspects of the locals' request for feasibility towards coastal protection are pragmatic, local solutions to arising coastal protection problems or challenges.

> *'... on the beach side, the dune side, we are also ... 15 years ago we were not allowed to bring in broken wood or branches and the like. But when windbreaks have formed, it is put in and the windbreak silts up very quickly, it works, in my eyes it is really wonderful, simple coastal protection, (...). So officially it is still not allowed, but they tolerate it because they can see the success.'*

This example refers to the (officially forbidden) practice of closing windbreaks in dunes with wood debris from the forest. It is one of several pragmatic solutions mentioned throughout the interview series that deliver quick and feasible results - developed by locals and based on local experience and knowledge of the natural processes on site. These solutions are perceived and described as highly feasible and therefore valued by the interviewees, while coastal protection measures originating from outside the island might often be regarded as too expensive in construction, too limited in function, too slow in implementation and basically infeasible. This caters to the local society's self-perception of knowing what is best for their living environment and stresses the relevance of local knowledge for coastal protection. Moreover, it reveals the interviewees willingness and interest to locally deal with coastal protection challenges and underlines the importance and potential of participation and cooperation throughout the conception, planning and implementation of coastal protection strategies.

Naturalness

The natural character of certain coastal protection measures is another quality highly valued by the interviewees, hence naturalness represents another important request towards coastal protection. A certain level of naturalness makes the locals feel connected to their environment, to nature, feeling the wind in their faces, the sand under their feet or listening to the waves washing ashore.

> *'And on this path, you really have to go up and down through the sand and there is really this - this primal nature. And it changes all the time because of the wind, it looks different every time (...). And when you look through the dunes, across the beach to the sea (...) ... your heart fills with joy.'*

Here, the appreciation for the primal naturalness, for natural processes and the dynamic landscape is expressed very clearly and a direct connection to mental and emotional health

is drawn with the expression of the *'heart [filling] with joy'*. The described dynamics and changes clearly represent an alternative concept to the clear, linear protection provided by dikes. Contrary to some aspects revolving around the KSR of safety, several interviewees value this level of connection to the sea and appreciate coastal protection that allows for this connection with the natural to occur. This KSR reveals, that not only safety through man-made separation of land and sea (cf. image of the *island as a fortress*), but also the intermingling of land and sea framed as naturalness is appreciated and therefore poses a societal request towards coastal protection that should not be neglected.
Furthermore, there are some comments that can be framed in terms of the national park's paradigm - *let nature be nature* – underlining the positive aspects of a natural coastscape.

> *'And when the sea comes, the sea is not necessarily bad, and they have salt marshes here and so somehow, there - there are completely different plants and animals living there and so on, (...). Actually, we should all behave in such a way that we don't defend every last island, or every last dwelling mound or every last piece of land where we have just put up a house. But, of course, we shouldn't put people at risk either.'*

Interviewees do not only see the harm and dangers, which the sea might inflict upon them, but also notice positive influences of the water and request sufficient space for naturalness, e.g. for wetland ecosystems such as salt marshes as referred to in this interview excerpt. *'But, of course, [without putting] people at risk'*, like this interviewee frames it. People's lives come first (hence safety as the basis of key societal requests) but there is room for negotiation. People's lives do come first does not necessarily mean that people always have to come first. This excerpt and the discussion touched upon here reveal that many conflicts of interest and the need for discussion and negotiation revolve around the request for naturalness. While some request for more naturalness in coastal protection, representing an open door for discussions about NbS for example, others emphasise the importance of human intervention and maintenance, as can be seen in the following two examples:

> *'My expectations, my personal expectations of coastal protection would be that it would perhaps become a little more natural.'*

> *'First of all, we have to realise that we are not living in a purely natural landscape, but in a cultural landscape. It is man-made and very fragile and must also be maintained by man if it is to be preserved as it is now.'*

Conflicts of interests or goals, mentioned by the coastal dwellers, revolve amongst others around nature conservation and coastal protection, nature conservation and agriculture, or space requirements of men and nature regarding the limited space on the islands. Taking the two excerpts above as examples for these varying interests, the two statements might seem conflicting at first in view of NbS. NbS, however, can bear the potential of bridging these gaps between conflicting positions. While floodplains and wetlands might only satisfy the first, and a dike to protect the arable hinterland might only satisfy the second interviewee, managed and monitored salt marshes or a combination of a dike with salt marshes in the foreland could basically cater to both interests and demonstrate to people that they are actually pursuing the same goals and that there is a possibility for a common path.

Integrity and fairness

Against the backdrop of these conflicts around coastal protection, the KSR of integrity and fairness emerges. For one, it entails the seemingly simple aspect of equal treatment, as requested here:

> *'Whoever gives away eight hectares can also get eight hectares.'*

This example deals with the dimensions of compensatory measures taken for the construction of coastal protection, suggesting that the area of the tidal flat, that is to be covered by a dike construction, should also correspond to the size of the required compensation area. In practice, however, one hectare of tidal flat might have a different associated value than one hectare of flood plain, which is accounted for in compensation. Therefore, the sizes of areas do not match. This is, in the eyes of this interviewee, unfair and represents a practice that does not comply with his or her KSR towards coastal protection.
Another perspective of the request for integrity and fairness addresses even more directly the underlying conflicts of interest between men and nature or island and mainland regarding the limited space on the islands:

> *'Well, I don't know, the fact that nature conservation and species protection (...) is put above the well-being of the population, which has to exist here, you know? That is a bit difficult. And those are always foreigners. There's hardly anyone from Amrum involved.'*

Here, the impression that one interest is put above the other is criticised, and the request for integrity and fairness towards strategies and measures in coastal protection is not met. Additionally, the point is raised that only *'foreigners'*, i.e. experts and officials who do not live on the islands, are making the decisions and local ideas and requests are neither being heard nor included. As already mentioned in the sections above, this shows again that locals are interested in the matter and demand participation, which not only caters the KSR of feasibility, but also the KSR of integrity and fairness.
Furthermore, the request for integrity and fairness can be based upon or drawn from a more holistic view including the natural and coastal environment, e.g.

> *'We don't just want to protect ourselves, we also want to protect the whole habitat around us (. . .), you know?'*

Coastal protection should, accordingly, benefit society and nature in terms of a *'whole habitat'*. The holistic approach to the topic also takes future developments and especially future generations into account. It requests from coastal protection not only to think and comply to what might be the best option now, but also to keep the responsibility and repercussions for the well-being of future generations and coastal ecosystems in mind.

Social ties

Permeating nearly all identified KSR in some way, the self-perception of the islanders, their high appreciation of local knowledge or the identification with their island environment have been discussed in the previous sections. In case of the KSR of social ties, it is the local identity that belongs to this category of perceptions and beliefs that underlie the requests regarding coastal protection.

> *'No one wants to destroy nature. No one wants to harm the animals. We all want the same thing, but you can't just say, I'll do it my way. No, you can't do that here on Amrum. Not in any way, shape or form.'*

Here, once again, the mistrust in and even rejection of concepts or ideas originating from outside the islands becomes apparent, but, furthermore, the aspect of the local identity is prominently stressed. The interviewee cited here, like many others, strongly identifies himself/herself with the island and even more so with the island community *'here on Amrum'*. Coastal dwellers are proud to be part of this environment, this community, and feel responsible for one another as well as for the islands. Many express their knowledge about the landscape and the natural processes and feel deeply tied to both since childhood – or even beyond, from memories and stories of their ancestry:

> *'But you can't tell an islander who has spent his life... they have been defending themselves against the North Sea for generations and if you now try to explain to them that we are opening the dike, from a nature conservation point of view it might even be... you won't get away with it.'*

The image of the fight against the enemy North Sea is still deeply rooted in the mind-set of many locals along the coast and closely intertwined with the social ties that are forged – consciously or subconsciously – with coastal protection and what people request of it. The ancestors' achievements in terms of coastal protection are something to be proud of and, even though boundary conditions have changed drastically since then and climate change puts people up to unprecedented challenges, not to be tampered with, as exemplifies the following interview excerpt:

> *'... and if all our ancestors saw that we were taking back the whole dike line, they would all turn over in their graves. How can you just ... We have ... we have piled this up with - with our hands, these things, right?'*

The manual labour which it took to build the dikes is highly appreciated and the mere effort it took for the 'ancestors' to build them seems to be justification enough for it not to be questioned or the concept to be rethought and changed. The strong ties that still exist to the previous generations emotionally reveal themselves by terms like *'we have piled this up'* or *'with our hands'*. Even though the manual construction of dikes happened decades ago, the interviewee here feels like having gotten his/her own hands dirty while helping with the construction. Thus, through the social ties with previous generations, locals also identify themselves with certain types of coastal protection measures on their islands. Existing social ties within the island communities, though, do not only go back into the past but also span into the future.

> *'(...) then many people might say, well, that's quite some time away, and what's ... what's half a metre? But if you reflect on it across the generations, it can make you feel queasy ... it must make you feel queasy.'*

As much as the ties to previous generations still influence coastal dwellers' requests towards coastal protection, this excerpt demonstrates that they also take future generations into consideration to a great extent. Due to their identification with the island and its community, they feel a great deal of responsibility for future generation of islanders, or better put, for safeguarding that there can be future generations living on the islands in the way they live there now. This feeling of responsibility and the appreciation of these social ties, impacting the coastal dwellers view on coastal protection, open up windows for discussion, participation and negotiation as long as the past is not disregarded when looking to the future.

7.3 Application at the selected investigation sites

In the following, the KSR determined above, which help to understand the societal scope of and in a coastal protection measure, are being assessed exemplary with regard to the possible nature-based or ‘constructional’ solutions for the selected investigation sites on Amrum and Föhr (described in section 4.4).

Amrum, Steenodder Kliff

At Steenodder Kliff, either a salt marsh in front the small coastal cliff or a revetment that secures and fixes this coastline, are possible solutions to the ongoing erosion and the increasingly frequent damages to the coast-parallel hiking and biking path. Just as the two measures are to be viewed and evaluated differently from the coastal protection perspective in terms of their services and resilience (cf. section 6.3), they also have different effects and impacts in terms of societal concerns. These can be assessed on the basis of the identified KSR.

Both measures can provide safety regarding erosion and land loss. While the salt marsh’s services would be subject to seasonal variations, the revetment provides a guaranteed level of safety according to the structure’s defined design criteria. Regarding future changes, the salt marsh holds a certain advantage due to its internal resilience.
The establishment of a salt marsh as well as the construction of a revetment are feasible measures. The existing boundary conditions determine the design criteria for the revetment and the suitability of the site for a salt marsh ecosystem and whether or not such an ecosystem needs engineering interventions for support.
While a revetment does not contribute to the naturalness of the coastal stretch, a salt marsh - even if man-made and therefore only ‘semi-natural’ - provides habitat for Wadden Sea specific flora and fauna. Hence, it combines coastal protection and nature conservation needs and interests.
Since both measures are small-scale, problem-specific solutions, they meet the locally expressed concerns and the perceived need for action at the Steenodder Kliff. Regarding the social ties, the connection of the measures to the coastal protection heritage on Amrum is given in both cases. The two options represent well-known techniques that have been used for generations in coastal protection on Amrum and in North Frisia.

A complete assessment for all 12 KSR is compiled in table 7.1.

Table 7.1: Comparative assessment of Key Societal Requests regarding a salt marsh or a revetment for the investigation site Steenodder Kliff on Amrum.

Key Societal Request	**Salt Marsh**	**Revetment**
Safety	• provides safety regarding erosion and land loss • possible adaptation to different future boundary conditions • possible seasonal variability	• ‘guaranteed’ safety up to design boundary conditions • further construction needed to ensure safety in the long term
Feasibility	• depends on waves and currents • sediment availability is key • engineering interventions may be needed	• design criteria according to boundary conditions • technically proven and established measure • numerous comparable projects
Naturalness	• ‘semi-natural’ landscape • habitat provision for flora and fauna	• none
Integrity / fairness	• provides protection as well as benefits for nature • does not harm major natural or societal interests	• only provides coastal protection
Social ties	• brushwood groyne construction is known from previous generations • historically, implemented by islanders • living connection between land and sea	• well-known and proven concept • local concerns and need for protection are met
Economic efficiency	• low costs • little maintenance effort • natural adaptability	• high construction costs • higher maintenance effort • adaptable only through retrofitting or new construction
Responsibility	• instigated by responsible authority • possible local participation	• construction and maintenance by responsible authority
Recreational value	• path is secured • calming effect through natural character	• path is secured • none in itself
Comprehension of the function	• challenging to understand • knowledge of sedimentation processes and vegetation / water interaction is needed	• easy to understand • ‘simple’ hard fixation of the coastline (armouring)
Aesthetic appeal	• ‘semi-natural’ landscape • typical Wadden Sea image	• asphalt or rock armour • hardly appealing
Participation	• possible	• not relevant
Connectedness	• typical Wadden Sea image	• not relevant

Föhr, Hedehusumer Geest

At Hedehusumer Geest on the south-west coast of Föhr, two possible measures to prevent increasingly frequent land losses during storm events are under consideration here. The development of dunes or the construction of a dike are assessed from the coastal protection perspective in section 6.3 with respect to their service and resilience. In the following, the assessment of the societal implications is carried out on the basis of the 12 identified KSR.

Safety against flooding and the land losses of agricultural areas could be provided by both a dune and a dike at Hedehusumer Geest. Dunes are dynamic ecosystems that can adapt to possible changes in future boundary conditions. A dike, representing *the* image of safety for most coastal dwellers, can be heightened with a 'cap' if already considered in the original design.
Both measures are technically feasible in the area. The dune, of course, depends on the sufficient availability of sand in the system. Regarding a dike and the administrative feasibility of its construction at the investigation site, the acquisition of the necessary land can pose a challenge. However, a dune also requires a considerable amount of space.
As for naturalness, a dune is a natural, dynamic coastal ecosystem that interacts with the adjacent beach. A dike, in the contrary, has little to no natural features apart from its vegetation cover. The use of a more diverse seed mixture can slightly improve this feature in terms of naturalness.
Assessing the measures integrity and fairness, a dike clearly puts protection first and above all else. A dune combines coastal protection with nature conservation interests. With a dune, though, the residents may have to deal with sand drifts on their arable land, whereas a dike construction would require that they give up and sell a much larger piece of land in order to protect the remainder.
With regard to social ties, dunes are a familiar coastal defence structure. The image of the dike is ubiquitous both in the landscape and in the minds of local people. Coastal dwellers on Föhr see a strong interconnection between dike construction and their ancestral coastal (protection) heritage.

A complete assessment for the 12 identified KSR is compiled in table 7.2.

Table 7.2: Comparative assessment of Key Societal Requests regarding a dune or a dike for the investigation site Hedehusumer Geest on Föhr.

