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North Sea Region
Building with Nature

Ministry of Environment and Food of Denmark
Coastal Authority

Building with Nature: Systems Description of Krogen

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Contents

1 Introduction

1.1 Building with Nature

The objective of the Building with Nature EU-InterReg project is to improve coastal adaptability and resilience to climate change by means of natural measures. As part of this project the Danish Coastal Authority (DCA) carry out research into different aspects of using natural processes and materials in coastal laboratories on Danish coasts.

Through the EU InterReg project "Building with nature" a better understanding of the interactions within the coastal system is sought.

The Building with Nature project is a combination of six different work packages, see Figure 1.

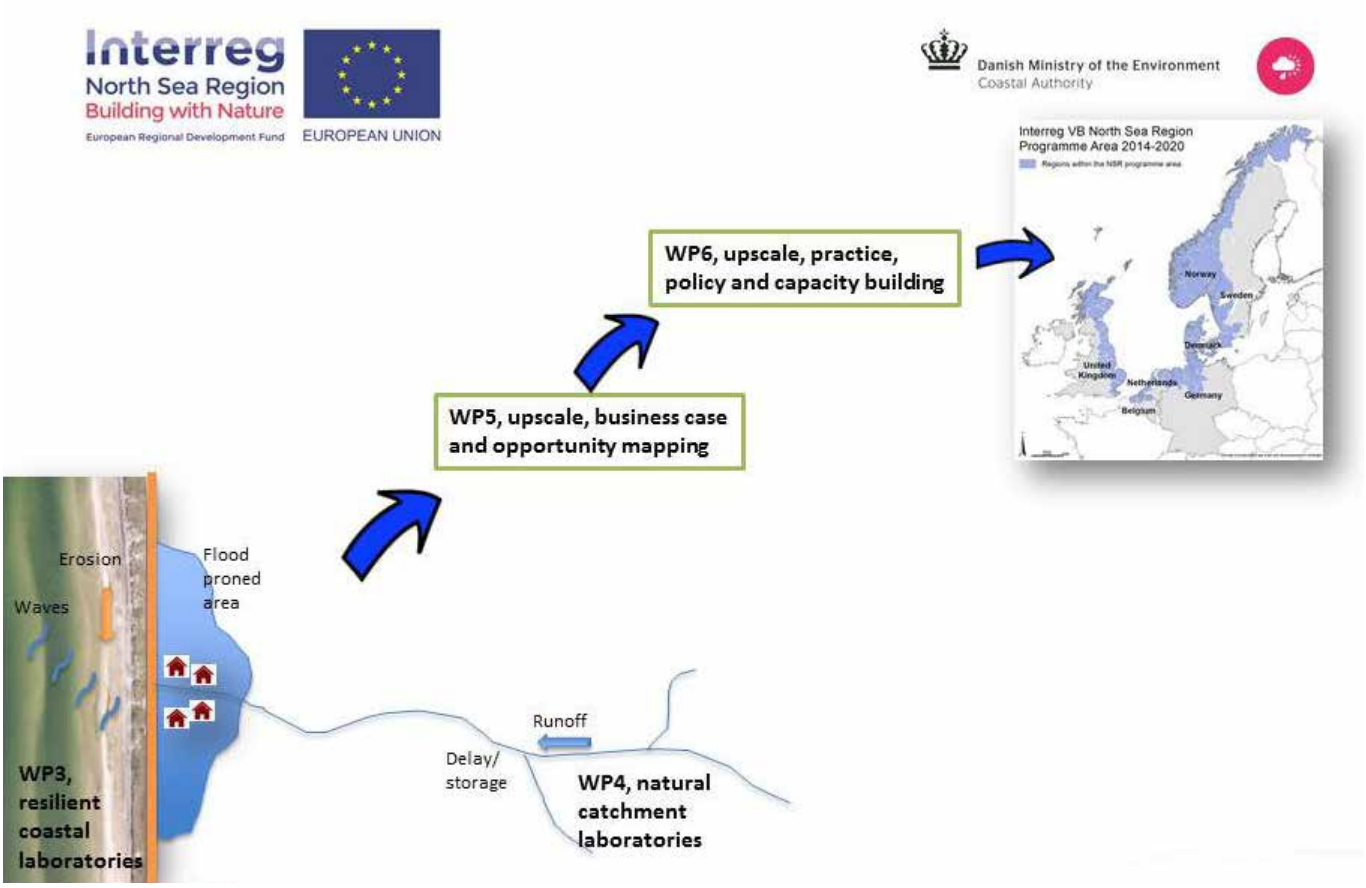

Figure 1: The connections between the 6 work packages in the Building with Nature project. WP1 - Project Management, WP2 - Communication Activities, WP3 - Resilient Coastal Laboratories, WP4 - Natural Catchment Laboratories, WP5 - Upscaling, Business Case and Opportunity Mapping, WP6 - Upscaling, Practice, Policy and Capacity Building.

The Danish Coastal Authority is mainly active in Work Package 3: Resilient Coastal Laboratories. This project comprises two living laboratories: Krogen and Skodbjerge. Each location will be monitored and examined with regards to erosion, nourishment and aeolian transport throughout the duration of the project.

The Danish Coastal Authority has an in-depth knowledge of coastal dynamics along the Danish North Sea coast; the Danish Coastal Authority has been engaged in coastal protection since 1872 and has collected measurements of the coast since 1876.