Key Societal Request	**Dune**	**Dike**
Safety	• provides safety of flooding and land loss • dynamic ecosystem that changes and can adapt to altered boundary conditions	• 'guaranteed' safety up to design boundary conditions • future heightening with a 'cap' is possible if considered in the original design • represents the image of 'safety' in the region
Feasibility	• sufficient sediment availability is key • stalk plantings to promote the establishment • stalk plantings to fix existing dunes • challenging regarding the acquisition of necessary land	• design criteria according to boundary conditions • technically proven and established measure • numerous comparable projects • challenging regarding the acquisition of necessary land
Naturalness	• natural, dynamic ecosystem • habitat provision for flora and fauna • interaction with adjacent beach	• little • possible use of a more diverse seed mixture
Integrity / fairness	• provides protection as well as benefits for nature • farmers may have to deal with sand drift	• puts coastal protection first • farmers have to sell land for the construction, hence their protection
Social ties	• familiar coastal protection measure • concept of stalk planting is historically well-established	• image of the dike is omnipresent in landscape and the people's mindset • strong connection between dikes and the coastal protection heritage
Economic efficiency	• low costs • little maintenance effort • natural adaptability	• high construction costs • higher maintenance effort • adaptable through retrofitting
Responsibility	• instigated by responsible authority • locals can conduct stalk plantings	• construction and maintenance by responsible authority • sheep grazing
Recreational value	• possible walking trails through the dunes • calming effect through natural character	• possible walking and biking on asphalt path • provides good views of the Wadden Sea
Comprehension of the function	• a little challenging to understand • knowledge of the concept of dynamic equilibrium is needed	• easy to understand • structure to fix the coastline and keep water out
Aesthetic appeal	• diverse and dynamic natural landscape • typical Wadden Sea image	• a certain scenic monotony to the eye • typical Wadden Sea image
Participation	• stalk plantings	• dike inspections
Connectedness	• typical Wadden Sea image	• strong linkage between coastal dwellers and the concept of diking

7.4 Summary and interim conclusion

In coastal protection, an abundance of different actors with varying levels of responsibility, affectedness and influence are involved. Within a coastal protection project, they all interact with each other as well as with the project. Focussing on local actors, the challenges of living on the coast have significantly contributed to their regional identity. Consequently, their interest in the matter of coastal protection and their willingness to support it - or in turn also their potential to obstruct certain measures - is substantial.
When, as is the case with NbS in coastal protection, a putative new aspect enters an established category system, actors may be dismissive for the time being. If there are, however, 'categories' to place this new aspect in the existing system, actors tend to be more receptive to it. Therefore, key societal requests were introduced in this chapter to clarify and illustrate *'which aspects or needs display the key requests the coastal population has for coastal protection and what are the underlying images or experiences, that shape and define these requests'*.
12 KSR were empirically identified and represent aggregated categories or points of reference to assess the societal scope in NbS or coastal protection in general. Thereby, they contribute to broadening the understand of the field at hand from a societal perspective. Safety and feasibility are the KSR mentioned the most. This is partly because they are of course amongst the most highly valued aspects of coastal protection by coastal dwellers and partly because they are in line with the image of the 'fight against the sea'. Therefore, in peoples' perception, they are closely linked to the evolution of coastal protection and the historic reclamation of their land. Emerging KSR like naturalness, participation or recreational value might be mentioned less often, as they are not yet that connected with coastal protection in peoples' awareness, but nevertheless represent highly valued requests which underline once more the paradigm shift that is taking place.
In the evaluation of the 12 KSR for the investigation sites at Steenodder Kliff on Amrum and Hedehusumer Geest on Föhr, advantages of NbS become apparent, as they cater to multiple benefits regarding protection, ecology and society. 'Conventional' structures, which mainly target coastal protection, do not benefit other KSR that much. All considered measures though - salt marsh, revetment, dune, and dike - can deliver protection from the identified problems. This can be a useful and illustrative way to demonstrate and communicate the comparability of NbS and conventional, structural measures to alleged laymen.
While a dike offers some recreational value and a very limited naturalness, a revetment does not benefit these KSR at all. NbS on the other hand integrate into the natural environment, offer aesthetic value, recreational possibilities, and tranquility. Here, the concept of KSR can be useful for the demonstration of additional benefits of NbS and their societal value and value for the implementation of a project to alleged laymen and experts alike and highlight the importance of these requests in comparison to safety and feasibility.
In summary, Key Societal Requests display a tool to assess the needs and values of a society that should be the basis for any coastal protection measures during all project phases. Furthermore, KSR offer categories to place, evaluate and compare measures and openly communicate the societal needs towards coastal protection.

8 Discussion

Coastal ecosystems can deliver substantial benefits to the coastal protection of sandy coasts and work as Nature-based Solutions for the sustainable adaptation of the existing protection concepts to climate change. In the scope of this chapter, issues like applicability, effectiveness, adaptability, economic efficiency, social acceptance as well as ecological value of NbS will be discussed on the basis of the insights generated in the previous chapters.

In theory, coastal ecosystems as NbS can be considered viable options at most stretches of sandy coast, since these areas represent their natural environment or habitat. However, the critical assessment of the **applicability** of NbS - or in other words, whether or not an ecosystem is able to thrive at a certain location - is far more complex and at the same time of great importance with regard to provided services and resilience. NbS are not a panacea for coastal protection adaptation, but hold promising potential if natural boundary conditions and processes are carefully considered.
Since sandy coasts are generally highly dynamic systems, the question can be raised as to whether or not nature-based measures, which usually take more time for implementation than structural measures, make sense. If one strives for a participatory development of such measures, the required time for full implementation and operability will become even longer. Coastal ecosystems are able to thrive in dynamic environments, there is no doubt about that. However, it is still a challenge to assess and predict their behaviour and future development, here with the focus on ensuring a certain degree of coastal protection. The behaviour of NbS in these dynamic systems can only be fully understood and assessed through an increased understanding of the processes obtained in pilot projects. It is therefore not a question of replacing existing protection structures. The applicability and functionality of NbS in these systems can be investigated in tinkering and experimentation as a supplement to and adaptation of existing protection - for example in areas with low vulnerability, in the presence of sufficient residual safety or a second line of safety.
At coastal sections where certain coastal ecosystems that are examined in this thesis once existed and are gone now - be it due to anthropogenic influences or natural changes in e.g. wave forcing or currents - one should not blindly aim for a re-establishment but investigate carefully why they disappeared. Only because a specific ecosystem existed at a certain location once, does not mean that this can work again. On the contrary, there are reasons for its disappearance and these have to be well known and understood to determine and assess the applicability of a Nature-based Solution in such a location. For example, as described in section 4.1, a salt marsh once existed at Näshörn on Föhr, protecting the adjacent dike and especially the dike foot - but why did it vanish? If it happened due to natural processes, one has to investigate whether or not these still pose an ongoing threat. If it disappeared due to anthropogenic actions, are these still present? And if so, can they be undone to return to a system state, in which the salt marsh could thrive

at Näshörn? Anyway, understanding the natural system and processes is always the key in coastal protection. Dealing with NbS, certain limits and threats can be overcome by engineering interventions (cf. chapter 6), which artificially promote the development and growth of the coastal ecosystems under consideration.

The **effectiveness** in terms of coastal protection as well as the **adaptability** or resilience of NbS are very case-specific variables. Although numerous studies exist that focus on the service and the resilience of NbS (cf. section 5.2), there are still significant uncertainties pertaining to the effects of seasonality, anthropogenic influences or climate change and their reliable prediction. More case studies and pilots with long-term monitoring of the ecosystem properties and their effects, development, importance and resilience are needed. To assure the comparability of results and draw generally valid conclusions, various locations with comparable boundary conditions should be analysed and compared with results from differing locations in order to be able to differentiate between the influences of the boundary conditions and the ecosystem properties. The concept of the engineering scope facilitates the identification of the most relevant boundary conditions and can thus advance monitoring studies at nature-based measures. Ultimately, this helps to give answers to the adaptive capacity and effectiveness of NbS as well as to the benefit and possible influence of engineering interventions to promote NbS.

If the coastal ecosystems adaptive capacity proves to be sufficiently strong to keep up with changes like SLR, this offers a major advantage of NbS in comparison to engineered structures regarding their **economic efficiency**. The application of the developed conceptual framework to the two investigation sites on the North Frisian islands of Amrum and Föhr emphasises this adaptive capacity of NbS. They may need some help in the form of engineering interventions in the system to overcome certain limits or restraints but are generally much less of an effort than structural measures. These usually either require retrofitting or a completely new design and construction.
Engineering interventions to promote NbS (e.g. brushwood groynes) are relatively small and low-cost. Provided they will trigger or foster the natural establishment, development or growth of an ecosystem, NbS can be more economical than traditional structural measures, especially when it comes to adaptation as well as maintenance. Because costs are ultimately a key criterion when considering different options, the more detailed economic assessment of nature-based measures and the identification of 'hard numbers' associated with coastal ecosystems for coastal protection can further promote NbS in political and societal discourse and debates.
Regarding sand nourishments, the economic efficiency has to be evaluated very critically - already today and even more so for future projects, since sand is an increasingly rare and therefore expensive resource and the global demand is rising (Bryan, 2023).

In order to thrive sustainably and unfold their full potential for Water, Nature and People, coastal protection in general must be understood as the socio-technical endeavour that it is, and engineering and 'the social' need to be combined. In the context of this thesis, this path was followed in order to disclose the importance of **social acceptance** and foster it. The most relevant actors were involved in the course of this process. When starting to discuss the adaptation of coastal protection to climate change, the questions *'Where?'*, *'Why?'* and *'What?'* should be addressed to the involved and affected actors (*e.g. through personal interviews or on-site discussions*). While the responsible authorities might have the bigger picture and overarching strategies in mind, local coastal dwellers or locally active NGOs personally witness and experience changes and needs first-hand and can draw on their local knowledge to assess them. Possible (nature-based) adaptations should then be evaluated by experts. Their possibilities, suitability, performance and prospects of success - the *'Why?* and the *'How?'* - have to be assessed with regard to engineering as well as ecology (*e.g. through discussion and expert rounds as well as scientific analysis on the basis of the disclosed engineering scope*). Potentials and limits must be carefully weighed against each other, both on a scientific basis and on the basis of experience. To sustainably embed these collaboratively engineered adaptations within the societal framework, the following issues are indispensable: the understanding of the underlying processes for coastal protection and the most relevant interrelations within NbS, knowledge and appreciation of their additional benefits besides coastal protection as well as the contextualisation of NbS in the existing conceptual categories of coastal protection and ones living environment. These are key for building common trust in and acceptance of them (*e.g. through discussion rounds, workshops and addressee-oriented communication and information on the basis of the disclosed engineering as well as societal scope, using the KSR*).

While the scope of this thesis is on the expansion of the engineering and the societal perspectives in NbS (*Water* and *People*), the **ecological value** (*Nature*) as one of the three core issues or areas of NbS shall not be left unmentioned here. Of course, man-made or anthropogenically influenced coastal ecosystem cannot be valued as exactly equivalent to respective natural ecosystems with regard to their 'naturalness' or ecological benefits. There are, for example, significant differences in the composition and structure of the natural salt marshes at Westerhever and the salt marshes on the west coast of Arum, that established due to brushwood groyne construction and were managed and maintained by man for decades (cf. section 5.2). Furthermore, man-made NbS cannot be assessed as purely positive for the prevalent ecological systems, since they may also have negative ecological impacts. Sand nourishments are to be assessed particularly critical in this respect, as their impact on the existing flora and fauna at the extraction as well as the implementation site is enormous.
Nevertheless, in comparison to structural measures in coastal protection, NbS benefit the ecology in many ways, as outlined in chapter 5. Compromise is essential for working in the highly stressed coastal zone, and NbS have the potential to unite and collaboratively pursue engineering as well as social and environmental interests. To ensure the best outcome for ecology (as well as society and coastal protection alike) and gain a deeper understanding of the ecological value of NbS and their natural development after implementation, it is necessary that measures are co-developed and monitored in close cooperation between coastal engineers, nature conservationists, biologists and experts from several other fields.

In conclusion, the analysis of the engineering scope gives a concise overview of the most relevant processes and interactions regarding the NbS' service, resistance and resilience in a coastal protection context. The conceptual framework displays the relevant building blocks or reference points (see also appendix F). In an analysis of a site-specific adaptation challenge, these building blocks can be filled with the respective ecosystem services and properties. Ecosystem properties are put into context with engineering design criteria, disclosing the engineering scope and guiding engineers as well as laymen through the conception, design and evaluation process. This can help to bridge the gap between coastal engineering and nature conservation and foster mutual understanding and the identification of common goals.

An assessment of an adaptation measure with respect to the identified KSR highlights obvious advantages (e.g. safety) and win-win situations, but also discloses unseen or so far neglected aspects (e.g. naturalness) and underlines their potential and the chances they hold. Comparing nature-based to structural measures with regards to the KSR, the application to the two investigation sites points out that both can provide protection, but NbS benefit or cater to much more KSR than 'just' safety and feasibility.

To advance coastal protection and be prepared for future challenges and changes, a re-diversification of protection measures and strategies holds the best chances to safeguard sustainable life along the sandy coastlines around the world. Traditional structural measures as well as nature-based measures must be considered when developing coastal protection adaptation. To close the still existing knowledge gaps regarding NbS for coastal protection and bring the understanding of NbS to the same level as the understanding of structural measures, further pilot projects as well as in-depth monitoring of existing ones are required. In low-risk areas, experimenting and tinkering within projects that feature NbS is indispensable to collect more data and gain deeper insights about the aforementioned key aspects, such as applicability, effectiveness, adaptability, economic efficiency, social acceptance or ecological value of NbS. The broadened perspectives on NbS for coastal protection, that are developed and presented in this thesis, can help to facilitate such pilot projects on a common ground (cf. appendix F) by creating a solid base for the collaborative discussion, conception, development, implementation, maintenance and assessment of nature-based adaptation.

9 Summary and conclusion

Parts of this chapter have already been published in Jordan and Fröhle (2022) and Jordan et al. (2023).

For centuries, coastal protection was characterised by the fight against nature, the powerful enemy sea. With increasing technical progress, coastal protection constantly developed as well, so that nowadays it enables a safe life and economic activity on the coasts, though constantly challenged by an increasing anthropogenic pressure in the coastal zones and multiple interests with regard to the existing and created values. Climate change poses new challenges to the existing coastal protection (cf. section 3.3) and requires substantial adaptations. In combination with a paradigm shift in society's view of the coastal landscape and nature in general (cf. section 1.1) as well as the increased importance of other societal concerns besides safety, a discourse on future technically possible, sustainable and sensible coastal protection is stimulated.
This thesis analysed the potential of coastal ecosystems as Nature-based Solutions for coastal protection of sandy coasts to be sustainable adaptations to climate change. The adopted inter- and transdisciplinary approach allowed the issues to be considered and assessed from different scientific disciplines as well as actors' perspectives. In order to adequately address the multi-layered aspects of the research questions posed at the outset of this work in chapter 1, a broad spectrum of analytical tools was required and by combining these, insights were generated that go beyond the spectrum of the disciplines involved (cf. chapter 2). In order to fill existing gaps and broaden the conceptual understanding of NbS, the North Frisian islands of Amrum and Föhr in the German Bight in the North Sea were selected as investigation area and studied in depth (cf. section 3.2). The approach and research results were then abstracted from the area and clustered so that the knowledge gained and described here can be applied to sandy coasts in general.

Sandy coastscapes are confronted with threatening impacts of the sea historically, now and in the future. Based on the islands of Amrum and Föhr in the North Frisian Wadden Sea, a diachronically and synchronically analysis in chapter 4 disclosed the social dynamics underlying coastal defence challenges. Significant natural events such as storm surges and floods constantly shaped, re-shaped and re-invented coastal protection. Co-determined by the respective prevailing natural and social environments, a constant and pragmatically oriented experimenting and testing of new measures and concepts - be they grey, green or combinations of the two – disclosing a dynamic rationale of coastal defence, revealed a different picture than the one currently existing which merely depicts a long history of diking. This indicated that coastal protection is not a purely technical, but rather a socio-technical endeavour. The interviews conducted with actors captured their framings of past, present and future coastal protection and unravelled insights that provide viable perspectives of how to adapt to a looming climate change. Based on the theory of social representations, the interdisciplinary analysis revealed how those involved in coastal protection produce diverging or converging representations of it and discuss, negotiate and contest underlying issues and values. The concept of diking is dominant in the mind-set of people, but the dynamic and pragmatic rationale, the tinkering and experimenting that characterises coastal protection - though less strong - exists as well. When it comes to NbS for future adaptations of coastal protection as a way to bridge the gap between coastal protection and nature conservation, conflicts from long ago might burden the relationship between the involved actors. However, shared ground and mutual goals are being recognised, and this window of opportunity should be used to focus on communication and co-creation of measures. Commonly developed projects in which people get to know each other, try out and practically experiment together – and by this build trust and accountability – are seen as a way out of these old conflicts, as they offer a socially feasible and viable way to engage with the future of coastal protection. Thus, the concept of coastal protection should be reshaped as a socio-technical endeavour in which the 'social' is capitalised. Exploring the past and present dynamics of coastal protection (and speaking about it with the people involved) can reveal the necessary understanding of social representations and technical developments to commonly find and explore signposts for the future of coastal defence.