1.2 The Joint Agreement (on the North Sea coast)

After a severe storm in 1981 it became apparent that the structural coastal protection established, mainly consisting of groins and dikes were not enough to safeguard the Danish North Sea coast. This is due to the fact that the coast line is subject to chronic erosion, which means that the natural retreat of the active coastal profile will vary between one and eight meters per year, see Figure 3. In this area, the combination of substantial natural coastal retreat, a relatively high water level during storms, a narrow dune belt and low hinterlands along long stretches of the coast create a serious flooding hazard; and in case of dune penetration homes and property would be destroyed. See Figure 2.

The Danish Government and the local municipalities therefore signed a joint agreement to protect the coast in the future. The Joint Agreements are financial agreements usually covering a five year period. This means that the agreement will be up for renegotiation every 5 years.

Since 1982, thanks to these agreements, protection of the 110 km stretch of coast from Lodbjerg to Nymindegab has been carried out as a joint effort by the local municipalities and the Danish government, see Figure 2. The basis for the agreement is a safety level objective as expressed in the average volume of sediment in the coastal profile.

Since the first agreement, 28 km of slope protection have been laid out, 145 breakwaters have been built and the coast has been nourished with some 59 million m³ of sand.

The current five year joint agreement will expire in 2018.

Since the 1990s, the coastal protection of the coast stretching from Lodbjerg to Nymindegab has primarily consisted of sand nourishment and slope protection in front of sand dunes and sand dikes. However, today the protective efforts almost solely consist of nourishment,

The building of solid constructions, only, reduced the retreat of the coastline, but not until a nourishment scheme was introduced, was the retreat brought to a halt. The annual coastal protection scheme of the Danish West Coast is planned on the basis of surveys, measurements and analysis of previous coastal developments, and the Danish Coastal Authority is continuously optimizing the coastal protection effort on the western coast of Denmark

In the current Joint Agreement covering the period from 2014 to 2018 two objectives have been implemented based on assessment and categorization of the impact of coastline retreat. The categorization serves as a means of prioritizing the resources of the joint agreement:

Stretches without slope protection, where homes and infrastructure are at risk and/or where there is risk of a dune breach during a storm and such an incident could lead to a flooding of the hinterland, the goal is to stop the coastal retreat.

At Havrvig and Skodbjerge, where the dunes have a small, extra sand buffer, the objective is to reduce coastal retreat to a maximum of one meter per year.

On stretches with slope protection, the objective is to reduce coastal retreat as much as possible with the remaining amount of sand for nourishment. Based on a calculation of the amount of sand available for nourishment, the coastal retreat can be limited to 3.2 m/year on the stretches where the natural retreat is above this objective.

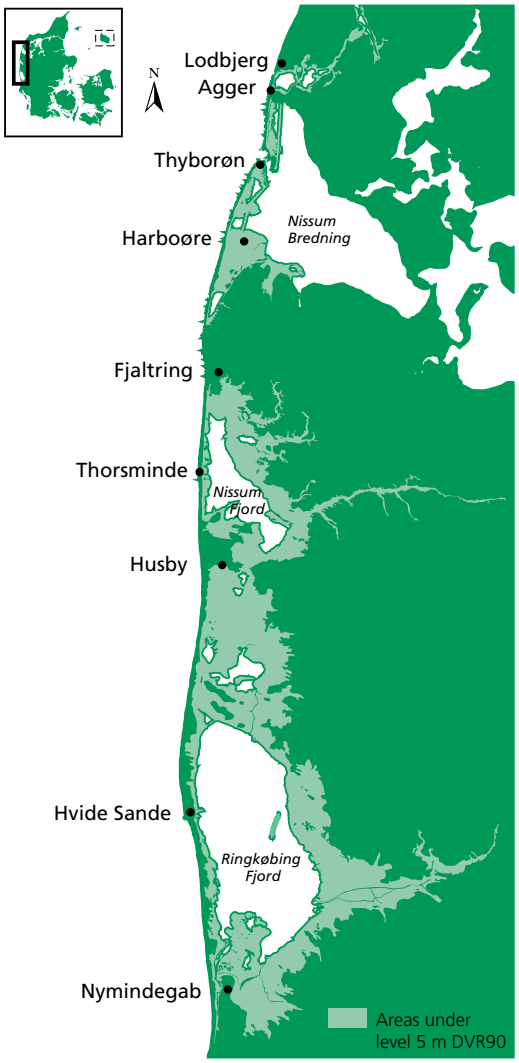

Figure 2 The 110 km stretch from Lodbjerg to Nymindegab. The map shows areas below 5 m DVR90.

The objective of the joint agreement for the period 2014-2018 is illustrated in Figure 3.