These signposts can be nature-based measures, which represent a promising adaptation option for sandy coasts. As outlined in chapter 5, coastal ecosystems thrive around the world under various, site-specific conditions and provide ecological and societal benefits in addition to coastal protection. With regard to their protective services, all analysed coastal ecosystems benefit storm protection or erosion control, often based on one or several of the following underlying principles:

- Limited water depth and the interaction with vegetation and structures cause a reduction of wave heights;
- the stabilisation of the sandy surface reduces the erosion potential;
- surface elevation and the absorption of hydrodynamic forces through sediment redistribution cause a reduction of flooding;
- and an increased bed roughness reduces shear stresses on the soft soil.

The most prominent effect regarding coastal protection is the attenuation of wave energy and wave heights, which - to different degrees of course - is provided by wetland, beach and reef ecosystems alike. As for erosion control or shoreline stabilisation, the promotion of sediment accretion is the major service provided by vegetation in wetland ecosystems or dunes as well as by reef structures. These are, of course, merely two examples of the different processes in favour of coastal protection provided by coastal ecosystems (for an extensive compilation see chapter 5). In summary, a high value can be assigned to coastal ecosystems in terms of protection.
NbS per se have an integrative moment, as they attend to environmental and societal concerns in addition to coastal protection. Amongst a huge variety of different supporting, provisioning, regulating and cultural ecosystem services, most of the coastal ecosystems

support a unique biodiversity and provide habitat to a highly specified flora and fauna above and under water. This significantly benefits nature. Several of the coastal ecosystems represent important nursery areas for marine organisms or breeding, foraging, and resting grounds for sea birds and sea turtles. From an ecological point of view, the improvement of water quality or carbon sequestration are also to be evaluated positively. The wide spectrum of recreational activities associated with coastal ecosystems such as beaches and dunes as well as the visual appeal or aesthetic ecological value of e.g. salt marshes or mangroves benefits people and human well-being. Tourism in ecosystems like mangroves or coral reefs, for example, strengthens local economies and therefore benefits society. Furthermore, several of the coastal ecosystems support fisheries, thus providing food and a source of income for local coastal communities.
The assessment of the relevance of NbS based on conducted interviews with experts from the German NSR completed chapter 5 and revealed comparable results to those from studies in the US. The experts considered NbS to be promising for the adaptation of the existing coastal protection to climate change, but also identified crucial knowledge gaps like missing guidelines, design criteria or tools to capture additional benefits. In general, NbS are seen as having the potential to close the gap and provide a way to resolve certain competing demands, if one works within the given natural boundaries and further illuminates the role of the NbS' properties, the societal impacts and the interaction of the two.

In order for the NbS to become established in future coastal protection practice and to fully exploit their potential for Water, Nature and People, it was revealed within chapters 4 and 5 that a broadened understanding of NbS from both engineering and societal perspectives is needed to facilitate cooperation across all levels. To develop new and effective ways of doing coastal protection not only requires an improved communication about scientific facts or better engineering. For one thing, it is better knowledge and understanding of natural dynamics and the way coastal engineering interacts with the coastscape, that is needed. For another, the acceptance that coastal protection is a sociocultural task has to grow, because the shape of the islands and the coast are a material outcome of the natural, the technical and the sociocultural. This was, therefore, the starting point for expanding the conceptual understanding from an engineering and a societal perspective in chapters 6 and 7.

In engineering terms, NbS can be challenging because their design parameters or properties can change over time, and the underlying interrelations are complex and multi-layered. The developed conceptual framework in chapter 6 broadens the conceptual understanding of NbS from an engineering perspective. It illustrates and analyses the engineering scope in NbS with regard to service, resistance and resilience, revealing interrelations and chains of effect. Most importantly, ecosystem properties represent the parameters that can be fine-tuned and therefore must be considered, evaluated and monitored at every phase of an adaptation project in planning, implementation and maintenance. The conceptual framework and its application to selected investigation sites on Amrum and Föhr showed that NbS can inherently adapt to changing boundary conditions, whereas traditional grey structures usually need expensive retrofitting. To overcome natural limits and push existing thresholds, engineering interventions can be applied. In this sense, the combination of grey and green measures can pose a beneficial option. So existing protection does not need replacement, but NbS function in combination with it as an addition to and adaptation of the status quo.

From the societal perspective, in order to overcome scepticism and doubt and enable true sustainability of nature-based measures, Key Societal Requests were defined and introduced in chapter 7. KSR help to place the 'new' concept of NbS within the existing category system of coastal protection. Specifically for the investigation area on Amrum and Föhr - but to be perceived as generally valid, if a few local-specific adjustments are made - 12 KSR were identified based on conducted interviews with coastal dwellers. The KSR range from *safety* and *feasibility* over *economic efficiency* and *integrity and fairness* to *naturalness* and *participation*. Some represent well-established thinking and public perception of coastal protection as 'the fight against the sea'. Others exhibit the ongoing paradigm shift and the enhanced appreciation of nature and natural coastal processes. The application to the selected investigation sites revealed that, generally, NbS cater to a larger set of KSR than structural measures. The concept can be used to communicate and illustrate this comparison. KSR display a tool to particularly make the additional benefits beyond protection more tangible and offer points of reference to discuss societal needs and requirements with regard to coastal protection.

In summary, it is evident that the mono-culture diking - mentioned here as one if not the most prominent example of the established coastal protection measures, at least in the investigation area in North Frisia - has been penetrated in depth in the course of the last centuries. However, with regard to SLR and further changes, it has its weaknesses and limitations. More resilience in the future will require a broader array of coastal protection options, hence more diversity in coastal protection. In this highly technical world, one sometimes gets the impression that it has been forgotten that coastal protection can also be practiced more diversely and was in fact practiced and functioned differently at some locations in the past. Healthy, functional ecosystems are robust by nature, as can be seen in accordance with past experiences. With this thesis, a contribution is made to enable relevant actors to make use of this again in the future. In this context, NbS are not considered a substitute or panacea for existing protection on sandy coasts but are a valuable addition and sustainable adaptation to climate change. Existing natural, functional or societal limits with regard to the application of NbS in coastal protection can in part be pushed or overcome. On the one hand through a better understanding of the engineering scope in NbS and the promotion of NbS with engineering interventions, on the other hand through participatory planning and open communication. Both require commonly developed and executed pilot projects and long-term monitoring of these, regarding the development of the relevant ecosystem properties as well as the key societal requests, outlined and developed in this thesis.

For the questions dealt within the present thesis, interdisciplinary work was undertaken in order to bring engineering and the social together. The experience gained has shown that true interdisciplinarity, which goes far beyond working side by side, i.e. multi-disciplinarity, requires not only a lot of effort and time from all those involved but above all mental openness and an honest willingness to listen to each other. The results of the interdisciplinary

work were then used to discuss the topic intensively with actors from the practice as well as the local population. In the transdisciplinary exchange, actors shared their knowledge and experiences in order to jointly generate new insights and to advance the discipline of coastal protection both professionally and in the societal arena.
Both perspectives broadened the conceptual understanding of NbS and, thus, ultimately make a contribution to the re-diversification of coastal protection for an increased and sustainable resilience.

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Appendix A Additional figures and tables

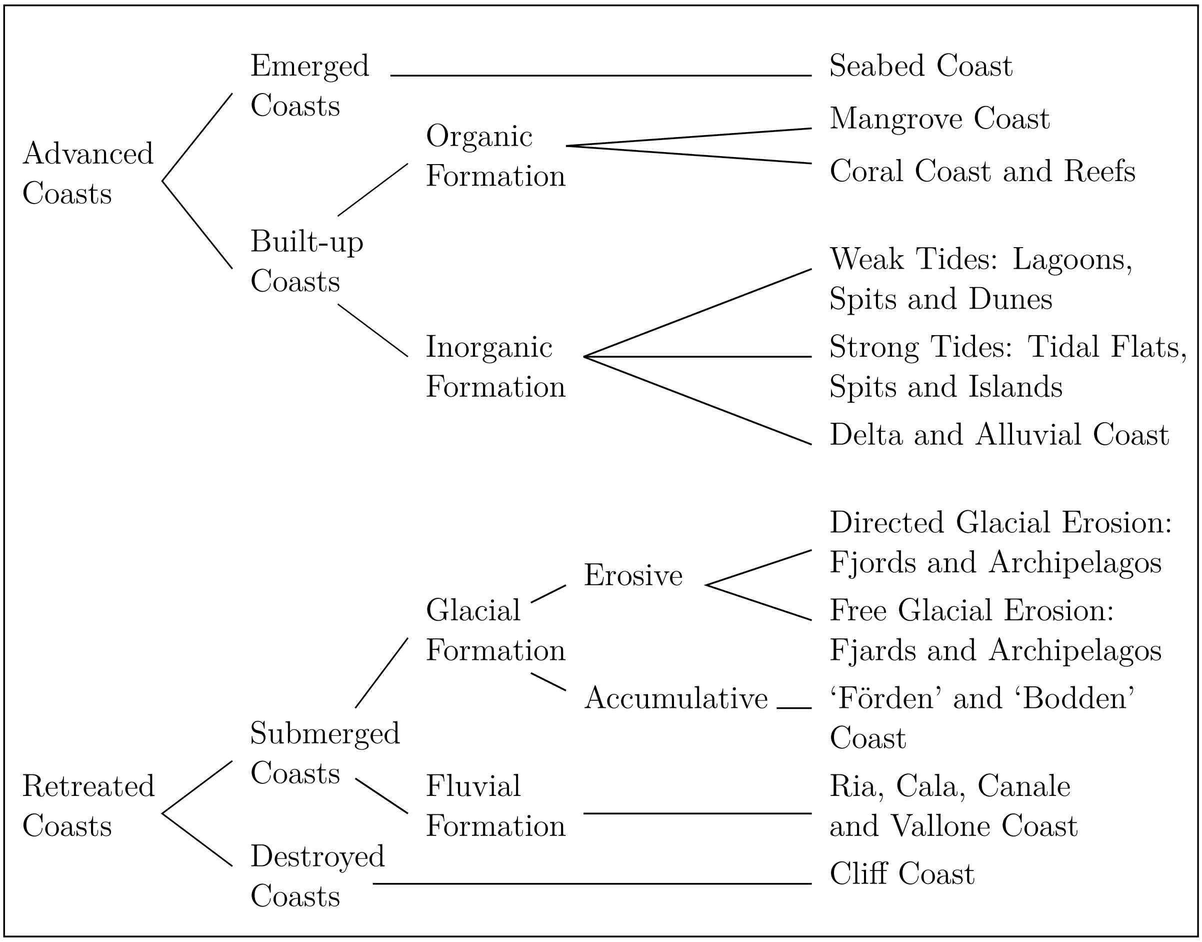

Figure A.1: Coastal classification system after Valentin (1952).

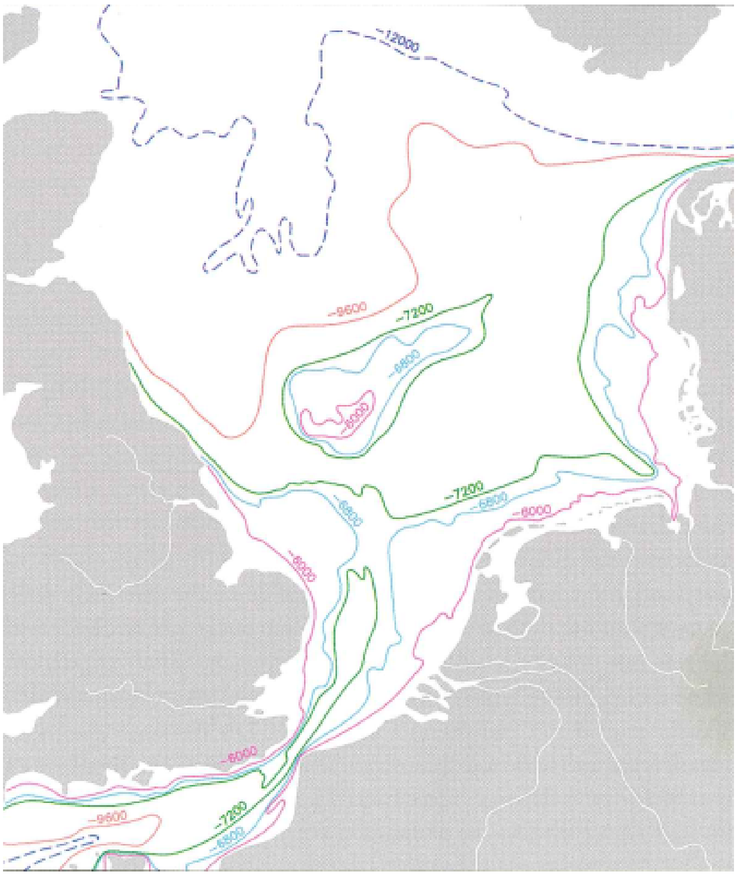

Figure A.2: Course of the North Sea coastline from 12,000 to 6,000 B.C. (Behre, 2008).

Figure A.3: The Wadden Sea UNESCO World Heritage Site (modified from base map: `https://www.waddensea-worldheritage.org/one-wadden-sea-one-global-heritage`).

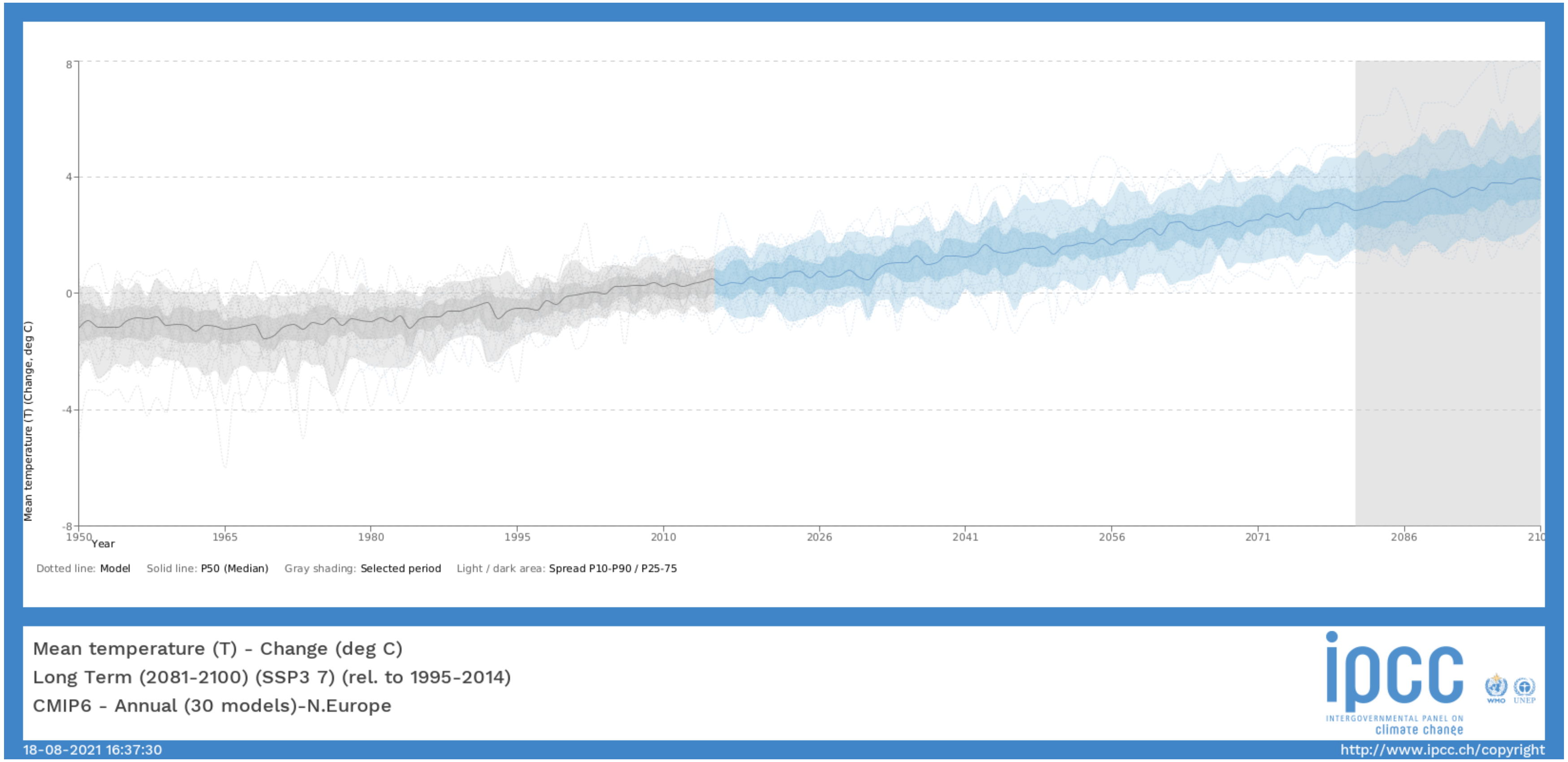

Figure A.4: Mean annual temperature change in °C in the long term (2081-2100, grey area) relative to 1995-2014 based on SSP3-7.0 scenario for the Northern Europe Region (NEU) from 30 CMIP6 model projections; with permission from J. M. Gutiérrez et al. (2021).

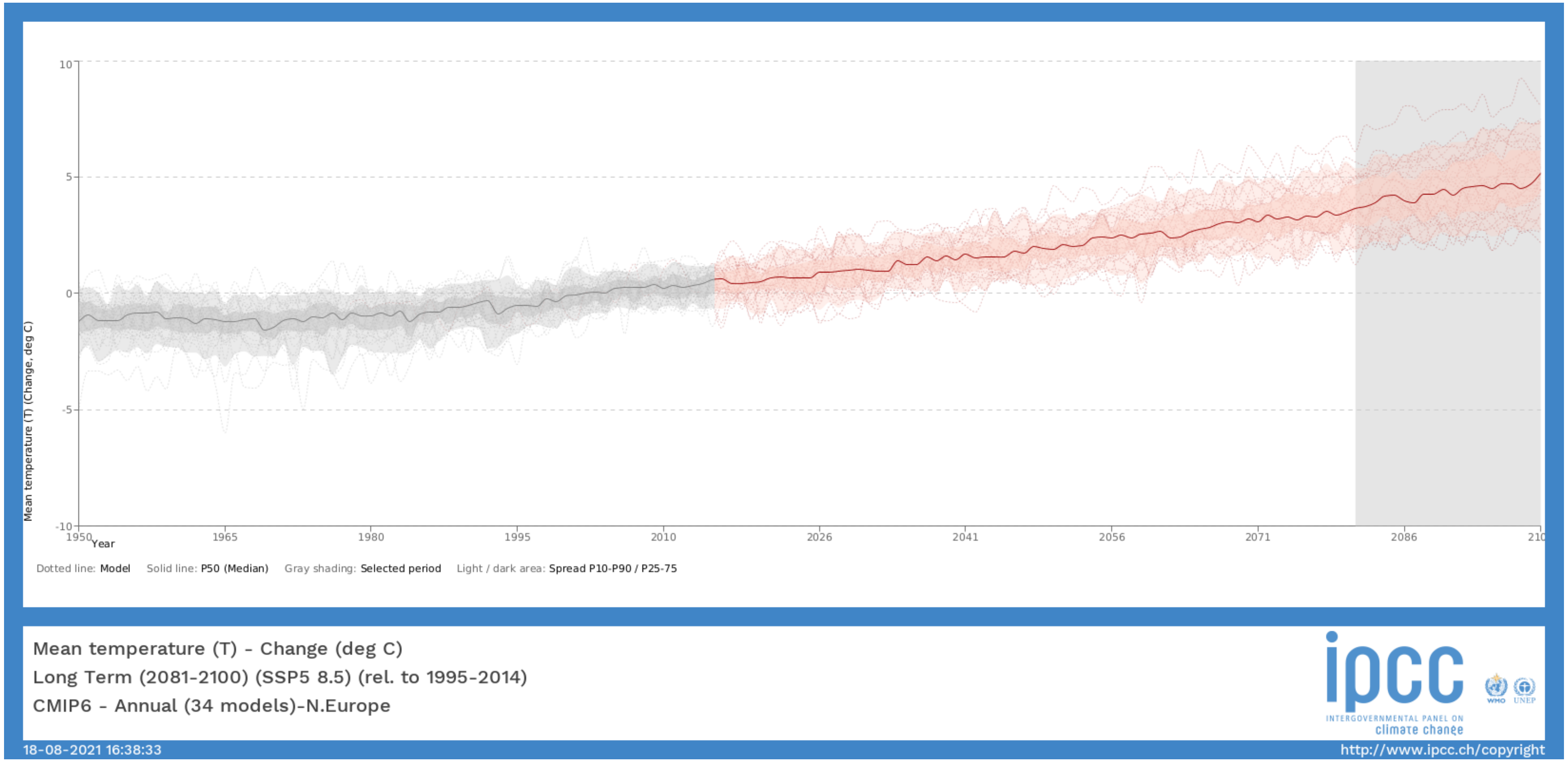

Figure A.5: Mean annual temperature change in °C in the long term (2081-2100, grey area) relative to 1995-2014 based on SSP5-8.5 scenario for the Northern Europe Region (NEU) from 34 CMIP6 model projections; with permission from J. M. Gutiérrez et al. (2021).

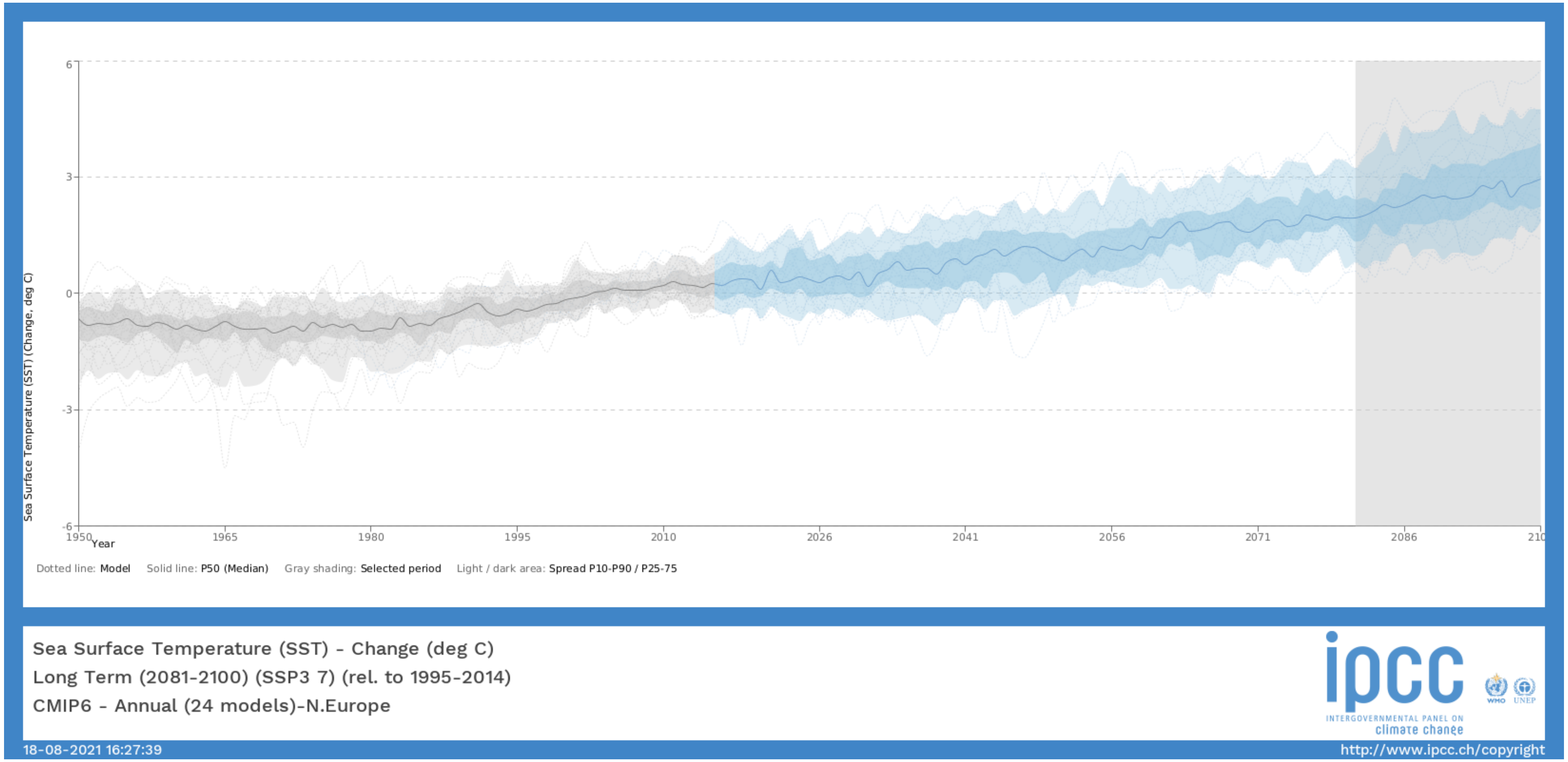

Figure A.6: Mean annual sea surface temperature change in °C in the long term (2081-2100, grey area) relative to 1995-2014 based on SSP3-7.0 scenario for the Northern Europe Region (NEU) from 24 CMIP6 model projections; with permission from J. M. Gutiérrez et al. (2021).

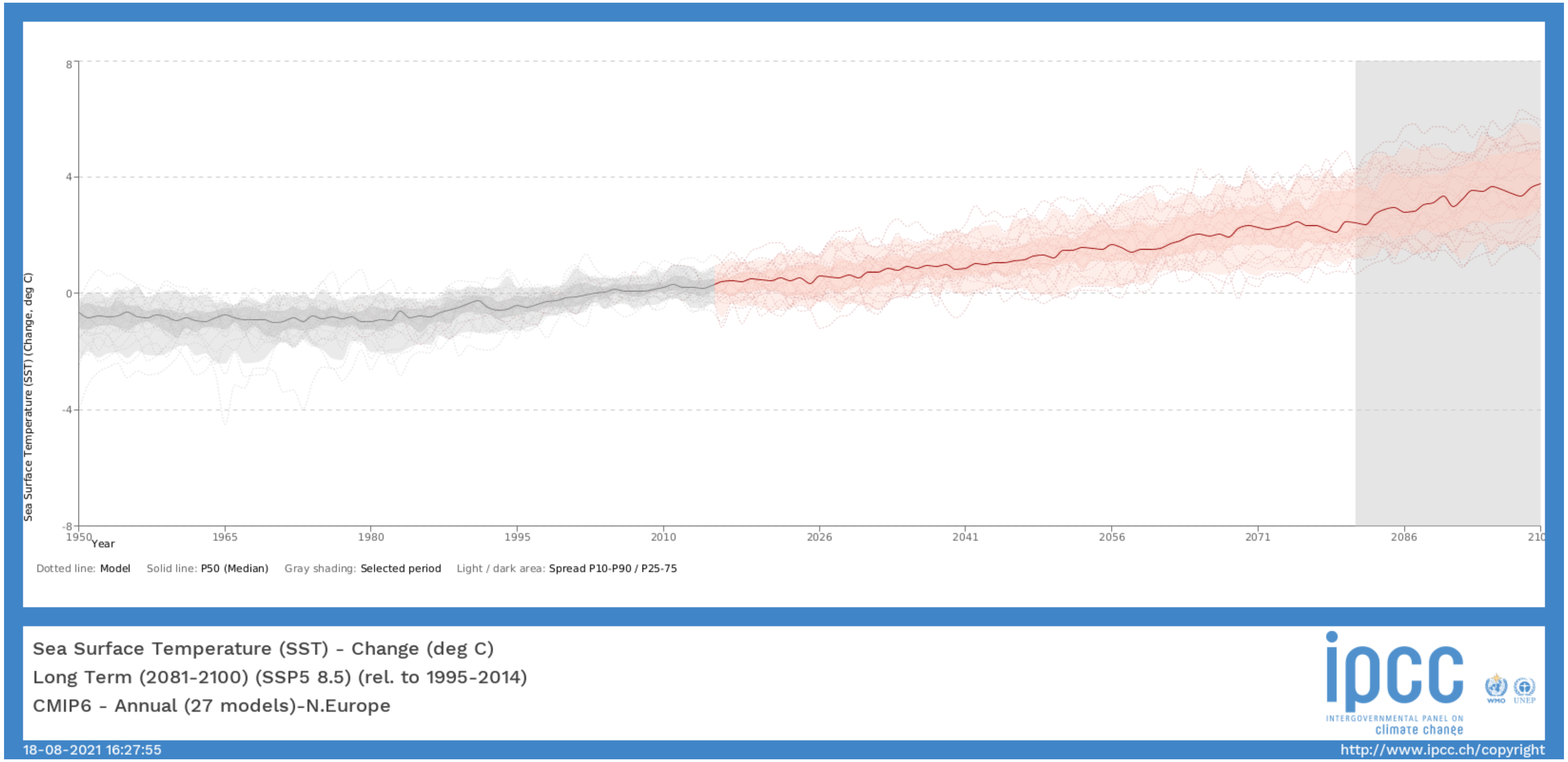

Figure A.7: Mean annual sea surface temperature change in °C in the long term (2081-2100, grey area) relative to 1995-2014 based on SSP5-8.5 scenario for the Northern Europe Region (NEU) from 27 CMIP6 model projections; with permission from J. M. Gutiérrez et al. (2021).

Figure A.8: Positions of DWD wind measurement points in the vicinity of the investigation area; satellite image of the area (modified from base map: `https://cloud.maptiler.com/maps/hybrid/`).

Figure A.9: Positions of LKN sea state measurement points in the vicinity of the investigation area; satellite image of the area is modified from NASA (2020).