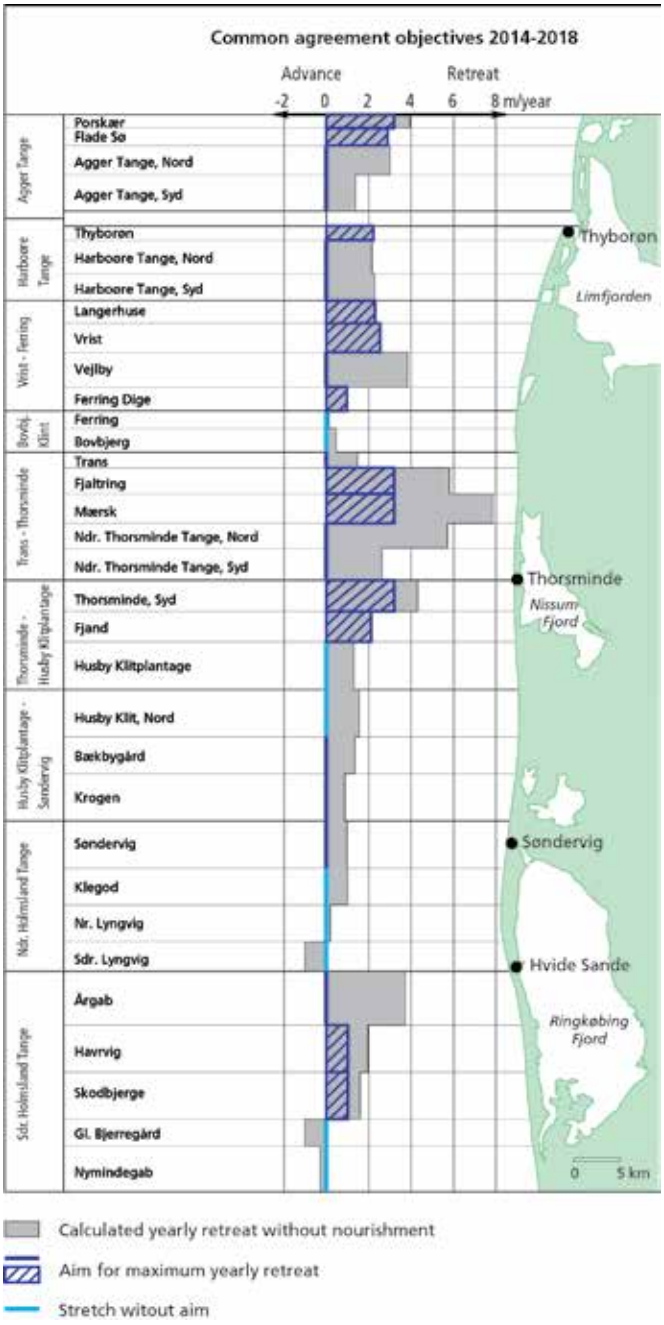

Figure 3: Joint agreement objectives 2014-2018

1.3 Safety Level of Joint Agreement from Lodbjerg to Nymindegab

The overall purpose of the Joint Agreement is to ensure that at the beginning of each winter season the dunes on this stretch of the coast will be resilient enough to withstand the erosion and prevent a breach during a storm with a 100 year return period. The only exception is Thyborøn where the objective is protection against a 1000 year storm event. The Joint Agreement for the coastline between Lodbjerg and Nymindegab specifies a safety level for erosion, which includes a protection level against dune breach and floods. This means that the dunes must have a minimum height and a minimum width based on the surveys and analyzes made by the Danish Coastal Authority.

Table 1 shows an overview of the different dune safety criteria on the coast between Lodbjerg and Nymindegab.

Stretch	Minimum dune height	Minimum dune width
Agger By	3.5 m	40 m [1]
Agger Tange	3.5 m	30 m
Thyborøn By	4.0 m	50 m
Harboøre Tange	3.5 m	30 m
Langerhuse til Bovbjerg	3.5 m	40 m
Bovbjerg to Husby Klitplantage	4.0 m	40 m
Husby Klitplantage to Nymindegab	4.5 m	40 m

Table 1: Dune safety criteria

This systems description will focus on the living laboratory Krogen which is found on the stretch Husby Klitplantage to Nymindegab.

This systems description will describe the area around Krogen, including the coastal protection, the local safety criteria and the factors affecting the area. The coastal system from the ocean to the hinterland will also be described.

1 *Minimum dune width 30 m where slope protection is in place*

2 The Area of Krogen

The area of Krogen has several interesting characteristics, which contributed to the decision to make it a Building with Nature living laboratory. The living laboratory of Krogen is located along the Danish North Sea coast, which is covered by the Joint Agreement between the local municipalites and the Danish state and the Danish Coastal Authority is responsible for meeting safety objectives on the coast. There are no hard coastal protection installations in the area but nourishments have been performed several times in the last decades. The nourishment scheme at Krogen is evidence of the apparent threat of dune breakthrough and subsequently flooding of the hinterland. This means that studying the system at Krogen can lead to a better understanding of the effects of beach and shoreface nourishments.

Figure 4 Location and photo of the living laboratory Krogen (© SDFE).

Krogen is located just north of Ringkøbing Fjord with Vest Stadil Fjord to the north, and Stadil Fjord to the east. The mainroad, Houvig Klitvej, runs parallel to the coast, about 700 m inland with the dunes to the west and the flat agricultural landscape to the east. At Krogen the road bends towards the coastline and is within about 170 meters of the vegetation line. Along Houvig Klitvej vacation houses are located in the dunes. The dune belt at Krogen was as narrow as 40 meters in 2012 and subsequently dune enhancement was performed in the area.

2.1 The Landscape at Krogen

The illustration in Figure 5 conceptualizes some of the important elements of the system at Krogen. Both shoreface and beach nourishment have been undertaken, dune enhancements have been performed, and vegetation has been established. Fully and partly exposed wartime bunkers are found along the beach and in the dunes. In the dunes and just behind them there are vacation houses. In the following, the geological setting, the coastal system, the land use and the infrastructure are described.

Figure 5: Schematic representation of the living laboratory at Krogen.

2.1.1 Geological Setting

The Danish landscape is primarily a glacial landscape; the coasts are predominantly made up from loose sediments and at the west coast the large amounts of available sand combined with consistent westerly winds have created dunes along the coast. The coastal dune landscape at Krogen consists of aeolian sand as well as marine sand and clay. In areas where the clay is exposed it affects the coastline resilience towards coastal erosion. Inland of the dunes the landscape consists of saltwater sand, lakes and moraine deposits. The seabed sediment is dominated by sand and small areas of till and gravel as well as coarse sand.

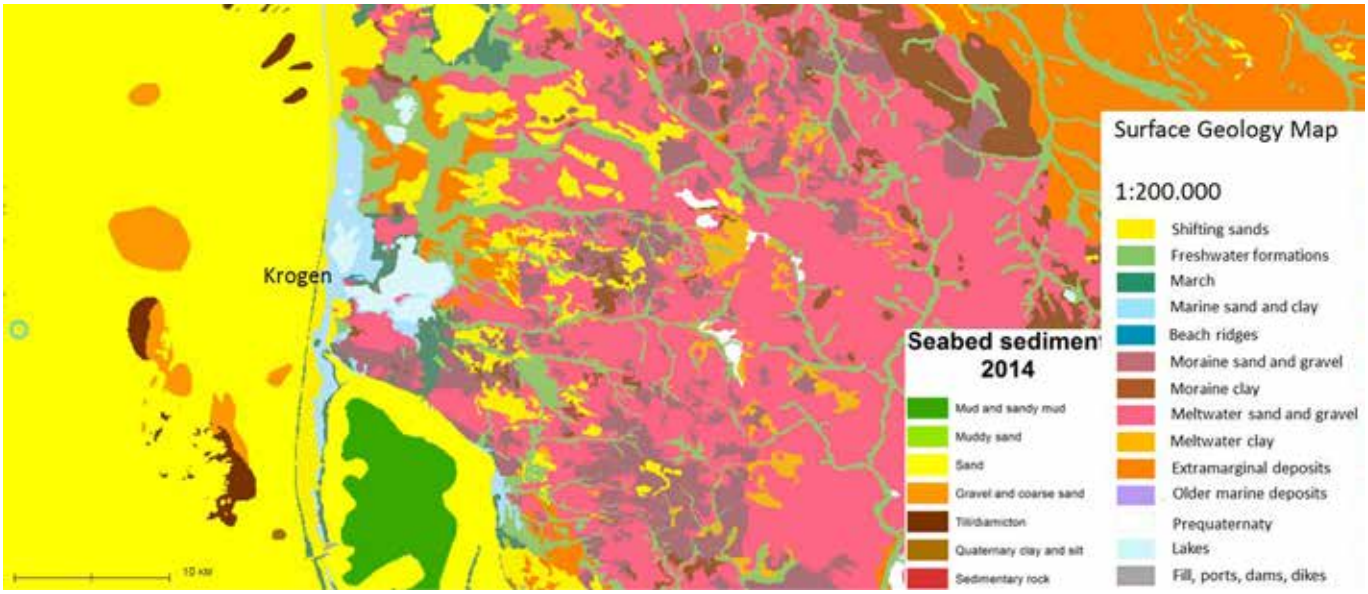

Figure 6: Map of seabed sediments and surface geology soil types (© GEUS)

2.1.2 The Coastal System

The Danish North Sea coast is a micro tidal wave dominated sandy coastline. The coast is highly dynamic and the morphology changes responding and adjusting to the climatic conditions. Large alongshore variations in the coastline have been documented along the Danish North Sea coast, rhythmic bar systems and separating rip currents create coastline perturbations and indentations, which migrate as the bar system migrates alongshore in the sediment transport direction. These coastline indentations are characterized by a narrowing of the beach, and mark potential erosional hotspots. The number of bars and the size and position in the offshore direction change rapidly, especially during storms the bars migrate offshore and under calm weather conditions they will migrate onshore and in some cases well on to the beach thus momentarily widening the beach.

At Krogen the morphodynamic changes are evident when comparing aerial photos. The variations in beach width, and the bar evolution are apparent in the photos from 1995, 2002, 2004, 2006, 2010, 2015 and 2017. The above described alongshore variations in coastline and bars are observed, as well, especially in 2008 and 2017. In 2010 a nearshore bar with relatively rhythmic rip currents is observed (Figure 7).

Figure 7 Arial photos covering Krogen from (© DDO 1954-2012, COWI), (© DDO 2015-2017, Geodanmark, SDFE)..

When examining the evolution of the coastline based on aerial photos the on-going beach and shoreface nourishments in the area should be taken into account as they blend into the natural dynamics. Untangling the natural variations from the nourishment effects is one of the main challenges of this study. The living laboratory has at least one sandbar and the dynamics and influence of the bar system will be further examined in the project as they influence the evolution and effects of beach nourishment.

2.1.3 Land Use and Infrastructure

At Krogen the main road, Houvig Klitvej, takes a turn to the west and is less than 170 meters from the dune front, the smaller access road to the vacation homes is within 50 meters of the dune belt, see Figure 4. Along the beach and within the dunes are both hidden and visible wartime bunkers. Vacation homes are scattered in and between the dunes, and further inland denser populations of vacation homes, such as Lodbjerg Hede, are found. The hinterland is mainly farmland used for grazing. Large parts of the area are governed by Natura 2000 and Ramsar legislation, as it is of great importance to migrating and nesting birds.