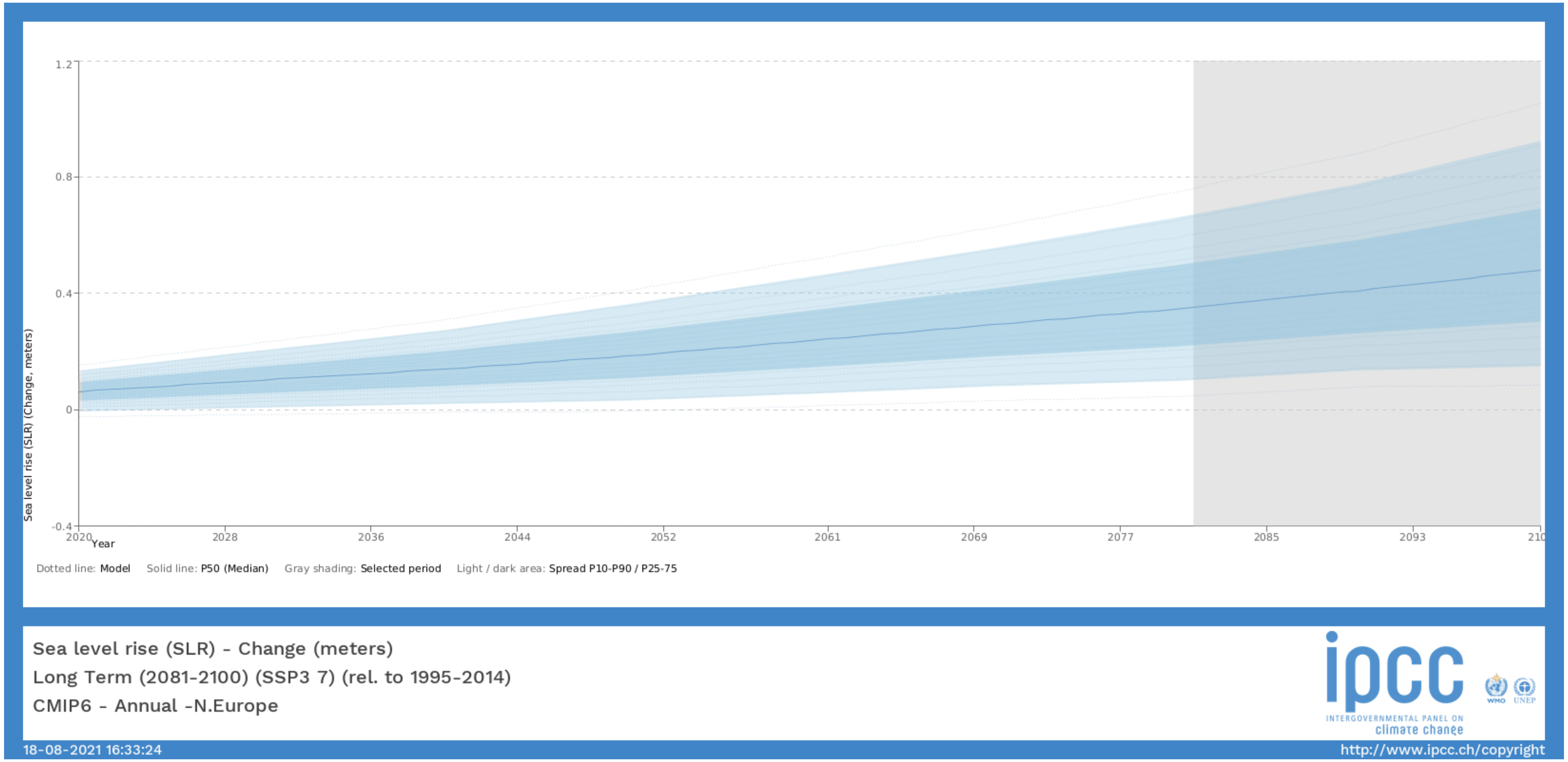

Figure A.10: Sea level rise (change in m) in the long term (2081-2100, grey area) relative to 1995-2014 based on SSP3-7.0 scenario for the Northern Europe Region (NEU) from CMIP6 model projections; with permission from J. M. Gutiérrez et al. (2021).

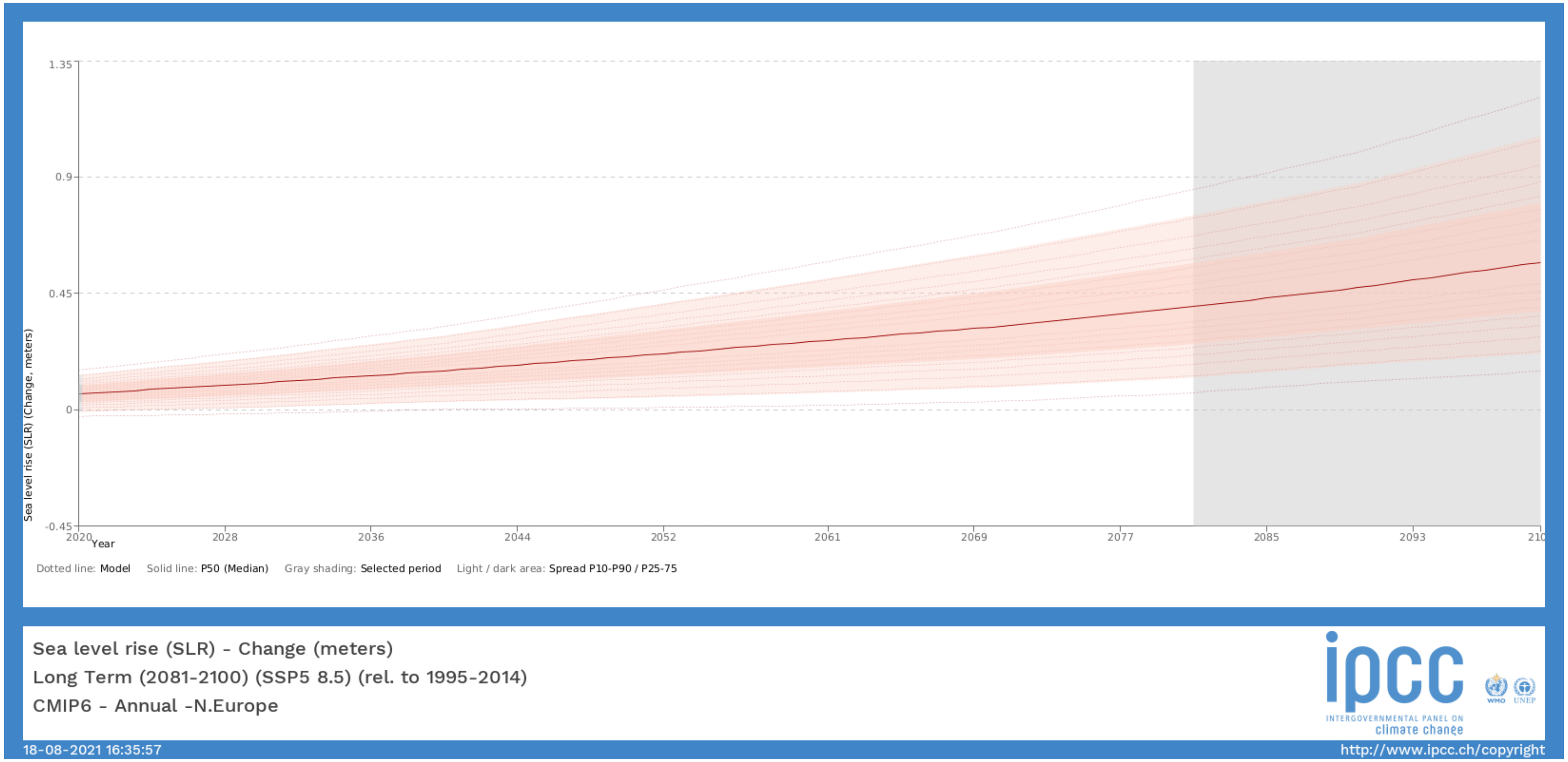

Figure A.11: Sea level rise (change in m) in the long term (2081-2100, grey area) relative to 1995-2014 based on SSP5-8.5 scenario for the Northern Europe Region (NEU) from CMIP6 model projections; with permission from J. M. Gutiérrez et al. (2021).

Table A.1: Key aspects of the different terms associated with and definitions of 'Nature-based Solutions'.

Term	**Key Aspects**
Ecosystem-based Adaptation, EbA (CBD, 2009)	• use of biodiversity and ecosystem services • adapt to the adverse effects of climate change
Ecosystem-based Mitigation, EbM (CBD, 2010)	• enhance benefits for biodiversity • conservation, sustainable use and restoration
Green Infrastructure, GI (Tzoulas et al., 2007)	• all natural, semi-natural and artificial networks of multifunctional ecological systems • multifunctional role, and the importance of interconnections between habitats
Green Infrastructure, GI (European Commission, 2013)	• semi-natural areas with other environmental features • designed and managed to deliver a wide range of ecosystem services
Green Infrastructure, GI (M. A. Palmer et al., 2015)	• a network of natural or semi-natural features • same objectives as grey (built) infrastructure
Natural and Nature-based Features, NNBF (Bridges et al., 2015)	• n: created by physical, geological, biological and chemical processes over time • Nb: created by human design, engineering, and construction to provide specific services
Natural Infrastructure, NI (Benedict and McMahon, 2006)	• strategically planned and managed network of natural lands • conserves or enhances ecosystem values and functions and provides associated benefits
Nature-based Infrastructure (Bridges et al., 2015)	• mimics characteristics of natural infrastructure • created by human design, engineering, and construction to provide specific services
Nature-based Solutions, NbS (IUCN, 2012)	• promote nature • climate mitigation and adaptation
Nature-based Solutions, NbS (European Commission, 2015)	• address environmental, social and economic challenges • inspired by, supported by or copied from nature
Nature-based Solutions, NbS (Cohen-Shacham et al., 2016)	• address societal challenges • human well-being and biodiversity benefits
Nature-based Solutions, NbS (European Commission, 2016)	• address societal challenges • inspired and supported by nature • environmental, social and economic benefits
Nature-based Solutions, NbS (C. Albert et al., 2019)	• challenge-orientation • ecosystem processes utilization • practical viability

Appendix B Evolution of coastal protection in the investigation area

The following lists include the well-documented coastal protection measures on Amrum and Föhr, which are depicted in figures 4.4 and 4.7 in chapter 4.

B.1 List of documented measures and events on Amrum

Table B.1: Well-documented coastal protection measures and storm surge events on Amrum which are included in figure 4.4.

Literature	Year	Measure	Category	Location
Müller & Fischer, 1937, p.181	1696	Oldest decree in Amrum's dune management: Prohibition of stalk picking and cutting	Administration & Decrees	Dunes & Kniepsand South, Dunes & Kniepsand West, Risum, Odde
Müller & Fischer, 1937, pp.181-182	1751	Decree against stalk thieves and appointment of a dune supervisor	Administration & Decrees	Dunes & Kniepsand South, Dunes & Kniepsand West, Risum, Odde
Müller & Fischer, 1937, p.182	1766	Designation of stalk harvesting sites	Administration & Decrees	Dunes & Kniepsand South, Dunes & Kniepsand West, Risum, Odde
Müller & Fischer, 1937, pp.184-185	1783	Formation of a cooperative to inhibit sand in-flow	Administration & Decrees	Dunes & Kniepsand South, Dunes & Kniepsand West, Risum, Odde
Müller & Fischer, 1937, pp.184-186	1784	Active stalk plantings to limit in-flow of sand	Green Measures	Dunes & Kniepsand South, Dunes & Kniepsand West, Risum, Odde
Müller & Fischer, 1937, p.190	1800-1801	Determination of land sizes as a yardstick for the planting load as a result of the land division of 1800	Administration & Decrees	all
Müller & Fischer, 1937, p.195	1802	First dune plantings after the land division	Green Measures	Dunes & Kniepsand South, Dunes & Kniepsand West, Risum, Odde
Müller & Fischer, 1937, p.196	1825	Dune breach at Risum during the storm surge in February	Storm Surge	Risum
Müller & Fischer, 1937, p.206-207	1865-1869	Bush fences and stalk plantings at Amrum's southern tip and at the Risumlücke	Green Measures	Dunes & Kniepsand South, Risum
Müller & Fischer, 1937, p.208	1869	Establishment of the Keitum Dune Inspectorate on Sylt to supervise the dunes of the North Frisian Islands	Administration & Decrees	all
Müller & Fischer, 1937, p.219	1887	Obligation of the residents of Amrum to plant stalk	Administration & Decrees	all

Table B.2: Continuation of table B.1.

Literature	Year	Measure	Category	Location
Müller & Fischer, 1937, p.231	1887-1898	Afforestation of heat areas between the dunes and the meadows/fields	Green Measures	Dunes & Kniepsand West, Risum, Odde, Norddorf, Nebel
Müller & Fischer, 1937, p.102	1894-1895	Construction of four stone groynes to protect the Risumlücke	Hybrid Measures	Risum
Müller & Fischer, 1937, p.109	1896-1897	Construction of six additional groynes	Hybrid Measures	Risum
Müller & Fischer, 1937, p.110	1898-1899	Construction of six wooden pile groynes as intermediate structures	Hybrid Measures	Risum
Müller & Fischer, 1937, pp.232-234	1902-1936	Further afforestation interrupted by war and fires	Green Measures	Dunes & Kniepsand West, Risum, Odde, Norddorf, Nebel
Müller & Fischer, 1937, p.230	1906	Stalk plantings at Wittdün are resumed	Green Measures	Dunes & Kniepsand South
Müller & Fischer, 1937, p.230	1908	Stalk plantings at Risumlücke are resumed	Green Measures	Risum
Müller & Fischer, 1937, p.128; Stadelmann, 2008, p.619	1914	Construction of a 625 m long dam to close the Risumlücke with connection to the high dune fields on both sides	Grey Measures	Risum
Müller & Fischer, 1937, pp.137-138; Stadelmann, 2008, p.637	1914	Construction of a 900 m long sea wall (sheet pile wall and concrete) off Wittdün (sea wall south), quickly proves to be too weak	Grey Measures	Wittdün
Müller & Fischer, 1937, pp.141-142; Stadelmann, 2008, p.637	1914-1915	Severe damages to the sea wall by storms in the Winter 1914/1915	Storm Surge	Wittdün
Müller & Fischer, 1937, pp.141-142; Stadelmann, 2008, p.637	1915	Restoration and improvement of the sea wall; 315 m long front wall with pile foundation and backfilling of the gap to the seawall with lean concrete	Grey Measures	Wittdün
Müller & Fischer, 1937, pp.141-142; Stadelmann, 2008, p.637	1915 & 1921	Foot protection at the combined southern sea wall	Grey Measures	Wittdün
Müller & Fischer, 1937, pp.143-144; Stadelmann, 2008, p.637	1915-1916	Extension of four existing groynes and construction of five new 50 m long groynes in front of the southern sea wall	Hybrid Measures	Wittdün
Müller & Fischer, 1937, p.128	1916-1917	Extension of the northern dam connection by 120 m	Grey Measures	Risum
Müller & Fischer, 1937, pp.150-153; Stadelmann, 2008, p.635	1919-1921	Extension of the wall around the south-east point and construction of the 80 m long south and 25 m long north groyne; extension of the foot protection in front of the existing wall	Grey Measures	Wittdün
Müller & Fischer, 1937, p.234	1920 ff	Maintenance works at the Amrum dunes are resumed	Green Measures	Dunes & Kniepsand South, Dunes & Kniepsand West, Risum, Odde
Müller & Fischer, 1937, pp.159-160; Stadelmann, 2008, p.634	1921-1923	Construction of a 280 m long sea wall (concrete wall on pile foundation) north of Wittdün (sea wall north)	Grey Measures	Wittdün
Müller & Fischer, 1937, p.235	1925	Stalk planting in front of the dam to create a fordune	Green Measures	Risum
Müller & Fischer, 1937, p.166	1926-1927	Storm surge damages	Storm Surge	
Müller & Fischer, 1937, p.166	1926-1927	Repair of storm surge damage; extension and reinforcement of groynes in front of the Risumlücke	Hybrid Measures	Risum
Müller & Fischer, 1937, p.235	1931 ff	Installation a closed row of bush fences along the entire length of the Risumlücke, which are repeatedly re-drawn after silting up at correspondingly higher elevations; subsequent planting	Green Measures	Risum

Table B.3: Continuation of table B.1.