2.2 Threats to the Krogen Area

Storm surges are recurrent in the winter season at Krogen. A storm surge can be defined by the resulting water level during a storm. There is a connection between high water level due to storm surges and large waves generated by strong winds. The vulnerability of the area of Krogen is apparent when examining the Danish elevation model of the area. The scan from 2017 shows the narrow dune ridge.

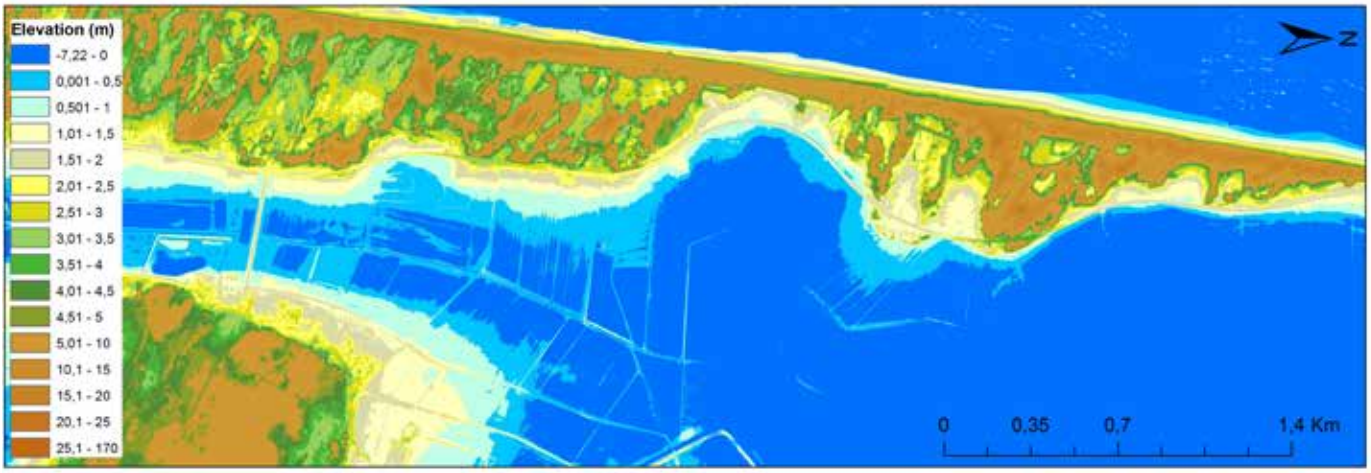

Figure 8 Map showing the Danish elevation model at Krogen (© Digital Elevation Model, 2014, SDFE).

Storms have high impact on the dunes, with risk of overtopping, erosion, breach and subsequent flooding of the hinterland. In the following sections the threats of erosion and flooding at Krogen are presented.

2.2.1 Erosion

Erosion can be categorized as either chronic or acute. Chronic erosion is long term and is often induced by alongshore gradients of the sediment transport; along coastlines where, as sediment transport rates increase, a sediment deficiency occurs leading to erosion of the coastal profile and a gradual landside displacement of the coastline. Acute erosion is temporary and occurs during storms with high water levels and high wave energy conditions (Acute erosion is part of the chronic erosion).The higher water levels and waves displace the erosional processes onshore leading to erosion of sediment on the back of the beach and the dunes. The Danish North Sea coast is recognized as an erosional coast which is subjected to chronic erosion caused by the southbound alongshore drift but furthermore, large acute erosion events will take place during storms, Figures 9 and 10.

Figure 9 Picture from Krogen/Krylen right after an acute erosion event in March 2008.

The chronic erosion at Krogen is about 1m/yr. As such, this erosion rate is not high compared to other sections of the Danish North Sea coast, see Figure 3, but serious, in the light of the narrow dune zone and the risk of acute erosion.

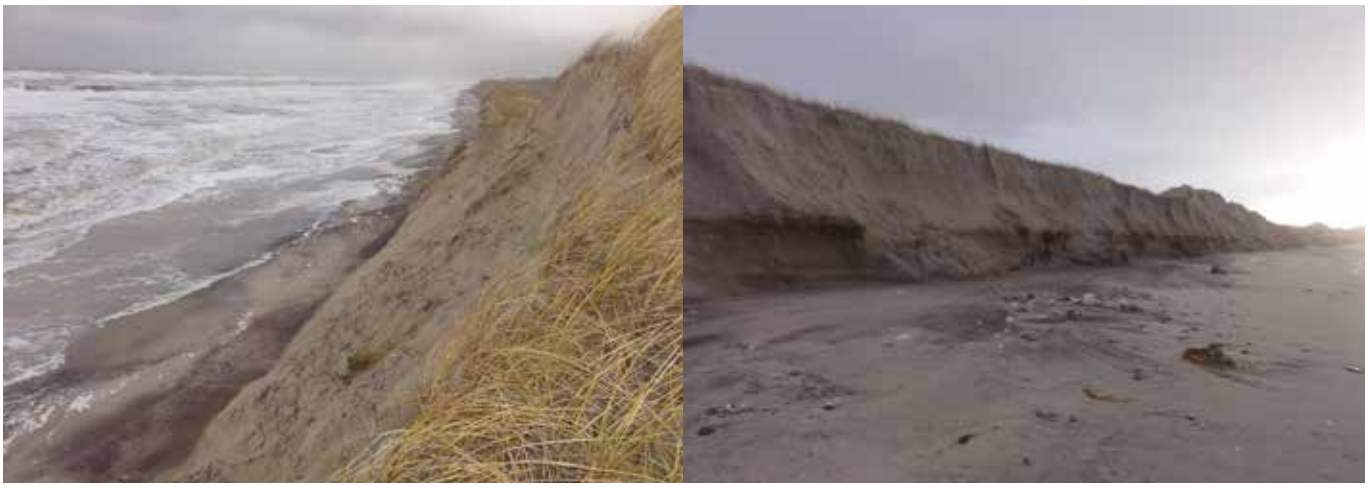

Figure 10 Pictures from Krogen/Krylen right after acute erosion event in January 2012.

Acute erosion at Krogen has previously influenced long stretches of dune, thus gradually exposing the bunkers which have been hidden in the dunes since they were built during World War II. Figures 9 and 10 show severe dune erosion at Krogen. The wave action during storms affects the dunes, eroding dune bases, which causes the dunes to collapse and makes erosion worse. In some areas the erosion was facilitated due to the presence of bunkers. The maximum recorded dune retreat at the Danish North Sea coast was 60 meters at Thyborøn and a retreat of 46 m was recorded at Vedersø in 1981 just 10 km north of Krogen. This indicates the scale of potential erosion at Krogen.

2.2.2 Flooding

The hinterland at Krogen is very flat and low; about 1 meter above sea-level with Vest Stadil Fjord to the north, Stadil Fjord to the east and Ringkøbing Fjord to the south. The 1 yr. and 100 yr. storm return periods are respectively; 2.02 and 3.11 meter above daily normal. In Figure 11 the national digital elevation model has been used to do a simple bucket fill analysis showing the area at risk in case of dune breach and subsequent flooding with a water level reaching as high as 3 meters above normal.

Figure 11: The maps show a flood risk analysis based on the national elevation model including houses. Left: Krogen, West Stadil Fjord, Stadil Fjord, and the most Northern part of Ringkøbing Fjord. Right: The local flood challenges at Krogen, especially to the vacation homes located in the dunes and along Houvig Klitvej (© Digital Elevation Model, 2014, SDFE).

This means that in the case of dune breach the water could spread far inland affecting vacation homes, farmland, infrastructure and protected nature (Stadil Fjord and Vest Stadil Fjord are governed by Natura 2000 legislation), and a potential flood might eventually reach Ringkøbing Fjord and the town of Ringkøbing. This scenario is mainly due to a connection between Stadil Fjord and Ringkøbing Fjord which means that if the dunes break at Krogen and water flows into Stadil Fjord the potential for flooding and damage is extensive. The potential damage could be economically significant due to valuable buildings and infrastructure in Ringkøbing. The inland barriers between Stadil Fjord and Ringkøbing Fjord are not fully capable of delaying the water, even though the dike height of 1.80 m is considered adequate..

2.3 Coastal Protection at Krogen

At Krogen both shoreface nourishment and beach nourishment have been undertaken, as illustrated in Figure 12. These were performed every year from 1996 to 2000 and then in 2003, 2005, 2007, 2008, 2009, 2012, 2015 and 2016 each to varying extent. In 1994, 1996, 2000 and 2001 scraping of the beach took place to better distribute the sediment that is deposited in the berm during calm weather. The Danish Coastal Authority no longer performs beach scraping, as this method has several disadvantages such as heavy machinery on the beach and interference with the natural distribution of sediment along the Danish North Sea coast.

At Krogen extensive work to enhance the dunes has been conducted to minimize the risk of erosion and flooding. Strengthening of the dunes has taken place in 1990, 2005 and 2008. The exact amount of sand, deposited as an enhancement in 1990, is unknown. Following the erosion event in March 2008 shown in Figure 12, the dunes were reinforced using 45,000 m³ of sand and the beach nourished with 176,000 m³ of sediment. The Danish Coastal Authority uses dead conifers, lyme grass and marram grass as a mean of stabilizing the newly established dunes. The final reinforcement and the nourishment process were photo documented which provides insight into the scale and placement of the beach nourishment and the reinforcement, see Figure 13 and Figure 14. The remodelled beach a year after nourishment is shown in Figure 15.