Literature	Year	Measure	Category	Location
Müller & Fischer, 1937, pp.235-236	1931 ff	Installation of bush fences at Wriakhörn	Green Measures	Dunes & Kniepsand South
Müller & Fischer, 1937 pp.168-169	1933	Foundation of the dike associations Norddorf and Wittdün	Administration & Decrees	Norddorf, Wittdün
Müller & Fischer, 1937, pp.174-175	1933-1934	Diking of the Norddorfer Marsch (1700 m dike between Norddorf and the dunes in the north)	Grey Measures	Norddorf
Müller & Fischer, 1937, p.175; Stadelmann, 2008, p.625	1933-1935	Diking of the Wittdüner Marsch (1600 m long dike between Wittdün and Steenodde)	Grey Measures	Wittdün
Müller & Fischer, 1937, p.175	1935	First dike inspection in Norddorf	Administration & Decrees	Norddorf
Müller & Fischer, 1937, p.175	1936	First dike inspection in Wittdün	Administration & Decrees	Wittdün
Müller & Fischer, 1937, pp.178-179	1936	Severe damages at he Wittdün sea wall by the storm surge in October	Storm Surge	Wittdün
Müller & Fischer, 1937, pp.178-179	1937	Reconstruction of the Wittdün sea wall	Grey Measures	Wittdün
Stadelmann, 2008, p.629	1937	Construction of a 124 m long dike foot revetment made of granite south of Wittdün harbour	Grey Measures	Wittdün
Stadelmann, 2008, p.620	1945 ff	Sand trapping fences and stalk plantings to stabilise the sand in front of the Risumlücke	Green Measures	Risum
Stadelmann, 2008, p.631	1953	Construction of a 180 m long asphalt revetment in front of the DRK-Heim Wittdün	Grey Measures	Wittdün
Stadelmann, 2008, p.621	1954	Dune breach: storm surge in January washes away dunes at Gearsdeel over a length of 300 m to the level of the marsh	Storm Surge	Odde
Stadelmann, 2008, p.622	1955	Construction of a 370 m long asphalt dike at Gearsdeel	Grey Measures	Odde
Stadelmann, 2008, p.622	1956	Construction of sand dike stretches for the northern and southern connection of the asphalt dike to the dunes	Hybrid Measures	Odde
Stadelmann, 2008, p.623	1956 ff	Installation of bush fences to stimulate sand deposition	Green Measures	Odde
Stadelmann, 2008, p.626	1959	Construction of two 150 m long wickerwork groynes (Bongossi battens between pairs of piles) between Steenodde jetty and Wittdün harbour	Hybrid Measures	Nebel
Stadelmann, 2008, p.627	1959	Construction of 80 m long rubble revetments to tie in the groyne roots	Grey Measures	Nebel
Stadelmann, 2008, p.627	1961-1962	Construction of rubble stone revetments in front of the dike at Wittdüner Marsch	Grey Measures	Wittdün
Stadelmann, 2008, p.620	1962	Dike Norddorfer Marsch breaks over a length of 300 m during the storm surge; up to 60 cm of sand is deposited on adjacent pastures	Storm Surge	Norddorf
Stadelmann, 2008, p.623	1962	Storm surge damages 5 houses in Nebel located in the area at risk of storm surge damage	Storm Surge	Nebel
Stadelmann, 2008, p.627	1962	Dike breach at Wittdüner Marsch over 75 m north of Gattel dike opening	Storm Surge	Wittdün
Stadelmann, 2008, p.627	1962	Quick restoration of damages at the dike Wittdüner Marsch	Grey Measures	Wittdün
Stadelmann, 2008, p.620	1962-1963	Reinforcement of the dike Norddorfer Marsch as an overflow dike with asphalt surface and dike defence path; new construction of an opening	Grey Measures	Norddorf

Table B.4: Continuation of table B.1.

Literature	Year	Measure	Category	Location
Stadelmann, 2008, p.642	1973	Sealing off the tideway forming in front of the southern sea wall with a sand dam to allow beach and dune formation at Wriakhörn	Green Measures	Dunes & Kniepsand South, Wittdün
Stadelmann, 2008, p.643	1973	Damages at the northern sea wall in autumn	Storm Surge	Wittdün
Stadelmann, 2008, p.634	1974	Restoration of the northern sea wall	Grey Measures	Wittdün
Stadelmann, 2008, p.639	1974	Eastern section of the southern sea wall is replaced by a basalt revetment	Grey Measures	Wittdün
Stadelmann, 2008, p.642	1974	Re-profiling of the sand dam at Wriakhörn	Green Measures	Dunes & Kniepsand South, Wittdün
Stadelmann, 2008, p.623	1976	Storm surge damages 5 houses in Nebel located in the area at risk of storm surge damage	Storm Surge	Nebel
Stadelmann, 2008, p.635	1976	Construction of the Wittdün ferry pier and connection to the northern seawall by means of a revetment	Grey Measures	Wittdün
Stadelmann, 2008, p.640-641	1976	Flank protection at the still existing southern sea wall and nourishment of 47,000 m^3 of sand	Green Measures	Wittdün
Stadelmann, 2008, p.641	1976	Breach of the sand dam	Storm Surge	Dunes & Kniepsand South, Wittdün
Stadelmann, 2008, p.642	1976	Re-filling after breach at Wriakhörn	Green Measures	Dunes & Kniepsand South, Wittdün
Stadelmann, 2008, p.624	1980	Construction of the Nebel embankment	Grey Measures	Nebel
Stadelmann, 2008, p.627-628	1980	Securing the still unprotected stretches of the Wittdüner Marsch with rubble stone covers and rows of piles for foot protection	Grey Measures	Wittdün
Stadelmann, 2008, p.641	1981	Breach of the sand dam	Storm Surge	Dunes & Kniepsand South, Wittdün
Stadelmann, 2008, p.642	1981	Re-filling after breach at Wriakhörn	Green Measures	Dunes & Kniepsand South, Wittdün
Stadelmann, 2008, p.628	1986	Dike heightening at Wittdüner Marsch over a length of 500 m under the association's own direction	Grey Measures	Wittdün

B.2 List of documented measures and events on Föhr

Table B.5: Well-documented coastal protection measures and storm surge events on Föhr which are included in figure 4.7.

Literature	Year	Measure	Category	Location
Müller & Fischer, 1937, p.63	15th	Houses are still located on dwelling mounds in the marsh, some areas secured by summer dikes	Grey Measures	all
Müller & Fischer, 1937, p.65	1492	Completion of the first (documented) sea dike on the island of Föhr	Grey Measures	Western Dike, Northern Dike, North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, p.70	1658	First decree regarding dike maintenance	Administration & Decrees	Western Dike, Northern Dike, North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, pp.154-155	1717-1720	The dike is largely destroyed by the storm surge of December 25; followed by further floods and inundations in 1718 and 1720	Storm Surge	Western Dike, Northern Dike, North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, p.72		Only after this series of storm surges can one speak of real sea dikes, before that only summer dikes	Grey Measures	Western Dike, Northern Dike, North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, p.155	1738	Beginnings of stone revetment construction on the outer side of the dike	Grey Measures	Western Dike
Müller & Fischer, 1937, p.156	1791	Storm surge damage at western and northern dike	Storm Surge	Western Dike, Northern Dike
Müller & Fischer, 1937, p.156	1791	Restoration and heightening of the dike after damages in March	Grey Measures	Western Dike, Northern Dike
Müller & Fischer, 1937, pp.85-86	1796	Still existing dike foreland near Kuham (Näshörn, today north/south of Boldixumer Vogelkoje) breaks off during storm surges and threatens to disappear	Storm Surge	Näshörn
Müller & Fischer, 1937, p.91	1803	Federal intervention: Introduction of the "General Dike Regulations of 06.09.1803"	Administration & Decrees	North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, p.166	1805	Introduction of new dike regulations	Administration & Decrees	Western Dike, Northern Dike
Müller & Fischer, 1937, p.95	1808	Foreland in the North-West is growing	Green Measures	Northern Dike
Müller & Fischer, 1937, p.219	till 1821	Planting of beachgrass to secure sand deposition	Green Measures	Clinic Utersum, Goting Cliff, Nieblum, Greveling
Müller & Fischer, 1937, pp.175-176	1825	Storm surge of February 3/4 causes severe damage; several ground failures, dike between Utersum and Dunsum washed away	Storm Surge	Western Dike
Müller & Fischer, 1937, pp.175-176	1825	Breach is closed within the same year	Grey Measures	Western Dike
Müller & Fischer, 1937, pp.99-101	1825	7 breaches and further severe damages after storm surge in February 3/4	Storm Surge	North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, pp.99-101	1825	Most dangerous locations are dammed up with piles as well as layers of earth and straw	Grey Measures	North-Eastern Dike, Näshörn, Wyk

Table B.6: Continuation of table B.5.

Literature	Year	Measure	Category	Location
Müller & Fischer, 1937, pp.186-187	1827-1833	Following the stone dike, the northern dike is also raised and flattened outwards	Grey Measures	Northern Dike
Müller & Fischer, 1937, p.184	1828-1829	Remaining part of stone dike is raised to 15 feet above design flood level	Grey Measures	Western Dike
Müller & Fischer, 1937, p.104	1833	Severe storm surge damages	Storm Surge	North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, p.104	1833	Severe damages repaired within the same year	Grey Measures	North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, p.187	1833-1834	Several storm surges in spring and autumn/winter cause damage	Storm Surge	Western Dike, Northern Dike
Müller & Fischer, 1937, p.187	1833-1834	Storm surge damages are promptly repaired	Grey Measures	Western Dike, Northern Dike
Müller & Fischer, 1937, p.108	1838 ff	Construction of angled groynes (Winkellahnungen) to protect the foreshore at Näshörn	Hybrid Measure	Näshörn
Müller & Fischer, 1937, p.111	1847-1848	Foreland and mudflats at Näshörn almost completely disappeared, foot of the dike even at low tide in water	Storm Surge	Näshörn
Müller & Fischer, 1937, p.112	1848-1849	Construction of stone revetments at the foot of the dike at Näshörn	Grey Measures	Näshörn
Müller & Fischer, 1937, p.114	1849	Bevelling and "Bestickung" of the foreland near Kuham, also construction of drainage ditches and "Begrüppelungen"	Green Measures	Näshörn
Müller & Fischer, 1937, pp.113-114	1852-1855	Dike heightening at Näshörn	Grey Measures	Näshörn
Müller & Fischer, 1937, p.115	1853-1861	Improvement of all foreshore areas through backfilling and drainage ditches	Green Measures	Näshörn
Müller & Fischer, 1937, p.191	1854	The height of the Western dike is accepted as "design height" and it is decided to bring the rest of the dike up to 2 feet below design height	Administration & Decrees	Western Dike, Northern Dike
Müller & Fischer, 1937, p.192	1855-1861	Raising the dikes to the agreed height	Grey Measures	Western Dike, Northern Dike
Müller & Fischer, 1937, p.116	1857	Construction of new groynes ("Lahnungen") at the protruding tip of Kuham	Hybrid Measure	Näshörn
Müller & Fischer, 1937, p.193	1863	Construction of two groynes ("Lahnungen") made of kelp and stone at the southern and northern end of the western dike	Hybrid Measure	Western Dike
Müller & Fischer, 1937, p.193	1864	Construction of two groynes ("Lahnungen") made of kelp and stone in front of the northern dike	Hybrid Measure	Northern Dike
Müller & Fischer, 1937, p.193	1865	Construction a groyne ("Lahnung") made of kelp and stone to protect the gravel embankment at the northern dike, east of the previously created groyne ("Lahnung"); heightening and extension of the groynes ("Lahnung") at the western dike	Hybrid Measure	Western Dike, Northern Dike
Müller & Fischer, 1937, pp.113-114	1865	Expansion of the stone revetment at Laglum and connection to the existing stone revetment	Grey Measures	Näshörn
Müller & Fischer, 1937, pp.113-114	till 1866	More and more dike reinforcements and heightening with connection to the dikes of Westerlandföhr	Grey Measures	North-Eastern Dike
Müller & Fischer, 1937, p.194	1866	Additional groyne ("Lahnung") construction and raising of the existing groynes ("Lahnung") at the Western dike	Hybrid Measure	Western Dike
Müller & Fischer, 1937, p.200	1869	Linking the Western dike to the moraine ("Geest") with a connecting dike of the same height	Grey Measures	Western Dike

Table B.7: Continuation of table B.5.

Literature	Year	Measure	Category	Location
Müller & Fischer, 1937, p.226	1871	Construction of five groynes in front of the Kleinmarsch	Hybrid Measure	Wyk
Müller & Fischer, 1937, p.205	1883-1894	Extension of the stone revetment at the northern end of the stone dike due to the relocation of the gravel embankment; 50m (1883), 30m (1890) and 60m (1894)	Grey Measures	Western Dike
Müller & Fischer, 1937, pp.233-234	1895-1896	Bank stabilisation (concrete cover) and construction of 14 groynes at Oldenhörn; construction of 18 pile groynes at the south-west corner	Hybrid Measure	Wyk
Müller & Fischer, 1937, p.206	1895	Severe storm surge damages in December 1895	Storm Surge	Western Dike, Northern Dike
Müller & Fischer, 1937, p.206	1896	Restoration of the severe damages	Grey Measures	Western Dike, Northern Dike
Müller & Fischer, 1937, pp.212-213	1897-1902	Reinforcement of the entire dike	Grey Measures	Western Dike, Northern Dike
Müller & Fischer, 1937, pp.212-213	1897-1902	Additional construction of three 40 m long groynes in the North-West	Hybrid Measure	Western Dike, Northern Dike
Müller & Fischer, 1937, p.144	1897-1902	Dike reinforcements are realised in the entire Osterlandföhr dike association	Grey Measures	North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, pp.213-214	1900	Reform of the maintenance of the sea dike	Administration & Decrees	Western Dike, Northern Dike
Müller & Fischer, 1937, pp.238-239	1904	Construction of a 280 m long concrete wall at the beach of Wyk	Grey Measures	Wyk
Müller & Fischer, 1937, pp.215-216	1905-1935	Meticulous maintenance of the groynes and groyne fields ("Lahnungsfelder") in contrast to Eastern Föhr	Hybrid Measure	Western Dike, Northern Dike
Müller & Fischer, 1937, pp.238-239	1908	Extension of the wall to the north by around 220 m	Grey Measures	Wyk
Müller & Fischer, 1937, p.239	1909	Construction of a 162,5 m long wall at the Boldixumer Südstrand (beach)	Grey Measures	Wyk
Müller & Fischer, 1937, pp.240-241	1909	Destruction of the wall at Boldixumer Südstrand over a length of 45 m by the storm surge of December 3, 1909	Storm Surge	Wyk
Müller & Fischer, 1937, pp.240-241	1910	After the destruction of 45 m of this wall, the remaining part is reinforced, secured by a sheet pile wall and extended to the west by 100 m. Construction of the Wyk sea wall and backward extension of groynes	Grey Measures	Wyk
Müller & Fischer, 1937, p.243	1912	Extension of the sea wall at the southern beach	Grey Measures	Wyk
Müller & Fischer, 1937, pp.245-246	1917	Severe storm surge damage, partly favoured by the lack of maintenance work during the war, especially off Boldixum	Storm Surge	Wyk
Müller & Fischer, 1937, p.145	1923	Issuing of new dike regulations (old dike regulations still from 1777)	Administration & Decrees	North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, p.248	1923	Storm surge damage on August 30, 1923; partly destroyed concrete cover in front of Oldenhörn	Storm Surge	Wyk
Müller & Fischer, 1937, p.248	1923	Partially destroyed concrete cover in front of Oldenhörn is replaced by a strong stone revetment with mortar-grouted joints	Grey Measures	Wyk
Müller & Fischer, 1937, p.249	1925	Dike association Mittelberg is founded	Administration & Decrees	Greveling
Müller & Fischer, 1937, p.; Stadelmann, 2008, p.583	1926	Construction of the 416 m long Greveling dike	Grey Measures	Greveling

Table B.8: Continuation of table B.5.