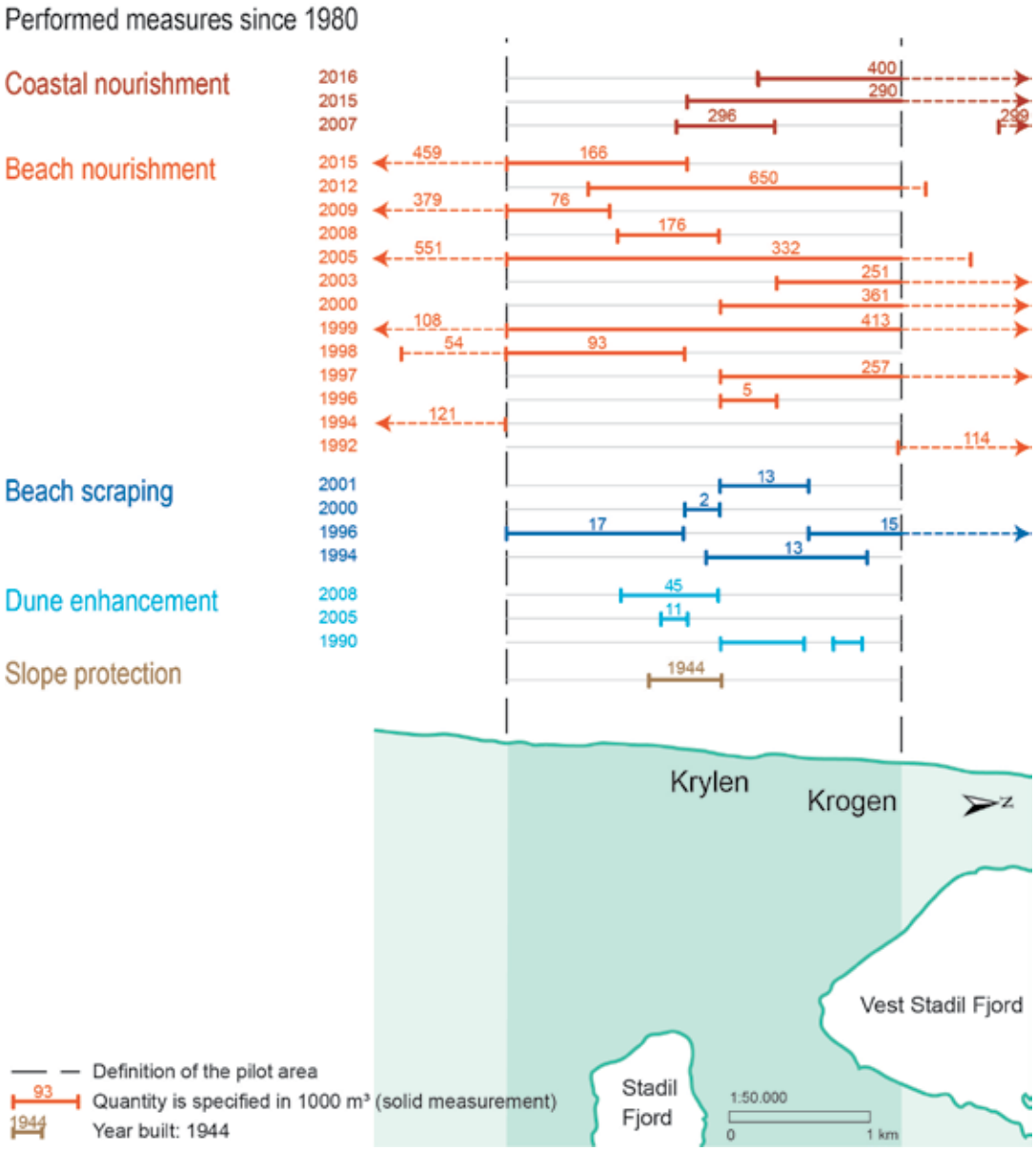

Figure 12: Performed measures at Krogen since 1980.

Figure 13 Dune reinforcement performed in September 2008.

Figure 14 Beach nourishment performed at Krogen/Krylen in September 2008.

Figure 15 Beach nourishment at Krogen/Krylen photographed in May 2009, a year after nourishment.

2.4 Effect of the Coastal Protection at Krogen

The effects of the coastal protection measures implemented as part of the Joint Agreement are evaluated at the end of each agreement period. Figure 16 shows the calculated annual coastal retreat without nourishment, the maximum accepted retreat as governed by the Joint Agreement and finally the actual annual retreat in the period of 2009-2016. At Krogen the expected erosion has been countered and an annual coastline advance of 2 meters has been observed from 2009 to 2016. This advance follows a period where the safety level e.g. dune strength at Krogen was compromised in 2007, see Figures 9, 13 and 14, this prompted extensive beach nourishment and dune enhancement in 2008. During the period from 2004-2016 the area of Krogen was nourished 8 times and the dune was enhanced, subsequently leading to an advance of the coastline and successfully countering the natural erosion. A continuous need for coastal protection is present at Krogen due to the substantial risk of erosion and flooding of the low hinterland.

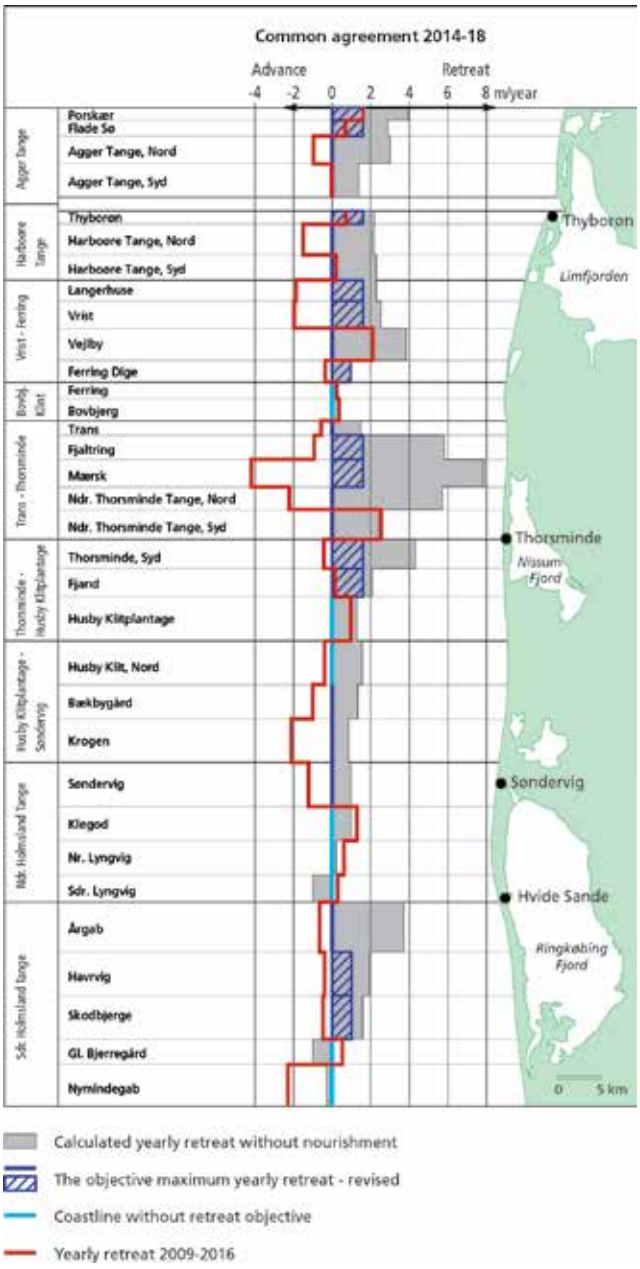

Figure 16 Evaluation of the costal retreat and advance along the Danish North Sea coast covered by the common agreement.

3 Source-Pathway-Receptor

The coastal system at Krogen can be described with a Source-Pathway-Receptor model.
In the Krogen system the sources are wind, waves, tide, marine surge and current. The model pathway is the coastal profile from the shoreface over the beach to the dunes. While the receptors are the infrastructure, vacation homes, Stadil Fjord, Ringkøbing Fjord, the towns along the two fjords and the protected nature around the Ringkøbing Fjord.

The consequence of the source action is erosion and retreat of the pathway (shoreface, beach, dunes) which can cause flooding at the receptor or erosion of the receptor. To prevent the sources from causing retreat and flooding, the pathway is strengthen with modifications such as nourishment, different kinds of hard coastal protection and planting of vegetation on the dunes. The BWN project focuses on modification of the pathway by using solutions based on nature.

Figure 11 shows the source-pathway-receptor-model in a schematic form.

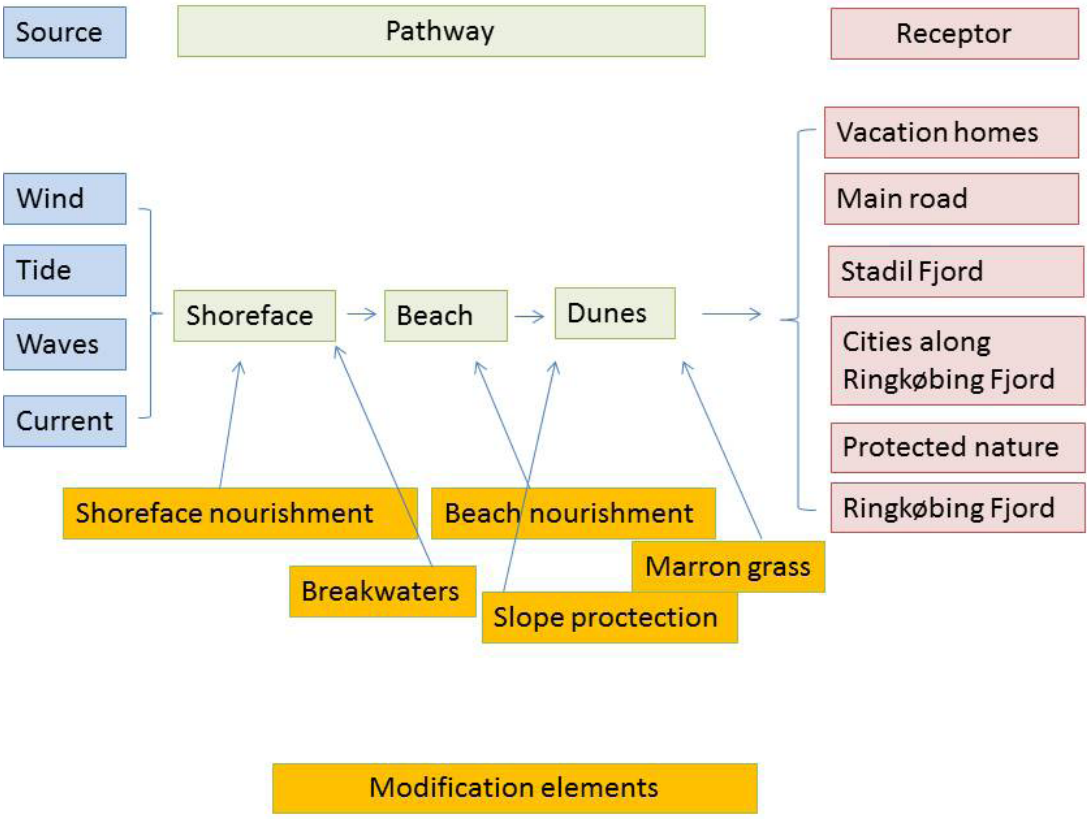

Figure 17: Shows the source, pathway and receptor model

Through the Building with Nature project different aspects of the modification elements in the pathway will be analyzed at Krogen.

The development of a shoreface nourishment will be analyzed in the software program Morphan. The storm data in the area will be used to make a classification of storms.

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