Literature	Year	Measure	Category	Location
Müller & Fischer, 1937, pp.252-253	1928	Severe damages at the Wyk sea wall (Wyk now including Boldixum) by the storm surge of October 09/12, 1926	Storm Surge	Wyk
Müller & Fischer, 1937, pp.252-253	1928	Restoration and reinforcement of the Wyk sea wall	Grey Measures	Wyk
Müller & Fischer, 1937, pp.148-149	1928-1930	Reinforcement of the dike at Näshörn	Grey Measures	Näshörn
Müller & Fischer, 1937, pp.252-253	1929	Securing of damaged sections by pre-driving Larssen sheet piles	Grey Measures	Wyk
Müller & Fischer, 1937, pp.150-151	1936	Storm surge damages in October 1936	Storm Surge	North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, pp.216-217	1937	Extension of stone revetments	Grey Measures	Western Dike, Northern Dike
Müller & Fischer, 1937, pp.150-151	1937	Further reinforcements of Eastern Föhr's sea dike after damages in October 1936	Grey Measures	North-Eastern Dike, Näshörn, Wyk
Müller & Fischer, 1937, p.257; Stadelmann, 2008, p.569	1937	Construction of an approx. 615 m long revetment made of basalt columns to protect the shore in front of the Clinic Utersum ("Nordseekurheim")	Grey Measures	Clinic Utersum
Stadelmann, 2008, p.538	1951	"Overall plan for securing the sea dike and the expansion of inland drainage on the island of Föhr"	Administration & Decrees	Western Dike, Northern Dike, North-Eastern Dike, Näshörn, Wyk
Stadelmann, 2008, p.569	1952	Loose association of communities interested in the protection of the south coast	Administration & Decrees	Clinic Utersum, Goting Cliff, Nieblum, Greveling, Wyk
Stadelmann, 2008, p.600	1953	Concrete revetment in front of Oldenhörn (lighthouse) is replaced by a basalt stone pavement; a revetment is also be placed in front of the adjacent wall	Grey Measures	Wyk
Stadelmann, 2008, p.541	1953-1954	1. BS (Building Section) of 2600 m starting at Wyk harbour	Grey Measures	Wyk, Näshörn
Stadelmann, 2008, p.578	1953-1963	bank erosion at Goting Cliff by 20 m	Storm Surge	Goting Cliff
Stadelmann, 2008, p.583	1954	Storm surge causes severe washout in the Greveling dike	Storm Surge	Greveling
Stadelmann, 2008, p.542	1954-1955	2. BS until km 3 and reconstruction of the Laglum dike opening	Grey Measures	Näshörn
Stadelmann, 2008, pp.543-544	1955-1956	3. BS until km 5,3 at Näshörn; partly asphalt cover on the outer slope over a length of 900 m	Grey Measures	Näshörn
Stadelmann, 2008, p.545	1956	4. BS between Dunsum and Utersum; partly with asphalt cover to protect the outer slope	Grey Measures	Western Dike
Stadelmann, 2008, p.547	1957-1958	5. BS from km 5,3 to 9,5; height remains at NN +6.60 m as in previous BSs; new feature is an erratic boulder cover at the foot of the dike, which is followed by an asphalt cover with rough stripes	Grey Measures	North-Eastern Dike
Stadelmann, 2008, p.547	1958	6. BS from km 16,2 to 17,5 (north of Oldsum)	Grey Measures	Northern Dike
Stadelmann, 2008, p.579	1959	Dam-like elevated dirt road along the Nieblum swale is raised	Grey Measures	Nieblum
Stadelmann, 2008, p.549	1959-1960	7. BS from km 9,5 to 13,1; reinforcement by scavenging	Grey Measures	Northern Dike, North-Eastern Dike
Stadelmann, 2008, pp.549-551	1960-1961	Dike foot protection from Wyk to Näshörn	Grey Measures	Wyk, Näshörn
Stadelmann, 2008, p.551	1961	From Laglum dike opening to Näshörn there are still some foreshore strips over a length of 2 km (partly only 25 m wide)	Green Measures	Näshörn

Table B.9: Continuation of table B.5.

Literature	Year	Measure	Category	Location
Stadelmann, 2008, p.540	1962	Severe damage due to storm surge on stretches that have not yet been reinforced; overly steep embankments; wave overtopping	Storm Surge	Western Dike, Northern Dike
Stadelmann, 2008, p.552	1962	Even before completion of the reinforcements decided in 1953, all dikes are to be reinforced again and given a sand core, flat outer slope, inner berm and dike defence road	Administration & Decrees	Western Dike, Northern Dike, North-Eastern Dike, Näshörn, Wyk
Stadelmann, 2008, p.583	1962	Dike breach over a length of approx. 120 m in Greveling	Storm Surge	Greveling
Stadelmann, 2008, p.554	1962-1963	Dike reinforcement from km 13,6 to 20,2 by scavenging	Grey Measures	Western Dike, Northern Dike
Stadelmann, 2008, p.554	1963	Reconstruction of approx. 3,300 m of stone cover between km 17,1 and 22,1	Grey Measures	Western Dike, Northern Dike
Stadelmann, 2008, p.569	1963	Extension of the revetment at the clinic to the north by around 150 m	Grey Measures	Clinic Utersum
Stadelmann, 2008, pp.603-604	1963	First sand nourishment in Föhr: 180.000 m³ between the harbour and Oldenhörn	Green Measures	Wyk
Stadelmann, 2008, p.583	1963-1964	Greveling dike to be reconstructed as a sand dike with a clover cover in its original form	Grey Measures	Greveling
Stadelmann, 2008, p.603	1963-1964	Construction of six 100 m long shallow groynes on Wyk's eastern beach; reinforced concrete instead of wooden piles	Hybrid Measure	Wyk
Stadelmann, 2008, p.580	1964	Construction of an approx. 1000 m long dike in the Nieblum Swale	Grey Measures	Nieblum
Stadelmann, 2008, p.555	1965	Dike reinforcement Dunsum to Utersum	Grey Measures	Western Dike
Stadelmann, 2008, p.616	1965-1966	Construction of the Wyk harbour dike, sand core with clover cover, top level NN +5,5 m	Grey Measures	Wyk
Stadelmann, 2008, p.555	1966-1968	Dike reinforcement outwards onto the existing foreland between km 10,7 and 13,4	Grey Measures	Northern Dike
Stadelmann, 2008, p.585	1967	Greveling dike suffers further storm surge damage	Storm Surge	Greveling
Stadelmann, 2008, p.585	1967	Greveling dike gets asphalt cover after renewed storm surge damage	Grey Measures	Greveling
Stadelmann, 2008, p.569	1969	Foundation of the South Coast Association ("Zweckverbands Südküste Föhr")	Administration & Decrees	Clinic Utersum, Goting Cliff, Nieblum, Greveling
Stadelmann, 2008, p.605	1969	Construction of a dike with sand core off the Lüttmarsch	Grey Measures	Wyk
Stadelmann, 2008, p.580	1971	Construction of a 250 m long groyne made of Baltic Sea boulders in front of Nieblum bathing beach	Hybrid Measure	Nieblum
Stadelmann, 2008, p.578	1975	Approx. 350 m before the Goting cliff, a 1000 m long and 100 m wide sand bar is constructed (nourishment) in order to reduce wave energy and height before reaching the cliff	Green Measures	Goting Cliff
Stadelmann, 2008, p.580	1975	Sand nourishment on the Nieblum beach, 290.000 m³	Green Measures	Nieblum
Stadelmann, 2008, p.563	1976	Risk area at the transition from the dike to the moraine near Utersum must be mitigated: Dike extension with sand core and asphalt surface by approx. 170 m	Grey Measures	Clinic Utersum, Western Dike
Stadelmann, 2008, pp.570-571	1976	Storm surge damage at the clinic revetment in January	Storm Surge	Clinic Utersum
Stadelmann, 2008, pp.570-571	1976	Restoration of the clinic revetment	Grey Measures	Clinic Utersum

Table B.10: Continuation of table B.5.

Literature	Year	Measure	Category	Location
Stadelmann, 2008, p.571	1977	First sand nourishment in front of the whole clinic revetment	Green Measures	Clinic Utersum
Stadelmann, 2008, p.571	1977	Construction of two 150 m long rubble stone groynes	Hybrid Measure	Clinic Utersum
Stadelmann, 2008, p.578	1977	Sandbar washed up in front of Goting Cliff in 1975 has disappeared	Storm Surge	Goting Cliff
Stadelmann, 2008, p.582	1977	Construction of a 160 m long revetment made of coarse asphalt concrete in front of the "Landkreis Hannover" property	Grey Measures	Nieblum / Greveling
Stadelmann, 2008, p.571	1982	Renewed sand nourishment off the clinic	Green Measures	Clinic Utersum
Stadelmann, 2008, p.580	1982	Sand nourishment on the Nieblum beach, 30.000 m³	Green Measures	Nieblum
Stadelmann, 2008, p.573	1984	Beach bank at Godelniederung breached in several places, therefore more frequent and deeper flooding	Storm Surge	Clinic Utersum / Goting Cliff
Stadelmann, 2008, p.587	1987	Scouring and revetment collapse at the Greveling revetment in autumn 1987	Storm Surge	Greveling
Stadelmann, 2008, p.558	1987-1988	Reinforcement of the dike between km 6,6 and 8,05; previously established sand depot	Grey Measures	North-Eastern Dike
Stadelmann, 2008, p.578	1988	Sand nourishment on the beach in front of Goting Cliff over 2000 m; disappeared again after 10 years	Green Measures	Goting Cliff
Stadelmann, 2008, p.587	1988	Restoration of the Greveling revetment after damages in autumn 1987	Grey Measures	Greveling
Stadelmann, 2008, p.571	1990	Storm surge damages in front of the clinic in January 1990	Storm Surge	Clinic Utersum
Stadelmann, 2008, p.571	1990	Renewed sand nourishment in front of the clinic in response to storm surge damage from January 1990	Green Measures	Clinic Utersum
Stadelmann, 2008, p.580	1990	Damages at Nieblum beach in January 1990	Storm Surge	Nieblum
Stadelmann, 2008, p.580	1990	Sand nourishment on the Nieblum beach as a response to damages in January 1990; 340.000 m³ over a length of 1.700 m	Green Measures	Nieblum
Stadelmann, 2008, p.597	1990	Sand nourishment at the southern beach	Green Measures	Greveling, Wyk
Stadelmann, 2008, pp.559-560	1990-1993	Reinforcement of the dike between km 2,1 and 6,6; previously established sand depot; existing revetment is supplemented by asphalt revetment and driftwood removal path	Grey Measures	Näshörn, North-Eastern Dike
Stadelmann, 2008, p.554	1990-1993	Inner dike reinforcement between km 0,0 and 2,1	Grey Measures	Wyk, Näshörn
Stadelmann, 2008, p.576	1991	Embankment for two farmsteads in Witsum, 260 m in length	Grey Measures	Clinic Utersum / Goting Cliff
Stadelmann, 2008, p.577	1992	Embankment Goting, 293 m in length	Grey Measures	Goting Cliff
Stadelmann, 2008, p.577	1994	Embankment Hedehusum, 525 m in length	Grey Measures	Clinic Utersum
Stadelmann, 2008, pp.601/609	1996-1997	In addition to the existing flood protection system, a new flood protection system is built in front of Oldenhörn: a sand ridge is replaced by a sheet pile wall with reinforced concrete; top level NN +6.5 m	Grey Measures	Wyk
Stadelmann, 2008, p.574	1999	Coastal protection plan for the south coast of Föhr ("Fachplan Küstenschutz Südküste Föhr")	Administration & Decrees	Clinic Utersum, Goting Cliff, Nieblum, Greveling
Stadelmann, 2008, p.591	1999-2001	Construction of the combined revetment Hamburger Wäldchen	Grey Measures	Greveling

Appendix C Questionnaires for stakeholder interviews

The questionnaires were cooperatively developed by the author of this thesis, Philipp Jordan, and Martin Döring (Institute of Geography, University of Hamburg).

C.1 Questionnaire for institutional actors

Guiding questions for a semi-structured interview with responsible institutional actors:

1. Introduction
    - Where do you live? What does it mean to you to live there?
    - What does it mean to you to work in the coastal zone?
    - What is coastal protection for you?
2. Work context
    - How long have you been working here? And why?
    - What exactly is your task?
    - What motivated you to do this work and this task?
    - Which parts of the coast are important to you? Why these places or areas?
    - Are there also areas on the islands that are important to you? Why?
    - Were there any decisive changes or events that changed your relationship with the coast? What were they?
    - What general problems/threats for the northern German coastal regions do you see currently and in the future?
3. Individual assessment and everyday relevance of the climate change issue

    The issue of human-induced climate change has been discussed for about 3 decades. There are also a number of considerations for your region on how to adapt and prevent the climate crisis. Against this background:

    - First of all, a general question: What is/means climate change for you?
    - Where and how does possible climate change show up for you, or not?
    - How is the problem of climate change perceived and evaluated in your work context?

- What problems does climate change currently cause?
- How is the problem of climate change dealt with?
- What challenges does climate change pose for you?
- Which local institutions/associations/interest groups/persons are dealing with the issue of climate change in addition to your institution in North Frisia?
- Do you work together with these institutions? If so, how?
- How does the cooperation work? What is working well and what is not?
- What is the situation on the islands in North Frisia?
- Are there any island-specific climate problems?

4. Knowledge about, experience with and evaluation of coastal protection

   As the saying goes in North Friesland: 'Keen nich will dieken, de mutt wieken.' ('The one who is not willing to dike has to leave.') Now climate change also requires an adaptation of coastal protection in North Frisia and on the islands of Amrum and Föhr.

   - What are your expectations of coastal protection on the islands / on the North Frisian coast?
   - What coastal protection measures are currently being implemented here? Which measures are currently being planned?
   - Why are these measures being carried out or planned?
   - Were there any conflicts in connection with these measures?
   - If so, what do you think were the reasons for these conflicts?
   - How could or can these conflicts be resolved?
   - Do these measures - apart from coastal protection - have other advantages or disadvantages? For the island? For the islanders?

   For some time now, in the context of coastal protection, alternative / soft measures and structures have been discussed in addition to hard structures, which for example take nature-based approaches into consideration.

   - Have you ever heard of these forms of coastal protection?
   - Spontaneously: Which measure would you rather consider and why? Hard structures or more nature-based approaches?
   - Where do they see the potentials and/or problems of these approaches?
   - How are these measures evaluated in your institution?
   - Why are these measures evaluated in this way? Can you explain this in more detail?

5. Local climate futures

Questions relating to human-induced climate change are largely concerned with the future or future developments. Against this background and in relation to your living environment:

- Which ‘climate futures’ do you see in general?
- How will climate change affect North Frisia?
- Which challenges and needs should be addressed immediately? Which ones later or never?
- What do you think the island or coastal landscape could look like in 30 years?
- In your opinion, what would sensible adaptation to climate change look like in the future?
- How has or will coastal protection have developed by then?
- What role will it play then?

C.2 Questionnaire for actors in science

Guiding questions for a semi-structured interview with coastal protection experts from science and academia:

1. Introduction
   - What is coastal protection for you?
2. Work context
   - What does it mean to you to work in the coastal sector/coastal protection?
   - How long have you been working on this topic and why?
   - What motivated you to do this work?
   - What exactly is your task?
   - Are there coastal sections in Germany that are particularly important to you? Why exactly these places or areas?
   - Are there also areas on the islands (Amrum and Föhr) that are important to you? Why?
   - Have there been any decisive changes or events that have changed your relationship with the coast/coastal protection?
   - What general problems/threats for the northern German coastal regions do you see at present and in the future?
3. Individual assessment and everyday relevance of the climate change issue

   The issue of human-induced climate change has been discussed for about 3 decades. There are also a number of considerations for your region on how to adapt and prevent the climate crisis. Against this background:

- First of all, a general question: What is/means climate change for you?
- Where and how does possible climate change show up for you, or not?
- How is the problem of climate change perceived and evaluated in your work context?
- What professional challenges does climate change pose for you?
- How are you currently dealing with the problems caused by climate change in your field of work?
- Which local institutions/associations/interest groups/persons are dealing with the issue of climate change on the North German coasts in addition to your institution?
- Do you work together with these institutions? If so, how?
- How does the cooperation work? What works well and what does not?
- Do you also work on the islands of the North German coast? And what is the situation there?
- From your perspective, are there island-specific climate problems and approaches to solving them?

4. Knowledge about, experience with and evaluation of coastal protection

   As the saying goes in North Friesland: 'Keen nich will dieken, de mutt wieken.' ('The one who is not willing to dike, has to leave.') Now climate change also requires an adaptation of coastal protection in North Frisia and on the islands of Amrum and Föhr.

   - What are your expectations of coastal protection on the islands / on the North Frisian coast?
   - What coastal protection measures are currently being implemented here? Which measures are currently being planned?
   - Why are these measures being carried out or planned?
   - Were there any conflicts in connection with these measures?
   - If so, what do you think were the reasons for these conflicts?
   - How could or can these conflicts be resolved?
   - Do these measures - apart from coastal protection - have other advantages or disadvantages? For the island? For the islanders?

   For some time now, in the context of coastal protection, alternative / soft measures and structures have been discussed in addition to hard structures, which for example take nature-based approaches into consideration.

   - Since when have NbS been relevant for you in your (scientific) work?
   - Has the concept of NbS changed during this time? What has changed?
   - Has, what is considered NbS and how research on NbS is conducted and perceived, changed?

- How was and is the NbS approach negotiated within the discipline?
- Have there been decisive decisions (conceptual? research policy?) that have helped NbS achieve a breakthrough nationally and internationally?
- Has there been a change in who contributes to the development and design of NbS?
- In your opinion, who were and are the most important protagonists in the field of NbS?
- Can you situate the concept of NbS historically for yourself?
- What is actually the 'natural' in the approach of NbS?
- Where do you see the potentials and/or problems of these approaches now and in the future?
- How are these measures evaluated in your institution?
- Spontaneously: Which measure would you rather consider and why? Grey, hybrid or purely nature-based approaches?

5. Local climate futures

   Questions relating to human-induced climate change are largely concerned with the future or future developments. Against this background and in relation to your living environment:

   - Which 'climate futures' do you see in general?
   - How will climate change affect North Frisia?
   - Which challenges and needs should be addressed immediately? Which ones later or never?
   - What do you think the island or coastal landscape could look like in 30 years?
   - In your opinion, what would sensible adaptation to climate change look like in the future?
   - How has or will coastal protection have developed by then?
   - What role will it play then?

C.3 Questionnaire for the local population / local actors

Guiding questions for a semi-structured interview with coastal dwellers / the local population:

1. Introduction
   - What does it mean for you to live here?
2. Social and emotional place attachment
   - What is 'Heimat' or sense of place for you?

- How long have you lived here? And why? Possibly: Why have you stayed here?
- Which parts of the coast on your island do you like best? Why these areas?
- What do natural areas such as dunes / beach / salt marsh mean to you?
- How do you use these natural areas in everyday life?
- Has your relationship with your 'Heimat' changed over the years? If so, how? How do you explain this?
- Were there any decisive changes or events that changed your relationship to your 'Heimat'? What were they?
- What exactly has changed as a result of this event and how was this change relevant to you?
- What general problems/threats to your 'Heimat' do you currently see? (Possibly refer specifically to other problem situations!)

3. Individual assessment and everyday relevance of the climate change issue

   The issue of human-induced climate change has been discussed for about 3 decades. There are also a number of considerations for your region on how to adapt and prevent the climate crisis. Against this background:

   - First of all, a general question: What is/means climate change for you?
   - Where and how does possible climate change show up for you, or not? (in general and in relation to your 'Heimat')
   - Is the topic of climate change relevant to you at all - also in everyday life? (In what way or in what way not?)
   - Do you have any personal experience with climate change? If yes, which ones?
   - What do you see as the biggest challenge of a changing climate?
   - How are you adapting to it?
   - How do others in your social environment see or assess climate change?
   - Which local institutions/associations/interest groups/persons are dealing with the issue of climate change in your living environment?
   - Who (persons/institutions) do you think should primarily deal with the issue of climate change?
   - What measures are you aware of?
   - What was the reason for these measures?
   - Are you involved in climate protection? (If no: What could you imagine doing?)

4. Knowledge about, experience with and evaluation of coastal protection

   As the saying goes in North Friesland: 'Keen nich will dieken, de mutt wieken.' ('The one who is not willing to dike, has to leave.') Now climate change also requires an adaptation of coastal protection in North Frisia and on your island.

- What are your expectations of coastal protection on the islands / on the North Frisian coast?
- What coastal protection measures have been carried out here in your living environment? (Which ones were carried out on other islands or also on mainland?)
- How did you learn about them?
- Why was this measure carried out?
- Who initiated it and how was it justified?
- Does this measure seem useful to you?
- Did it meet your expectations?
- Were there any conflicts in connection with these measures?
- If so, what do you think were the reasons for these conflicts?
- How could or can these conflicts be resolved?
- Do these measures - apart from coastal protection - have other advantages or disadvantages? For the island? For you directly?

For some time now, in the context of coastal protection, alternative / soft measures and structures have been discussed in addition to hard structures, which for example take nature-based approaches into consideration.

- Have they ever heard of these forms of coastal protection?
- Spontaneously: Which measure would you rather consider and why? Hard structures or more nature-based approaches?
- What do you think of this type of coastal protection? (Why do you rate it this way?)
- Where do you see the potentials and/or problems of these approaches?
- What is natural about these measures for you?
- How are these measures evaluated in your social environment?
- Why are these measures evaluated in this way? Can you explain this in more detail?
- Will the topic of climate change and coastal protection continue to be of concern to you and in what way?

5. Local climate futures

   Questions relating to human-induced climate change are largely concerned with the future or future developments. Against this background and in relation to your living environment:

   - Which ‘climate futures’ do you see in general?
   - How will climate change affect North Frisia?
   - How will climate change affect your island?

- Which challenges and needs should be addressed immediately? Which ones later or never?
- What do you think your island or coastal landscape could look like in 30 years?
- In your opinion, what would sensible adaptation to climate change look like in the future?
- What information do you need or expect from science to implement meaningful adaptation?
- How can science and policy help with the challenges of climate change?
- How do you assess the current collaboration between science, practice and policy?
- How has or will coastal protection have developed by 2050/2100?
- What role will it play then?

Appendix D Interview analysis on actors' perspectives

This apendix has already been published in Jordan et al. (2023).

D.1 Set of categories for the interview analysis

1. Sense of place or 'Heimat'
2. Professional motivation
3. Worldly motivation
4. Profession
5. Coastal Protection
6. Participation
7. Wadden Sea landscape
8. Strategy 2100
9. Interface Coastal Protection - Nature Conservation
10. Conflict
11. Scientific legitimacy
12. Prevention (federal states‘ planning)
13. Society
14. Climate Change
15. Adaptation to climate change
16. Images of the future
17. Nature-based Solutions
18. Image of the climate
19. Climate Change in the future

20. International comparison
21. Climate adaptation on the holms
22. Future of coastal protection
23. Cooperation

D.2 Set of subcategories for the four selected categories

- Coastal Protection
- Nature-based Solutions
- Interface Coastal protection – Nature conservation
- Future of coastal protection

with indication of temporal reference

1. What was…?
2. What is…?
3. What will be… in coastal protection?

D.2.1 Category: Coastal protection

Subcategories:

- Acceptance (3)
  - Aspect of economic efficiency
  - Bold action in coastal protection
  - Political issue
  - Institutional acceptance
  - Social acceptance
- Aspect of innovation (2, 3)
  - Pilot projects
  - Changing current practice
  - NbS as good practice
  - Perception of NbS
  - Opportunities and limitations
  - Integrative approaches

- Forces of nature (2, 3)
  - Erosion
  - Process understanding
  - Natural resistance
- Natural dynamics (2)
  - Natural resistance
  - Use in the sense of NbS
  - Perception
  - Process understanding
- Sand (2)
  - Availability
  - Coastal protection with sand
- Technologies (1, 2, 3)
  - Outdated technologies
  - Proven technologies
  - Coastal fixation vs. dynamics
  - Inland drainage
- Current situation (2)
- Aspects of coastal protection (2)
  - Local solutions
  - Protection from people
  - Protection from the sea
  - Natural interrelationships
- Dike construction (1, 2, 3)
  - Historical dike construction vs. technical progress
  - Dike maintenance
  - Status of dikes
  - Modern dike construction
- Development of the coastal zone (1, 2)
  - Coastal protection measures
  - Natural processes
  - Tourism

  - Political will
- Local identity (1, 2)
- Sea level rise (1, 3)
  - Significance for coastal protection
  - Development of the coast
- NbS in the scientific context (2)
- Organisational structures (1, 2, 3)
  - Development
  - Responsibilities
- Participation (2, 3)
- Forecasts (3)
- Status of coastal protection (1, 2, 3)
  - Changed expectations
  - High relevance
  - Storm surge references

D.2.2 Category: Nature-based Solutions

Subcategories:

- Acceptance (1, 2, 3)
  - Aspect of economic efficiency
  - Bold action in coastal protection
  - Political issue
  - Institutional acceptance
  - Social acceptance
- Aspect of innovation (1, 2, 3)
  - Pilot projects
  - Changing current practice
  - NbS as good practice
  - Perception of NbS
  - Opportunities and limitations
  - Integrative approaches
  - Participation

- Forces of nature (1, 2)
  - Erosion
  - Process understanding
  - Natural resistance
- Natural dynamics (2, 3)
  - Natural resistance
  - Use in the sense of NbS
  - Perception
  - Process understanding
- Sand (2, 3)
  - Availability
  - Coastal protection with sand
- Technologies (1, 2, 3)
  - Outdated technologies
  - Proven technologies
  - Coastal fixation vs. dynamics
  - Inland drainage
- Application examples (2, 3)
  - Proven measures
  - Pilot projects
- Understanding of the term NbS (1, 2, 3)
  - Guidelines from nature
  - Minimisation of impacts
  - Ecosystem services
  - Use of natural processes
- Finding a compromise (3)
  - Sand as a compromise with nature conservation
- NbS in the institutional context (2)
- Visions (3)

D.2.3 Category: Interface coastal protection - nature conservation

Subcategories:

- Conflict coastal protection - nature conservation (1, 2)
  - Necessity of negotiation
  - Diverging protection rationales
  - Potential areas of conflict
  - Diversity of perspectives
  - Problem of participation and cooperation
  - Institutional structure
  - Existing conflicts
  - Political strategy
- Images of coastal protection (2)
  - Destroys nature
  - Path-dependency Coastal protection
  - Rational coastal protection
  - Institutional structure
- Cooperation coastal protection - nature conservation (1, 2, 3)
  - Converging problem perception
  - Relevance of cooperation
  - Institutional structure in North Frisia
- Images of nature conservation (2, 3)
  - Rational nature conservation
  - Critical reflection of the National Park's motto
- Images of nature (1, 2, 3)
  - Non-nature through interventions
- Expectations and challenges (3)
  - Changing the rationale behind coastal protection
  - Development of integrative concepts
  - Creative novel solutions
  - Conceptual change in coastal protection

D.2.4 Category: Future of coastal protection

Subcategories:

- Retrospective (1)
  - Necessity of adaptation
  - Natural process understanding
  - Concept of nature
- Institutional change in coastal protection (2)
  - Lack of motivation
  - Institutional structures
- Present situation in coastal protection (2)
  - Land losses
  - Sediment transport
  - Drainage
  - Legal mandate
  - Economic dimension
  - Need for conceptual change
  - Path dependency
  - Current state coastal protection
- Coastal protection policy (3)
  - Conceivable measures
  - Change in coastal protection
  - Future protection measures
  - Political and institutional change
  - Preconditions for change in coastal protection
  - Willingness to experiment
  - Need for inter- and transdisciplinarity
- Socio-economic dimension (3)
  - Social compatibility
  - Financial resources
  - Intensified cooperation
  - Socio-economic dimension
  - Societal change

- Change in the natural system (3)
  - Sea level rise
  - Climate change
  - Sediment shortage
  - Material shortage
  - Natural developments
- Rationale of protection (3)
  - Sediment accretion
  - No regret measures
  - Relocation of water/land interface
  - Exposure of North Frisia in climate change
- Past natural dynamics (1)

Appendix E Interview analysis regarding Key Societal Requests

E.1 Identified Key Societal Requests (KSR) from the interview analysis

The number of referenced citations (No.Ref) and number of interviewees referring to this KSR (No.Int) are given in brackets (No.Ref/No.Int).

1. Safety (67/17)
2. Feasibility (28/15)
3. Economic efficiency (18/12)
4. Naturalness (18/9)
5. Responsibility (17/9)
6. Integrity / Fairness (16/9)
7. Recreational value (15/9)
8. Comprehension of the function (13/9)
9. Social ties (12/8)
10. Aesthetic appeal (9/6)
11. Participation (8/5)
12. Connectedness (3/2)

E.2 Set of subcategories for the identified KSR

E.2.1 KSR: Safety

Subcategories:

- Threat
- Feeling of safety

- Dike
- Island as a fortress
- Protection of livelihood
- Protection of property
- Protection of lives
- Protection of the landscape
- Community engagement
- Mistrust in professional expertise
- Lack of knowledge
- Relying on professional expertise
- Future safety
- Conflicting interests

E.2.2 KSR: Feasibility

Subcategories:

- Sea level rise
- Pragmatic solutions / Islanders' ideas
- Limits
- Technical feasibility
- Societal feasibility
- Cooperation

E.2.3 KSR: Economic efficiency

Subcategories:

- Tourism
- Limited resources
- Agriculture
- Wasteful spending
- Sensible spending

E.2.4 KSR: Naturalness

Subcategories:

- The primal
- Relaxation through nature
- ‘Let nature be nature.’
- Protection through nature
- Conflicts
- Threats

E.2.5 KSR: Responsibility

Subcategories:

- Communication
- Local engagement
- Costs for coastal protection
- Maintenance
- Planning for the future

E.2.6 KSR: Integrity / fairness

Subcategories:

- ‘Let nature be nature.’
- Equal treatment
- Coastal protection as a task for society as a whole
- Holistic view
- Future generations

E.2.7 KSR: Recreational value

Subcategories:

- Place to take a stroll
- Connectedness / identification with the island
- Relaxation
- Place for sports
- Fascination

E.2.8 KSR: Comprehension of the function

Subcategories:

- Mistrust, due to lack of understanding
- Trust, despite lack of understanding
- Local ‘expertise’
- NbS

E.2.9 KSR: Social ties

Subcategories:

- Previous generations
- Future generations
- Local identity

E.2.10 KSR: Aesthetic appeal

Subcategories:

- Perception of grey coastal protection
- Perception of NbS
- View to the sea
- Wadden Sea
- Nature

E.2.11 KSR: Participation

Subcategories:

- Interest
- Common goals
- Acceptance
- Benefit from local knowledge

E.2.12 KSR: Connectedness

Subcategories:

- Image of dike and coast

Appendix F Compilation of identified NbS items and key criteria

The following table provides a compilation of the relevant items and key criteria to facilitate the assessment of coastal ecosystems as NbS with regard to the engineering as well as the societal scope as identified, developed and described in chapters 6 and 7.

Table F.1: Compilation of the relevant identified items and key criteria to facilitate the assessment of coastal ecosystems as NbS with regard to the engineering as well as the societal scope.

Boundary Conditions	**Coastal Ecosystem**	**Ecosystem Properties (EP)**	**Ecosystem Services (ES)**	**Key Societal Requests (KSR)**
Wave height; Wave angle; Water level; Storm surge height; Storm surge frequency; Tidal regimes; Current velocity; Current direction; Salinity; Water temperature; Air temperature; Wind speed; Wind direction	Salt marshes; Mangroves; Seagrass meadows; Beaches; Dunes; Coral reefs; Shellfish reefs	Height; Width; Distance from shore; Presence of vegetation; Structural integrity; Vegetation density; Vegetation species; Vegetation stiffness; Slope; Bed roughness; Subsoil stability and cohesion; Sediment type; Water saturation	Wave breaking; Wave attenuation; Reduction of currents; Water retention; Prevention of flooding; Wind speed reduction; Sediment accretion; Groundsoil stabilisation; Reduction of shear stresses; Sediment exchange and storage; Sediment generation	Safety; Feasibility; Economic efficiency; Naturalness; Responsibility; Integrity and fairness; Recreational value; Comprehension of the function; Social ties; Aesthetic appeal; Participation; Connectedness

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